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Analysis of requirements and definition of specifications for obstacle detection and track intrusion systems

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Table of Contents

Executive Summary

This report presents the results of the Task 1.2 (RAMS-related requirements), Task 1.3 (Technical requirements) and Task 1.4 (Technical specifications for all potential sub-systems and their interfaces), which will be considered in further SMART2 activities within Work Package 1 "WP1 Use Cases, Requirements and Specifications" of the SMART2 project.

Deliverable D1.2, together with Deliverable D1.1, presents the base for the realization of further activities in WP2-WP6. It comprises all relevant information for development and evaluation of Obstacle Detection and Track Intrusion Detection (OD & TID) systems.

The introductory part comprises information about the background of the SMART2 project, in general and of Task 1.2, Task 1.3 and Task 1.4 in particular (in Section §1), and about the specific objective of the tasks (in Section §2).

The following Section §3 presents the summary of use cases for OD&TID system defined in SMART2 Deliverable D1.1.

Section §4 provides an overview of the overall requirements for OD&TID systems.

The following Section §5 presents an overview of SMART2 OD&TID concept as well as an overview of the possibilities for SMART2 evaluation tests. These overviews are followed by the requirements for SMART2 OD&TID system.

Section §6 presents technical specifications of the development prototype of the SMART2 OD&TID system.

Finally, Section §7 draws the conclusions of the study.

The list of references cited in this document D1.2 is given in Section §8.

The Appendix presents the state of the art in technologies relevant to SMART2 subsystems.

Abbreviations and acronyms

Abbreviation/ Acronym	Meaning
ARC	Air Risk Category
ARCC	Automated Rail Cargo Consortium: Rail freight automation research activities to boost levels of quality, efficiency and cost effectiveness in all areas of rail freight operations (S2R IP5 project)
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
AUT	Rail authority
AWS	Automatic Warning System
BVLOS	Beyond Visual Line of Sight
CCS	Control Command and Signalling
CCTV	Closed-Circuit Television
DB	Deutsche Bahn (German Railways)
DSS	Decision Support System
EASA	European Union Aviation Safety Agency
ERA	European Rail Agency
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
GIS	Geographic Information System
GoA	Grade of Automation
GRC	Ground Risk Class
GSM-R	Global System for Mobile communications for Railways
HMI	Human-Machine Interface
HS/HC	High-speed/High-capacity
IM	Infrastructure manager
IP2	Innovation Programme 2 of Shift2Rail (Advanced Traffic Management and Control Systems)
IP5	Innovation Programme 5 of Shift2Rail (Technologies for Sustainable & Attractive European Rail Freight)
JARUS	Joint Authorities for Rulemaking on Unmanned Systems

LADAR	LAser Detection Active Ranging
LiDAR	Light Detection and Ranging
LMA	Limit of Movement Authority
MAAP	Multi Annual Action Plan
OD	Obstacle Detection
OD & TID	Obstacle Detection and Track Intrusion Detection
OPTIYARD	OPtimised real-TIme YARD and network management (S2R IP5 project)
OTH	Other end-users
RADAR	Radio Detection and Ranging
RAMS	Reliability, Availability, Maintainability and Safety
RU	Rail undertaking
S2R	Shift2Rail Joint Undertaking (under the H2020 framework)
SBB	Schweizerische Bundesbahnen (Swiss Federal Railways)
SMART	Smart Automation of Rail Transport (S2R IP5 project)
SNCF	Société Nationale des Chemins de fer Français
SORA	Specific operations risk assessment
SRI	Serbian Railways Infrastructure (Serbian Cyrillic: Инфраструктура железнице Србије)
SWIR	Short Wave InfraRed
TID	Track Intrusion Detection
TMS	Traffic Management System
TPWS	Train Protection & Warning System
TSI	Technical Specification for Interoperability
UAV	Unmanned Arial Vehicle
UC-FS	Freight specific use cases
UC-GAF	General use cases, also applicable to freight
VLOS	Visual line of sight
X2RAIL-1	Start-up activities for Advanced Signalling and Automation Systems (S2R IP2 project)
X2RAIL-4	Advanced signalling and automation system - Completion of activities for enhanced automation systems, train integrity, traffic management evolution and smart object controllers (S2R IP2 project)

List of figures

List of tables

Glossary of terms

Term	Definition / Description *
Active sensors	Active sensors emit energy and detect the return of that energy from the surroundings, such as radar.
Drone-based OD&TID system	Sensors mounted on a drone used for detection the objects on the/near the track
Operational Efficiency	Ratio between the outputs gained from an operation versus the inputs to the operation, such as the profit earned as a function of operating costs.
Obstacle Detection	Detection of objects on the rail tracks ahead of the train, which are not supposed to be presented on the railway tracks and present potential hazard
On-board OD&TID system	Sensors mounted onto the front profile of the locomotive (or driving/control vehicle), used for detection of objects on the/near the railway tracks
Passive sensors	Detect and respond to different inputs from the physical environment, such as cameras that capture reflection of sun energy in visible wavelengths or remission of energy from the objects in thermal infrared wavelengths
Resilience of Operations	The ability of a system (e.g., the railway system in our case) to resist absorb, accommodate and recover quickly from disruptions or disasters, and therefore the ability of the system to maintain services at, or return services to the same level as under normal or optimal conditions
Sensor (Data) Fusion	Method used to combine input from multiple independent sensors to extract and refine information not available through single sensors alone.
Track Intrusion Detection	Detections of objects near the rail tracks. If objects are people near the rail tracks, they represent possible intrusion if they are not authorised persons
Trackside OD & TID system	A sensor system located at or near the trackside used for detection of objects on, near, or approaching the track, which are currently or potentially obstacles, or have intruded or could intrude on the railway environment.
User Interface	Interface designed to display appropriately the information from, or about the OD & TID system to meet the needs of the user, i.e., a person involved in the operation of the railway system.

* The above glossary includes a list of key specific terms that are used throughout the SMART2 project, and their definitions and/or descriptions, as adopted and used by the project consortium. It should be noted that the definitions are not strictly those in dictionary and/or standards, and some of them have been slightly adjusted to better reflect the project approach and specific use of these terms.

1. Background

This document represents the Deliverable D1.2 “Analysis of requirements and definition of specifications for obstacle detection and track intrusion systems” of the Shift2Railfunded project SMART2.

The SMART2 project is part of Innovation Programme 5 (IP5) “Technologies for Sustainable & Attractive European Rail Freight” of the Shift2Rail (S2R) programme, within the framework of Horizon 2020. The present document constitutes the Deliverable D1.2 “Analysis of requirements and definition of specifications for obstacle detection and track intrusion systems” in the framework of the TD5.1 – Fleet Digitalisation and Automation and, in particular, TD 5.1.3 – Freight ATO of IP5 (Shift2Rail MAAP version November 2015 and ANNUAL WORK PLAN and BUDGET for 2019).

In addition, the Shift2Rail members involved in the Innovation Programme 2 (IP2) “Advanced traffic management and control systems” are working towards the completion of a Technology Demonstrator, TD 2.2 - Railway network capacity increase (ATO up to GoA 4), which addresses general traffic, for both freight and passenger trains. Therefore, due to significant synergies with activities and developments planned in the same period in IP2, SMART2 is complementary to the IP2 project, X2RAIL4 (Advanced signalling and automation system - Completion of activities for enhanced automation systems, train integrity, traffic management evolution and smart object controllers), and will provide relevant contributions towards the achievement of D2.2_1 of IP2 - ATO (from GoA2 up to GoA4) for different Railway market segments.

In this context, the analysis of requirements and definition of specifications for obstacle detection and track intrusion detection systems, in agreement with Shift2Rail members involved in IP2 and IP5, is essential for subsequent activities in the SMART2 project.

According to use cases identified and discussed in the first report of Work Package 1, D1.1 “Freight specific use cases for obstacle detection and track intrusion systems”, requirements and specifications for OD&TID systems have been defined for selected use cases, to which the SMART2 concept is highly relevant.

The SMART2 objective is to research, innovate, implement and validate advanced holistic obstacle detection and track intrusion detection (OD&TID) system for railways. In that sense, SMART2 will develop a prototype of a novel holistic OD&TID system for railways, consisting of three sub-systems, on-board and trackside/airborne, which will be demonstrated in a realistic environment under realistic test conditions (TRL 6/7).

2. Objective

This document has been prepared to present the outcomes of work carried out in Task 1.2 “Overview and analysis of RAMS and Security related requirements”, Task 1.3 “Overview and analysis of technical requirements” and Task 1.4 “Technical specifications for obstacle and track intrusion detection system” within Work Package 1 “WP1 Use Cases, Requirements and Specifications” of the SMART2 project.

The focus of all three above mentioned tasks has been on requirements of end users (IMs and RUs) and industry stakeholders from S2R Members in IP2 and IP5.

The specific objective of Task 1.2 is to analyse and review RAMS-related requirements of OD&TID systems as to whether they are applicable or suitable for the freight specific use cases, and use cases common to all types of traffic. The task has been divided into two sub-tasks, one focusing on reliability, availability, and maintainability (RAM) aspects, and the other focusing specifically on safety and security aspects.

The outcomes of this task have been used as input into Task 1.3 to support the definition of technical specifications, and into Task 1.5 for further assessment and definition of a new set of requirements for the proposed system.

The specific objective of Task 1.3 is to review and assess technical requirements for OD&TID systems, including all potential sub-systems and their interfaces, as to whether they are applicable or suitable for the freight specific use cases. The task has been divided on three subtasks, one focusing on Diagnostic system requirements, the second one focusing on Object Classification and Detection Requirements and the third one focusing on Open Interfaces Requirements.

The outcomes of this task have been used as input into Task 1.4 to support the definition of technical specifications, and into Task 1.5 for further assessment and definition of a new set of requirements for the proposed system.

Additionally, Task 1.2 and Task 1.3 outcomes would be used as benchmark for assessing the system performance after the prototype testing in WP6.

Starting from the requirements identified in Task 1.2 and Task 1.3, the specific objective of Task 1.4 is to define high-level specifications of the overall OD&TID system prototype to be developed in the SMART2 project, considering all potential sub-systems and their interfaces.

This deliverable elaborates the first set of requirements. These would be continuously updated with respect to inputs from S2R members working on complementary project X2RAIL-4 in IP2. A constant exchange of information with the complementarity project will be established, so as to ensure that the requirements developed in X2RAIL-4 are considered for the proposed system.

Following on from the outcomes of Tasks 1.2 and 1.3, reported in this deliverable, further inputs and feedback from the X2RAIL-4 project will be considered in Task 1.5, which will harmonise the requirements for the OD&TID system with those of relevant traffic management and control systems required for the implementation of a standard ATO system up to GoA 3-4, both existing ones (e.g., ERTMS) and emerging ones, under development (e.g., train integrity system, moving block, virtual coupling, etc.). The outcome will be deliverable D1.3 “Recommendation for a new set of lower complexity requirements for obstacle and track intrusion detection system”.

3. Summary of use cases for OD&TID

This chapter presents the relevant use cases (UC) that have been identified and analysed by the SMART2 consortium in relation to further development of the OD&TID system, which is the scope of the project.

Potential use cases for OD&TID systems have been identified and analysed in (SMART2 D1.1, 2020). The analysis and subsequent description of each use case has considered inputs received from stakeholders, particularly from those involved in Shift2Rail IP2 and IP5.

The use cases have been defined and classified with respect to **two major aspects/criteria:**

- Railway operation type that the use case relates to, which determines two categories:
  - Use cases relating to general railway traffic (passengers and freight), which apply to freight operations;
  - Use cases that are specific just to freight operations;
- The grade of automation (GoA), which determines two major categories:
  - Use cases in GoA 0-1 scenarios, mostly driver-assisted;
  - Use cases in GoA 2-3-4, involving Semi-Automatic Train Operation (SATO) and Automatic Train Operation (ATO).

A general description of each of the identified use case is presented in (SMART2 D1.1, 2020) with specific details. Use cases have been analysed with respect to the following aspects and features, which are essential for designing the OD&TID system:

- **Scope and brief description** of the use case, including the GoA conditions under which the train is operated, and scenario(s) that apply to train operations in the use case;
- **Involved stakeholders** (actors), which include the primary system actors, primary business actors and other interested parties (such as: secondary line manager, yard manager, safety investigation bodies, etc.);
- **Frequency of use,** i.e., the estimated frequency of use of the proposed OD & TID system during the operation of a freight train;
- **Pre-conditions,** which describes the conditions which must exist for the use case to be applied, both in terms of the conditions and procedures concerning the operation and control of trains, and the functionality and status of the OD & TID system;
- **Typical use case implementation** takes into consideration the main actions carried out by the OD & TID system in a number of different circumstances, the expected response to be made by the actors and systems involved in each use case, and set of circumstances with regard to the actions of the OD & TID system;
- **Post-conditions,** which describes the condition that the train ends in as a result of the action made by the OD & TID system and involved actors, in different scenarios considered for each use case;
- **Post-use scenario** describes the condition of the train and OD & TID system after the use

case, with respect to specific scenarios considered for each use case;

- **Implementation constraints, risks and requirements** mainly include compatibility requirements for the OD & TID system with the ETCS and TMS systems, risks due to hazards and failures related to the system, and special requirements for each use case;
- **Estimated priority** is the priority level with respect to the requirements of users and business criteria;
- **Assumptions and open issues** describe unspecified or uncertain conditions that the OD & TID system, which might affect the implementation of the OD & TID system in particular, and the use case in general.

The list of Use Cases has been given here and the detailed description of each of use cases has already been presented in (SMART2 D1.1, 2020).

The listed Use Cases below present the base for specifying OD&TID requirements on general level and for defining technical requirements and specification for SMART2 demonstrator.

3.1 General use cases applicable to freight (UC-GAF)

- Operation on mainline with reduced visibility due to temporary environmental conditions (GoA 0-1)
- Operation on mainline sections with vision issues (GoA 0-1)
- Operation on mainline sections with specific hazards – reduced visibility due to permanent causes (GoA 0-1)
- Operation on mainline sections with specific hazards – constructions sites (GoA 0-1)
- All conventional ATO trains on mainline (GoA 2-3-4)
- All ATO trains on marshalling yard, depot, or similar controlled environment (GoA 2-3-4)

3.2 Freight specific use cases (UC-FS)

- Freight train with long stopping distance operating on mainline (GoA 0-1)
- Freight train with long stopping distance operating on mainline (GoA 2-3-4)
- Freight train operating on shunting yard or similar controlled environment (GoA 0-1)

4. Overall requirements for OD&TID system

The outcome of the analysis of the use case requirements by SMART2 is the proposal of a set of requirements for obstacle and track intrusion detection systems for all use cases, with emphasis on freight use cases. These proposed requirements have been specified, defined, and classified in terms of the functional requirements, operational requirements, and capability features of the OD&TID systems. This will provide a common framework for considering the requirements for all use cases, identifying common areas and areas of difference, allowing harmonisation and integration of OD&TID systems; it will also form a reference point for other systems involved in ATO.

This will be a significant advance beyond the current state where individual systems associated with rail automation are defined separately and generally without consideration of the freight use case. It will also provide a framework for considering all requirements for rail automation systems which, if adopted for other automation systems, could contribute to the development of harmonised and interoperable rail automation systems which meets the requirements for creating an integrated system suitable for all use cases. This could then be integrated into technical standards and standards for interoperability related to automation of large rail networks which is an area which needs further definition if an efficient interoperable system of automated rail operation is to be developed in the future, and the SMART2 classifications for general and freight use cases could be adopted directly.

In order to provide high-level requirements and specification for OD&TID systems, ***four types of requirements*** have been considered, analysed and defined: performance, functional, operational, and compliance with regulation and standards. All these types of requirements have been divided into ***three categories:***

1. RAM – related to reliability, availability and maintainability (RAM) aspects;
2. Safety & Security (S&S) – related to safety and security; and
3. Technical – those tackling technical features of the system, meant to be directly addressed by specifications of subsystems and interfaces.

The performance/KPI-related requirements describe how well the system and its subsystems will perform certain functions. The speed of response, interface throughput, execution time, storage capability, and detection capability, while equipment reliability are considered in RAM performance requirements. The S&S performance requirements mainly relate to the SIL standard which the system should comply with, and the compliance with regulation and standards requirements deal with the regulations and standards the system should comply with in order to be considered suitable for use as part of the railway system and within the overall environment.

The functional requirements relate to functions of the entire system or its subsystems, which shall determine the response of the system in different scenarios. The RAM related functional requirements take into consideration time/distance-based failure rate and mean time between maintenance of the system and subsystem. The S&S functional requirements relate to the capability of the system to resist hazardous incidents in its operational circumstances.

Operational requirements relate to the needs of train operators, railway operators and yard operators, and consider aspects such as failure diagnose and maintenance, risk forecast and data generation and analysis. Compliance requirements benchmark the compliance of the OD& TID system to existing standards and regulation, which ensure the interoperability of railway operation across the EU countries.

All the requirements are described with respect to four features including:

1. requirement description;
2. related end-users; these include: infrastructure managers (IM), rail undertakings (RU), rail authorities (AUT) and other end-users (OTH);
3. related use cases (see the use cases summarised in §3); and
4. obligatoriness with respect to envisaged SMART2 concept; the requirements have been assessed as: Mandatory, Recommended and Not Applicable (N/A).

The complete list of all four types of overall requirements for OD&TID systems is presented in the following sub-sections.

4.1 Performance Requirements (KPIs)

In order to assess the performance of the OD&TID system with respect to certain functions under specific conditions, Performance requirements have been defined and analysed.

Performance requirements fall into the broader category of non-functional requirements, which specify criteria that can be used to judge the operation of a system, rather than its specific behaviour. They are contrasted with functional requirements that define specific behaviour or functions.

4.1.1 Reliability, availability and maintainability (RAM) performance requirements

In order for the system to fulfil its role and function effectively, it must be:

- reliable in its function;
- operational and available;
- maintainable, for being kept in a reliable and operational condition.

The OD&TID system must carry out its functions reliably, since safety critical decisions are to be made based on the outputs of the system, whether that be outputs related to the detection of obstacles, outputs indicating that there are no significant objects detected in the area of interest, or outputs related to the condition of the system. The system reliability depends on the reliability and the accuracy of the output, not just the presence of the output. The system must also have high availability, i.e., it must be in operational condition and fully functional as near to possible continuously, since the lack of availability could significantly affect the ability to operate trains safely. Also, it must be technically and economically feasible to maintain the system in operational condition, otherwise basing the operation of trains on output from the system would not be viable in the long-term; this includes the ability to upgrade and modify the system in the future as requirements, complementary systems, and technology changes.

The requirements described below specify the required RAM-related characteristics of the system in order for the system to operate according to its functions and specifications.

KPI-RAM-01 System shall check the system interfaces and the connection between sub-systems. The system should check the robustness of the system continuously and detect system failures and generate feedback.

Required by: rail undertaking (RU) and infrastructure manager (IM), to enable checking of system connectivity and sub-system interconnectivity, to verify the reliability and completeness of the results and level of system functionality.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

KPI-RAM-02 RAMS Design verification shall ensure various functions to detect hazards perform better or equal to existing detection method in majority of conditions (longer range, more reliably, less affected by conditions) and verify the compliance with specified RAMS requirements.

Required by: rail undertaking (RU) and infrastructure manager (IM).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The various functions formulated should:

- predict the RAMS performance for detecting hazard efficiently for different conditions, e.g., longer range, night vision, blurred sunlight etc.;
- compare the performance of functionalities with that of old systems (e.g., driver observation).

KPI-RAM-03 (a) OD components of the OD&TID system shall be active at least as far ahead of any train as necessary to detect any hazards within the breaking distance of the train.

Required by: rail undertaking (RU) and infrastructure manager (IM).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

This requirement states the minimum active period for OD components (applies to trackside components, in particular); however OD components could be active continuously or for a significant period in advance of approaching trains to detect obstacles sooner and enable more effective and timely mitigation actions (e.g., avoid or wait at previous station rather than emergency stop).

KPI-RAM-03 (b) TID components of the OD&TID system shall be configurable to be active either in relation to the approach of a train (at least as far ahead of any train as necessary to detect any intrusion within the breaking distance of the train), or continuously.

Required by: rail undertaking (RU) and infrastructure manager (IM).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

KPI-RAM-04 The speed of data processing for Identification of obstacles shall be such that it is completed in the required time for the determined maximum system load.

Required by: rail undertaking (RU) and Infrastructure Manager (IM) to evaluate the output and inform IM, OTH and AUT.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

Obstacle and Intrusion detection and identification data acquisition and processing must be done in real time. The system shall reliably process the data in the required time, regardless of the number of simultaneous objects or processes, up to a pre-determined maximum number, i.e. the system must not only respond in the required time for a single detected object but also if a reasonable number of objects are detected simultaneously.

KPI-RAM-05 The connection between TMS, signalling subsystem and OD&TID detection system shall be in real-time, with minimum communications lag; any lag shall be within predetermined limits for all levels of system load.

Required by: Infrastructure manager (IM), yard management (IM/RU/OTH) and railway undertaking RU (operating loco) to evaluate the output depending on the scenario.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

KPI-RAM-06 The OD&TID system shall ensure management of data storage at all points in the system to enable reliable capture and high availability of data. System and components/sub-systems shall have sufficient data storage allocated from its total data storage capacity ready for an approaching train or next period of operation (relating to trackside and on-board (or continuously operating trackside) respectively) and enable erasing of the oldest/least relevant data from storage. If an incident is identified, system should ensure that relevant data is protected from deletion.

Required by: IM, RU, AUT and OTH to ensure data capture and availability for evaluation with respect to different scenarios.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The components of the system should have enough data storage capacity for the current object detection process and the storage of data from the previous time frame. In principle, the oldest data should be deleted from the longer term storage to create space for the ongoing process. However, the system should preserve data identified as being relevant to an incident (e.g. collision with object) to be available for an investigation, this could either be preserved locally or until it is confirmed as having been moved to storage specified for incidents/long-term storage elsewhere. The total capacity should be sufficient for multiple object detection processes.

KPI-RAM-07 The complete OD&TID system shall perform reliably and efficiently according to strategic analysis performed during the design of the system considering various factors such as:

1) *Weather;*
2) *Environment;*
3) *Power cut;*
4) *Software failure;*
5) *Infrastructure failure;*
6) *Unexpected situations.*

Required by: IM, RU, AUT and OTH to ensure system is fit for purpose.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The strategies include characterising Failure Mode effect and Criticality Analysis (FMECA) or Reliability Block Diagram (RBA) for inter-correlation of failures of the subsystem and system all together.

KPI-RAM-08 System architecture shall enable integration of new OD&TID system with existing systems with minimum effort and in a short time.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

KPI-RAM-09 OD&TID System shall perform reliably and efficiently both as an individual subsystem and also in coordination with the TMS/signalling system according to the risk assessment analysis considering various factors like:

1) *Weather;*
2) *Environment;*
3) *Power cut;*
4) *Software failure;*
5) *Infrastructure failure;*
6) *Unexpected situations.*

Required by: IM, RU, AUT and OTH to ensure system is fit for purpose and interacts effectively with other systems critical to its role.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The Assessment for the hazard analysis includes first the characterization of Failure Mode effect and Criticality Analysis (FMECA) or Reliability Block Diagram (RBA) for inter-correlation of failures of the subsystem and system altogether. For RAM, a distinctive risk acceptance principle (RAP) is to be followed to assure tolerable safety risk of a railway system is dependent upon the risk acceptance criteria (RAC) which is used to give weightage to the different failure mode.

KPI-RAM-10 Trackside OD&TID systems shall be inspected under preventive maintenance and enable the replacement of faulty parts onsite immediately with modular replacements.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The purpose of this requirement is to ensure the system and system reliability can be maintained effectively.

KPI-RAM-11 On-board OD&TID mounted on the driving/controlling vehicle shall be inspected under preventive maintenance and enable the replacement of faulty parts onsite immediately with modular replacements.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The purpose of this requirement is to ensure the system and system reliability can be maintained effectively.

KPI-RAM-12 The RAMS performance of the components and whole system should be better than, or at least equal to current train control and operations systems.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The introduction of the OD&TID system, as required by an essential function for the operation of trains, should not adversely impact the reliability of the operation of the railway network, and the new advanced train control and operation system as a whole should be more reliable than the current conventional system(s), or at least as reliable. As a benchmark, the OD&TID system should be more reliable than current systems or subsystems of equivalent criticality to the safe operation of trains, such as current signalling, interlocking, operational control systems, etc. A lower level of RAMS performance of components and sub-systems associated only with yard operations might be tolerated, as the safety and operational impact of a failure concerning a yard might be lower (lower speed means reduced consequences of incident, and fewer trains and parts of the network affected by some yard failures with easier mitigations). RAMS performance should be compared with respect to operating environment.

KPI-RAM-13 The mean time/distance between service failure (MTBF/MDBF) shall be as large as possible.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The reliability and availability of the OD&TID system will be affected by the frequency of failures, therefore, the time/distance between failures shall be as large as possible, and sufficient to enable the reliable operation of the railway network. However, minimising failures is a compromise between the cost of making the system reliable (e.g., building in redundancy) and the cost of failures; the frequency of failures of the OD&TID shall be as low as possible without excessive costs. Where possible, failures should be predictable by monitoring or statistically. A lower MTBF/MDBF of components and sub-systems associated only with yard operations might be tolerated, as the safety and operational impact of a failure concerning a yard might be lower (lower speed means reduced consequences of incident, and fewer trains and parts of the network affected by some yard failures with easier mitigations).

KPI-RAM-14 Lifecycle of the system shall be cost effective.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

Cost of installing, maintaining, upgrading/replacing and disposal of the system should be economically justifiable in relation to labour savings (enabling driverless trains), capacity increase, and safety improvements.

4.1.2 Safety and security (S&S) performance requirements

In order for the system to fulfil its role effectively, it must be safe and secure.

The main safety and security aspects relate to:

- The accuracy of the output. The accuracy of the output of the system is important because safety critical decisions are to be made and implemented on the basis of that output. The accuracy of the output might be related to the detection, determining the location, and identifying objects and obstacles accurately. An example of where the accuracy might be important would be where a rock on the track (substantial object posing a potential derailment risk) being inaccurately identified as an empty plastic bag (insubstantial object), which could lead to an inappropriate output and response to the output in terms of the potential effect of the obstacle on the safe operation of trains, and the response to the detection of the object.
- Detection of failures in the system. In addition to the accuracy of the system operating nominally, it is important that any failures or degraded operational states of the system are detected; this is, so that operational decisions can take into account potential failure, including its effect on the output of the system. An example of this would be avoiding situations such as where the failure of a sensor is not detected and the lack of an obstacle detection from that sensor is treated as there being no obstacle, rather than the presence of an obstacle being an unknown due to the failure of the sensor.
- The security of the system processes. It is important that the system is secure so that the output of the system can be relied upon as being true and accurate and free from interference; as part of this, the system should detect intrusion attempts and other forms of interference or attempted substitution of data.

The requirements described below specify the required safety- and security-related characteristics of the system in order for the system to operate at the required level of performance according to its functions and specifications.

KPI-SS-01 OD&TID system shall be able to detect and quantify loss of performance of operation on a subsystem and/or component level, whether on-board or trackside considering various factors like:

1) *Weather;*
2) *Environment;*
3) *Power cut;*
4) *Software failure;*
5) *Component/sub-system failure;*
6) *Infrastructure failure;*
7) *Unexpected situations.*

Required by: IM, RU and OTH evaluate the output with respect to different scenarios.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

Failure Mode Effect and Criticality Analysis (FMECA) or Reliability Block Diagram (RBA) analysis shall be carried out to find points of failure in the system. Quantification of loss of performance could be used in the hazard analysis, i.e. loss of performance of OD&TID system increases the hazard level for operating trains.

KPI-SS-02 The OD&TID system (and associated systems) and the operational procedures related to the use of the OD&TID system shall prevent/detect human/software errors, to ensure robustness of the system.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The OD&TID system (and associated systems) and the operational procedures related to the use of the OD&TID system, including the process for implementing actions based on the output, or failure of, the OD&TID system shall prevent/ detect human/software errors

KPI-SS-03 The hazard rates of the system shall be acceptable according to accepted established safety principles and standards.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

One of the established safety principles: the “Globalement Au Moins Aussi Bon” (GAMAB) principle of France, the “Minimum Endogenous Mortality” (MEM) Principle of Germany and the British “As Low as Reasonably Practicable” (ALARP) principle should be used to determine the acceptability of the risk/hazard rates.

KPI-SS-04 The system shall produce an alert when failures of one or more subsystem of the OD and TID system are detected, and output the diagnosis of the source of the failures.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

Common Cause Failure (CCF) analysis should be carried out considering design, location, maintenance, software failure, etc., which can cause failure of one or more subsystem together, which may lead to complete failure of whole system.

KPI-SS-05 The safety functions of the system shall comply with the safety requirements up-to SIL 4.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

A lower SIL of components and sub-systems associated with yard operations might be tolerated, as the consequences of a failure concerning a yard might be lower (lower speed and no passengers), however staff, assets, and environment still at risk.

4.1.3 Technical performance requirements

The technical performance requirements cover technical demands related to non-functional performance requirements. These requirements are based on technical requests that have to be fulfilled such as (among others) obstacle detection range and communication between different parts of described system.

KPI-T-01 Obstacle detection range. OD& TID system shall detect existing (i.e., those already in place) large obstacles (hazards to train) sufficiently far in advance of the train for the train to be able to stop before colliding with the obstacle

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator</u>: Recommended

OD&TID system shall be capable of detecting and estimating the size of a detected obstacle, and classifying whether it may be harmful to a train or categorising the level of risk. According to the risk assessment, OD&TID system shall provide information in time for the train to be able to stop, or for some other relevant action to be implemented before running into the obstacle.

KPI-T-02 The communication connection between the OD&TID subsystems, and between the OD&TID system and other systems must be robust and reliable enough, and with sufficient bandwidth, for the full and proper functioning of the OD& TID system.

<u>Required by:</u> IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

<u>The requirement is relevant/applicable to:</u> all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator</u>: Mandatory

The communication between OD &TID sub-systems, and between the OD&TID system and other systems in all areas must be robust for the OD&TID and dependent systems to function properly.

KPI-T-03 The central processing unit shall have the necessary computational processing and storage capability, to process and store the data acquired from the various OD&TID subsystems, in a timely manner and make it available for other systems.

<u>Required by:</u> IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

<u>The requirement is relevant/applicable to:</u> all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator</u>: Mandatory

The OD&TID devices are expected to use high resolution imagery and other sensor data, which are processed to recognise image features (detect objects in camera images). The specifications of OD&TID system will determine the amount, and location, of data communication, storage and processing required for an obstacle detection algorithm to process the data within a timescale for the information derived from the data to be useful (i.e. before an incident).

KPI-T-04 The OD&TID system shall be capable operating with, or configurable to operate with, generalised multi-level European railway traffic management and train control systems (ERTMS/ETCS), as well as with special systems in different countries (e.g., KVB in France, LZB in German and Austrian, AVE in Spain, etc.).

<u>Required by:</u> IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

<u>The requirement is relevant/applicable to:</u> all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator</u>: Recommended

The outputs of the OD&TID system, the interaction of it with the train control and traffic management systems might be different for different train control/traffic management systems (or level of ATO system), the system shall be compatible with/configurable to operate with all levels of ETCS, and consider the ability to be made compatible with other systems, e.g., those used in different regions of Europe by different operators, in the future.

KPI-T-05 The system shall be modular enabling variations in the combinations of numbers and types of subsystems to be integrated into the system, and new ones to be added, to provide the required level of detection coverage.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

New sensor subsystems, or changes in the conditions (such as construction of new buildings next to the railway) might change the combinations of numbers and types of subsystems needing to be deployed as different locations or vehicle installations to obtain the required level of detection coverage. The system should be flexible enough to allow changes in the subsystem configuration without the need to replace the whole system.

KPI-T-06 Where the OD&TID system is used as an input for ERTMS/ETCS, the quantifiable contribution to operational availability, due to hardware failures and transmission errors, shall be not less than 0.99984

Required by :IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline use cases.

Level of obligation for SMART2 demonstrator: Recommended

The probability of failure of hardware are based on hazard rates calculation. The probability must satisfy the SIL standard and specifications.

4.2 Functional Requirements

Functional requirements define the basic system behaviour and relate to what the system does or must not do, and can be thought of in terms of how the system responds to inputs. Functional requirements usually involve calculations, technical details, and other specific functionality that define what a system is supposed to accomplish. Behavioural requirements describe all the cases where the system uses the functional requirements, these being captured in use cases. Functional requirements are supported by non-functional requirements, which impose constraints on the design or implementation (such as performance requirements, security, or reliability) and have been presented in the previous sub-section.

4.2.1 Reliability, availability and maintainability (RAM) functional requirements

The overall category of RAM-related requirements has been discussed in the introduction of §4.1.1.
The requirements described below specify the required RAM-related characteristics of the system that are relevant to the system behaviour during its operation, according to its functions and specifications.

FR-RAM-01 Mean time to repair (MTTR) of any corrective maintenance for the various fault modes of OD&TID system, as a whole, and its sub-systems shall be at least the same or as less than faults with equivalent consequences for current train control/signalling system response.

Required by: IM and RU.

The requirement is relevant/applicable by: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A

A longer MTTR of components and sub-systems associated with only yard operations might be tolerated, as the safety and operational impact of a failure concerning a yard might be lower (lower speed means reduced consequences of incident, and fewer trains and parts of the network affected by some yard failures with easier mitigations).

FR-RAM-02 Mean time between failure (MTBF) or/and mean distance between failure (MDBF) for the OD&TID system, as a whole, and its sub-systems shall be at least the same or as less than current train control/signalling systems for failure with equivalent consequences.

Required by: IM and RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

A lower MTBF/MDBF of components and sub-systems associated with only yard operations might be tolerated, as the safety and operational impact of a failure concerning a yard might be lower (lower speed means reduced consequences of incident, and fewer trains and parts of the network affected by some yard failures with easier mitigations).

FR-RAM-03 Airborne subsystems shall be able to dynamically move position, target location/area and focus to achieve OD&TID of required location/area.

Required by: IM and RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

Airborne subsystem shall be able to autonomously set the movement paths and specify the field of view and focus of the airborne assets in order to achieve the required detection coverage. IM should also be able to direct assets to specific locations.

4.2.2 Safety and security (S&S) functional requirements

The overall category of safety- and security-related requirements has been discussed in the introduction of §4.1.2.
The requirements described below specify the required safety- and security-related characteristics of the system that are relevant to the system behaviour during its operation, according to its functions and specifications.

FR-SS-01 System failure detection. In the event that a part or sub-system of the OD&TID system fails, the failure shall be detected, and the failure must not result in a false negative (no obstacle detected) signal

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

Failure Mode Effect and Criticality Analysis (FMECA) or Reliability Block Diagram (RBA) analysis shall be carried out to find points of failure in the system.

FR-SS-02 The outcome of a hazard identification analysis on the OD&TID system, based on system failure, shall be acceptable with regard to the risk of collision, derailment, death and/or injury, fire/smoke, electrocution, environmental impact, or other hazardous incident.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A

OD&TID system failure modes to be considered might include; loss of power, impact damage to components/subsystems, failure of components/subsystems. The hazard identification analysis on the OD&TID system is an essential safety review process for the verification of the safety of a system operating in a safety critical role, and would be required for the operation of trains, which were depending on the OD&TID system. However, this is outside of the scope of SMART2, as in SMART2 the OD&TID system will only be a supplementary system (to the approved conventional systems, such as driver observation), operated to collect results on the performance of the system and will not be relied on to ensure the safe operation of any trains.

FR-SS-03 The outcome of a hazard identification analysis on the OD&TID system, based on communication failure between OD&TID subsystems, shall be acceptable with regard to the risk of collision, derailment, death and/or injury, fire/smoke, electrocution, environmental impact, or other hazardous incident.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A

The hazard identification analysis on the OD&TID system is an essential safety review process for the verification of the safety of a system operating in a safety critical role and would be required for the operation of trains which were depending on the OD&TID system. This is outside of the scope of SMART2, as in SMART2 the OD&TID system will only be a supplementary system (to the approved conventional systems, such as driver observation) operated to collect results on the performance of the system and will not be relied on to ensure the safe operation of any trains.

FR-SS-04 The outcome of a hazard identification analysis on the OD&TID system, based on communication failure between OD&TID and other systems, shall be acceptable with regard to the risk of collision, derailment, death and/or injury, fire/smoke, electrocution, environmental impact, or other hazardous incident.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A

The hazard identification analysis on the OD&TID system is an essential safety review process for the verification of the safety of a system operating in a safety critical role and would be required for safety approvals for the operation of trains which were depending on the OD&TID system. However, this is outside of the scope of SMART2, as in SMART2 the OD&TID system will only be a supplementary system (to the approved conventional systems, such as driver observation) operated to collect results on the performance of the system and will not be relied on to ensure the safe operation of any trains.

FR-SS-05 The OD&TID system shall produce alerts for the failures of the system, subsystems, or loss of signal from subsystems.

Required by: IM, RU and OTH to enable mitigation measures to be implemented with respect to different scenarios.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

The central control system shall get alerts when there is a failure (e.g., physical breakage) of any of the OD&TID system components, or no-communication or failure of communication between any of the OD& TID system components (including communication to critical external systems, such as TMS).

FR-SS-06 The OD&TID system shall not suffer from degraded performance or loss of functionality due to the electromagnetic environment produced by the electric traction current supply equipment.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

FR-SS-07 The OD&TID system shall respond appropriately to the presence of flora and fauna in the detection area.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

The OD&TID system shall identify or disregard flora and fauna which might be in the detection area as appropriate. For example, detection of sensor responses to inconsequential objects such as insects or leaves might be disregarded, other flora and fauna such as fallen trees and cows should be detected and classified.

FR-SS-08 The overall health and safety risk to staff, public, property and the environment, from the operation of the OD&TID system shall be at an acceptable level.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

It is not possible to entirely eliminate all risks to staff, public, property and the environment, from the operation of the OD&TID system. Such risks might include, for example, risks to staff accessing the trackside to maintain the systems, or risks resulting from a fully functional drone colliding with a bird and crashing. However, such risks should be minimised through system design and operating/maintenance procedures to an acceptable level.

FR-SS-09 The system shall ensure data integrity of saved video data as according to standard IEC/TS 62580-2:2016

Required by: AUT.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In the event of an incident, saved data from OD&TID system would be required for incident investigation.

FR-SS-10 The encryption of saved video data shall be according to standard IEC/TS 62580-2:2016

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

Encryption is required to ensure data is secure, reliable and cannot be tampered with or replaced/substituted by 3rd parties (or any attempts at tampering/interference with the data are detected).

FR-SS-11 Saving of video data shall be on fail-safe memory, or automatically switched to another storage medium in case of memory failure, and fulfil the Sicherungsgrad 4 in standard IEC 62676-1-1:2013

Required by: AUT.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In the event of an incident, saved data from OD & TID system would be required for incident investigation.

4.2.3 Technical functional requirements

The technical functional requirements cover technical demands related to functional requirements. These requirements are based on technical requests that have to be fulfilled such as (among others) modularity and flexibility to failure of subsystems and high-level of reliability and accuracy for detection and track intrusion.

FR-T-01 The OD&TID system shall either be in fixed known positions of have automatic positioning systems.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

This enables the position of moveable subsystems to be determined, the relative position of any detected object or target area to be identified, and for sensors to be targeted on specific objects/areas (and the relative location of the targeted object/area to be known)

FR-T-02 OD&TID shall be modular and resilient to failure of a subsystem.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

It should be possible to integrate new subsystems without the need to replace the whole system. And failure of one subsystem should not cause failure of the whole system, i.e. system should still acquire and process data from functional subsystems, even if detection performance is reduced due to the failed subsystem. Modularity enables failed components and sub-systems to be replaced, and full functionality restored, quickly.

FR-T-03 Detection of obstacle and track intrusion with high level of reliability and accuracy.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

To achieve GoA3-4 for train operation, a high level of accuracy is required to ensure the safe operation of trains; the required threshold level depends on the analysis of the overall risk and hazards of operating trains whilst depending on the OD&TID system to detect hazards. Generally, the risk level should not be greater than that which is considered acceptable depending on driver observation for OD&TID, therefore, the detection capabilities and accuracy of an OD&TID system should at least be greater than that of a driver in most circumstances. Additionally, where automated OD&TID systems are being implemented, significant improvement in detection accuracy might be required to justify their implementation. In order to achieve this, artificial intelligence algorithms could be used to increase the level of accuracy, and reduce the time taken for detecting objects, recognition, and hazard classification. Accuracy in terms of the location and identification of detections is important to ensure the correct actions are taken in response to detection and avoid false detections/identifications.

FR-T-04 The OD & TID shall be able to fulfil all functions adequately regardless of the traffic characteristics of the line of the vehicle, including frequency of traffic and speed *of train(s), up to the maximum operating speed and route capacity occurring in European freight operations.*

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

System should consider potential future speed upgrades and higher speed trains operating alongside the freight trains.

FR-T-05 The on-board OD&TID sub-system must be able to fit different front-profiles of different vehicles/locomotives and be easily mounted onto the vehicle without obstructing the driver's sight.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

System (on-board subsystem) should be applicable for mounting on vehicles of different size, shape and weight, and be mountable in such a way as not to obstruct the view of the driver/attendant (for GoA where relevant).

FR-T-06 The OD&TID system shall be able to detect significant objects ahead of a train at a distance relevant to maximum operational speed of the train and the reaction and braking distances of the train (up to 2000m)..

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

Object detection could include fusion of data from multiple sensors at different positions to provide coverage of detection area. The expected detection distance of the OD&TID system should be in accordance to train's maximum operational speed and significant obstacles such as persons, vehicles or large objects, which could be a hazard to the train. For the SMART2 OD&TID system, the target is to achieve detection of objects at up to 2000m ahead of the train.

FR-T-07 The OD&TID system shall store a log of all data sent to other systems for a defined period of time, which can be recalled and resent after upon request.

Required by: AUT & RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

The OD & TID system shall store data sent to other systems (such as TMS) for a defined period, so that data can be resent on request, for example, for incident investigation.

4.3 Operational Requirements

Operational requirements relate to use cases and specific scenarios within which the system will operate and specify operations or behaviours that a system or part of a system must perform in specific situations. In general, the system must support and facilitate the operation of trains, including the operations and processes involved in that operation; additionally, in order to achieve the reliable operation of trains, the system must interact with other related systems, which also introduces operational requirements to the system.

4.3.1 Reliability, availability and maintainability (RAM) operational requirements

The overall category of RAM-related requirements has been discussed in the introduction of §4.1.1.
The requirements described below specify the required RAM-related characteristics of the system that are relevant to the system operation and behaviour in specific use cases and relevant scenarios.

Operational requirements are those statements that "identify the essential capabilities, associated requirements, performance measures, and the process or series of actions to be taken in effecting the results that are desired in order to address mission area deficiencies, evolving applications or threats, emerging technologies, or system cost improvements" (Kossiakoff et al., 2003). The operational requirements assessment starts with the Concept of Operations (CONOPS) and goes to a greater level of detail in identifying mission performance assumptions and constraints and current deficiencies of or enhancements needed for operations and mission success. Operational requirements are the basis for system requirements.

Operational requirements relate to the needs of infrastructure managers, railway operators, yard operators and freight customers, and consider aspects such as failure diagnose and maintenance, risk forecast and data generation and analysis.

OR-RAM-01 Maintainability: The OD&TID system components shall be easily maintainable and configurable.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

To minimise life cycle cost (LCC) and disruption in event of failure, the actions required on-site for preventive and corrective maintenance, including installation and configuration of replacement components, should require only a short time, be of minimal complexity, and require the minimum of training/skills.

OR-RAM-02 The reliability of the subsystems and the integrated system shall be such that the risk from the failure of the sub-system/system shall be assessed as being acceptable.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A

For RAM, a distinctive risk acceptance principle is to be followed to assure tolerable safety risk of a railway system is dependent upon the risk acceptance criteria (RAC).

OR-RAM-03 The OD&TID system shall minimise hazard rate, and achieve an acceptable hazard rate, for the whole system and subsystems due to operator error, incorrect maintenance or human error.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A

The system Human Machine Interface (HMI), controls, and operational procedures relating to the system should minimise the hazard rate from the operation of trains using the system, including hazards due to operator errors, and shall achieve an acceptable hazard rate.

OR-RAM-04 The OD&TID system shall provide the necessary data for train control/TMS systems to make proper control decision to avoid collisions with object/obstacles, or restrict severity of collisions to the extent that the operational risk is assess as acceptable.

Required by: RU, IM and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

In yards, alternative traffic management system for yards might be used; however, OD & TID system shall still provide the necessary data for train control/yard management systems to make proper control decision to avoid collisions with object/obstacles, or restrict severity of collisions to the extent that the operational risk is assessed as acceptable.

OR-RAM-05 The OD&TID system shall detect failures, should diagnose those failures, and as far as possible identify expected time and resources to repair.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

OR-RAM-06 The OD&TID system shall reliably fuse detection and location data of each object and intrusion event detected. Including fusing data from multiple sensors and ensure that the correct number of objects/intrusion events are perceived by the system at the correct locations.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

The problem of detecting and perceiving of objects and intrusions is not limited to detecting a single object/intrusion event by a single sensor. For example the system should be able to determine reliably and accurately if an object detected by two sensors is one object detected from two different perspectives, or two objects. The system should fuse all the data for the object(s) and its/their location(s) and assign appropriate unambiguous identifiers to the detections.

4.3.2 Safety and security (S&S) operational requirements

The overall category of safety- and security-related requirements has been discussed in the introduction of §4.1.2.
The requirements described below specify the required safety- and security-related characteristics of the system that are relevant to the system operation and behaviour in specific use cases and relevant scenarios.

OR-SS-01 The OD&TID system should be fail safe, failure of the system or any subsystem should not create a false negative (i.e. if something is not detected because of fault/failure, the system should not interpret that as there being no object)

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

OR-SS-02 The system algorithm shall calculate the hazard rate associated with a detected object and communicate the hazard rate and detection information to other systems.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

OR-SS-03 The OD&TID system shall generate a table of hazards and associated hazard rates and write them to a log file.

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A.

The tables of detected objects and the hazard levels assigned to each object shall be generated at subsystem and whole system levels. In case of emergency and lack of communication between subsystems or between the OD & TID system and the TMS, the log file (or other form of persistent data on the TMS side) of the table of hazards will be a persistent reference for the operator.

4.3.3 Technical operational requirements

The technical operational requirements fulfil technical requests of operational requirements such as (among others) efficient information about detected objects and carrying out data fusion.

OR-T-01 The OD&TID system shall provide information efficiently about the characteristic of object detection like if objects are static or moving, object's dimension etc.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The algorithm used could have features of pattern recognition in real time and may contain AI to distinguish obstacle efficiently. Possible object characteristics include dimensions, velocity, and predicted future position/path.

OR-T-02 The TID system shall be able to identify any intrusion on track efficiently.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The algorithm used could have features of pattern recognition in real time and may contain AI to distinguish intrusion efficiently. System might be required to distinguish between detection of legitimate objects (e.g. staff/equipment in authorised work area/access route) and illegitimate objects (e.g. trespassing members of the public, fallen tree, and unauthorised staff in a restricted area). The scale of the demonstrator means that it will not be possible for the demonstrator TID system to provide full coverage of an entire railway network or route with a small number of trackside installations and drones. However, it is mandatory for the demonstrator that the TID system demonstrates TID capabilities in the target coverage area of the demonstrator components/sub-systems, so that the result could be extrapolated to determine the capabilities of the developed TID system/sub-systems if fully implemented to provide the required coverage along a route.

OR-T-03 The OD&TID system should encrypt the results output from the system and subsystems for communication. The communicated encrypted outputs should be able to be decrypted by the OD&TID system of other connected systems.

Required by: AUT & RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

Where communications are open to interference, safety critical information should be encrypted to prevent interception or replacement of data by third parties.

OR-T-04 The OD&TID system shall be able to carry out data fusion to incorporate data from multiple sources to increase the reliability and accuracy of detection and identification.

Required by: AUT & RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

Ability to fuse data from different sensors provides redundancy of the system in order to fulfil very rigid safety requirements and improves the accuracy and reliability of detection. Data fusion needs to correctly distinguish between two close objects detected by different systems, and one object detected by two systems from different viewpoints.

OR-T-05 The DSS shall be able to control train on-board OD&TID device viewing direction to search, target, and focus on objects, locations and areas.

Required by: RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

Ability to adapt and change detection properties of on-board OD&TID device to provide reliable information related to detection and classification of the potential obstacles.

OR-T-06 The DSS shall be able to control trackside OD&TID device viewing direction to search, target, and focus on objects, locations, and areas.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH).

The requirement is relevant/applicable to: all mainline.

Level of obligation for SMART2 demonstrator: Recommended

Ability to adapt and change detection properties of trackside OD&TID device to provide reliable information related to detection and classification of the potential obstacles.

OR-T-07 The OD&TID system shall have pre-determined emergency and safety protocol (both automated response of the systems and manual response) for all OD&TID system and sub system failure modes.

Required by: AUT & RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The protocol will enable the programming of the response of other systems, and development of procedures for operators to follow in the event of a failure.

OR-T-08 In case of sudden failure in communication between OD&TID system with DSS, data should be recoverable and resent to central control centre.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The protocol will enable the programming of the response of other systems, and development of procedures for operators to follow in the event of a failure.

OR-T-09 The OD&TID UAV should have ability to patrol on predefined missions.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

This requirement enables OD&TID system to have in time information of potential obstacles.

OR-T-10 The OD&TID UAV should be able to inspect area in front of the moving train.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In order to provide reliable and in time information of potential obstacles, it is necessary to provide that OD&TID UAV can inspect area in front of the moving area.

OR-T-11 The OD&TID UAV should be able to monitor marshalling yard area and processes on marshalling yard.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

In order to provide reliable and in time information of potential obstacles on yards when train is approaching or for monitoring processes on yard while train is located on yard, OD&TID UAV shall be able to monitor marshalling yard area.

4.4 Compliance requirements

Compliance requirements specify if and how the system shall conform to the relevant rules, such as specifications, policies, standards or regulation. In order for the system to fulfil its role effectively and be accepted, it must comply with certain accepted industry practices and standardised procedures that are in effect to ensure the reliability, availability and maintainability, safety and security, and technical coherence of systems in general, and those involved in the operation of trains in particular.

4.4.1 Reliability, availability and maintainability (RAM) compliance requirements

The overall category of RAM-related requirements has been discussed in the introduction of §4.1.1.
The requirements described below specify the required RAM-related characteristics of the system with respect to their compliance with the relevant standards and regulation in force.

CR-RAM-01 The assessed risk associated with the OD&TID system shall be compliant with the risk assessment procedures and acceptable levels of risk required by standards and regulation.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A.

For RAM, system should comply with the risk assessment performed for each subsystem and for the integrated system according to the formulated risk acceptance principle (RAP). A distinctive risk acceptance principle is to be followed to assure tolerable safety risk of a railway system is dependent upon the risk acceptance criteria (RAC).

CR-RAM-02 The OD&TID system shall perform according to requirements for certifications of system RAMS.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A.

CR-RAM-03 The OD&TID system and sub-systems shall pass functional/black box testing according to EN 50128 as required for the target Safety Integrity Level (SIL) of the system.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A.

For a system, passing functional/black box testing according to EN 50128 for software components is considered mandatory for SIL 3/SIL 4 systems, and it is highly recommended for software of SIL 0/SIL 1/SIL 2 systems.

CR-RAM-04 The data format shall comply with the international published standards IEC 62676-1-1:2013

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

This is to ensure a functional system and enable interoperability.

CR-RAM-05 System Lifecycle shall comply with standards

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A.

This is to make the system compliant with required, approval, certifications and inspections.

CR-RAM-06 The OD&TID system shall be compliant with current safety regulation and legislation; or, where regulation and legislation does not consider hazard detection functions performed OD&TID system, be compatible with minimum changes to regulation and legislation to take into account role of OD&TID with the same or higher level of safety.

Required by: IM, RU and OTH, and AUT involved in generation of new standards and updating of existing ones.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommend.

Standards previously developed from points of view that a driver and other staff would fulfil the functions of an OD & TID system, and might be centred around this concept making it impossible for an OD & TID system to be compliant, however with modification of the standards to consider automated OD & TID systems fulfilling the detection roles (either partially or totally) safety levels could be maintained or improved.

4.4.2 Safety and security (S&S) operational requirements

The overall category of safety- and security-related requirements has been discussed in the introduction of §4.1.2.
The requirements described below specify the required safety- and security-related characteristics of the system of the system with respect to their compliance with the relevant standards and regulation in force.

CR-SS-01 Tools like software etc. used for synthesis of the functional system shall be compliant with IEC 61508-3 / EN 50128

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

CR-SS-02 The formulated safety system and specifications shall have compliance with the Safety Integrity Level 4 Requirements.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

CR-SS-03 The OD&TID system shall comply with the standards prescribed for the health and safety of workers and public, should not cause any damage due to operation or failure.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

CR-SS-04 The system shall comply with data privacy requirements of GDPR (General Data Protection Regulation)

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

This requirement is due to the need to comply with existing data protection laws, which all interested parties (IM, RU, AUT, and OTH) have a responsibility to ensure that their operations are compliant with.

CR-SS-05 The OD&TID system shall comply with radar frequency regulation ETSI TR 102 704 v1.2.1 :2012-03 if radar is used

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

This requirement is due to the need for radar equipment specifications to be compliant with the relevant regulations.

CR-SS-06 The OD&TID system shall comply with laser eye safety class regulations EN 60825-1:2014 (VDE 0837-1) if active laser sensors are used

Required by: IM, RU and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

This requirement is due to the need for equipment emitting laser light to be compliant with the relevant existing standards in order to be considered safe for operation.

4.4.3 Technical compliance requirements

The technical compliance requirements fulfil technical requests of compliance requirements such as climate immunity, compliance of safety specifications, etc.

CR-T-01 Climate immunity. The OD&TID system shall operate in the railway environment. All pieces of equipment constituting the system should be able to operate with full nominal performance in relation to the following environmental conditions, with regard to the level of protection from the environment afforded by their installation location:

1. Temperature

2. Humidity

3. Rain

4. Snow

5. Exposure to sun

6. Air pressure

7. Altitude

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

Some systems might be protected from the environment (e.g. processor trackside), in this case the protection should be suitable for resisting the environmental effects so the system can continue to function in those conditions.

CR-T-02 The outcome of the assessment of the system with respect to HAZOP report, SIL Determination Report, and SIL Verification Report must be satisfactory before the system can be implemented in a safety critical role.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A.

The system shall comply with all mandatory safety requirements according to SIL.

CR-T-03 Safety specifications shall demonstrate compliance with the relevant safety management system requirements set out in Commission Delegated Regulation (EU) 2018/762.

Required by: AUT & RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: N/A.

Safety specifications of the system shall be in line with safety management system requirements set out in Commission Delegated Regulation (EU) 2018/762. Safety management system for the OD&TID as a safety critical system.

CR-T-04 Failure detection. The diagnostic system shall continuously monitor the OD & TID system status, detect the failures and produce diagnostic information about the failure type, location, and manifestation of the failure, and finally, cause of the failure.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

Failures of components and subsystems must be detected, and the implications for the detection coverage of the system identified (e.g. "blind spots" crated by the failure). Diagnostic information should be generated considering possible failures of one or more subsystems and provide an appropriate diagnosis of the failure source. Keeping in mind the main goals that should be accomplished within the realization of the SMART2 project, special attention will be made to the diagnosis of cameras' and drones' faults. The analysis of overall and technical requirements of these subsystems will be singled out and presented separately in the following sections.

CR-T-05 Camera faults. The diagnostic system shall provide performance and functional check-ups of all cameras.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

The main faults of cameras that shall be diagnosed are: the camera is not operating, communication with the camera is lost, and the low quality of a picture is received. Related motors' statuses of rotating cameras should also be monitored.

CR-T-06 Drone faults. Diagnostic tools shall provide performance and functional check-ups of all involving drones.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

Unmanned aerial vehicles shall be observed as follows: potential faults of sensors' and functional states of propellers should be detected, and observed anomalies diagnosed and identified. Additionally, the battery's health and the current status should be monitored continuously, and the availability of a power supply monitored regularly.

CR-T-07 Automatic diagnosis. The diagnostic system shall automatically detect and diagnose faults and failures.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

For the automatic detection and diagnosis of faults and failures, computer vision and deep learning techniques could be applied for reliable emulation of human experience in detecting faults and anomalies in the OD & TID system.

5. Requirements for SMART2 OD&TID demonstrator system

In order to provide detailed requirements of SMART2 OD&TID system, the list of specific requirements is presented. This list encloses some of general requirements defined in Section 4 as well as some requirements that specifically relate to SMART2 OD&TID system. The main focus is on technical requirements related to safety and security issues, object detection and object classification and to interfaces. According to holistic approach of SMART2 concept solution, the overall requirements of SMART2 OD&TID system have been divided into four subsystems related to on-board OD&TID, trackside OD&TID subsystem for level crossings, airborne OD&TID subsystem and decision support subsystem. The SMART2 demonstrator technical requirements are divided into four categories: functional, operational, evaluation and safety and security. They are presented in subsections 5.3, 5.4, 5.5 and 5.6 respectively.

5.1 Concept of SMART2 OD&TID system

The SMART2 project builds upon the results achieved in SMART project (SMART, 2019), by advancement, innovation, and development of the SMART2 on-board long-range all-weather OD&TID system.

An overview of OD&TID system concept proposed to be developed in SMART2 is shown in Figure 1. The SMART2 project will study operation conditions of trains in general and freight trains in particular, and propose a prototype OD&TID system to assist real-time train operation. SMART2 OD&TID system will consist of three sub-systems: the on-board, airborne and trackside OD&TID sub-systems. All three sub-systems will be integrated into a holistic OD&TID system with interfaces to a central Decision Support System (DSS), which will have the role to manage the OD&TID system according to the different operational and environmental conditions and potential hazards.

Therefore, the SMART2 project focuses on:

- The improvement of the on-board OD&TID system developed by S2R SMART project as a sub-system;
- The development of new trackside and airborne OD&TID sub-systems;
- The integration of all sub-systems into a holistic OD&TID system.

The target for the distance ahead of a train for the holistic OD&TID system to detect dangerous objects on, or approaching the train's path is 2000 m. The approach adopted in SMART2 to achieve this, is to improve the on-board train passive and active detection systems developed in the S2R SMART project (particularly with regard to detection capabilities at long range), and use fusion of data from the on-board, trackside and airborne sub-systems to further increase detection coverage and accuracy.

The approach proposed for the trackside OD&TID sub-system to be developed in SMART2 mainly focuses on the detection of obstacles and track intrusions at level crossings, where there is a high risk of obstacles and intrusions, using a laser optics system, which would be integrated into the holistic SMART2 OD & TID system.

The approach for the airborne sub-system is to equip a commercial drone with detection systems and integrate the control of the drone with the DSS, so that the drone can be deployed in a variety of operational modes (e.g., regular patrol, scan specific area, etc.) to detect hazards along the route, particularly where the coverage of other sub-system is less than complete.

The overall concept of the SMART2 OD&TID system, and the approaches adopted for each sub-system, as well as the integration of the sub-systems, will be investigated in detail as the technical development in the project progresses and the development outcomes and results will be reported in future deliverables.

Figure 1: Concept of SMART2 holistic system for OD&TID consisting of on-board, trackside and drone-based OD&TID sub-systems, interfacing with central DSS unit

A holistic approach to autonomous obstacle detection for railways using the input from multiple sensor sub-systems would enable the detection area ahead of the train to be increased in many situations, compared to systems solely mounted on the front of the train. This includes situations where line of sight from the front of the train to areas behind a curve, slope, tunnels and other elements is blocked, as well as increasing the effective detection range ahead of the train in all situations, including on long straight tracks. The data recorded by the sensors of each of three OD&TDI systems (on-board, trackside and airborne) will be processed, and can be used to inform DSS about possible obstacles and track intrusions in their fields of view, as well as the ATO/TM system. DSS will integrate and process the information coming from the three OD&TID sub-systems (e.g., classification of the detected object or intrusion, determination of its location, etc.) and will make decisions concerning the OD&TID system control and management actions required (e.g., directing sensors and vectoring airborne sub-system units). The output of SMART2 system on detection, location and classification information regarding detected objects and intrusions could be sent to ATO and/or TM system, which will determine and implement the appropriate train control response. SMART2 platform will be flexible and open for interfacing additional OD&TID modules based on existing and future technologies.

The SMART2 DSS will be implemented in cloud environment. An illustration of SMART2 architecture is shown in Figure 2, where a high-level representation of communication of locally implemented OD&TID blocks (drone (UAV)-based, trackside and on-board) with DSS cloud architecture is presented.

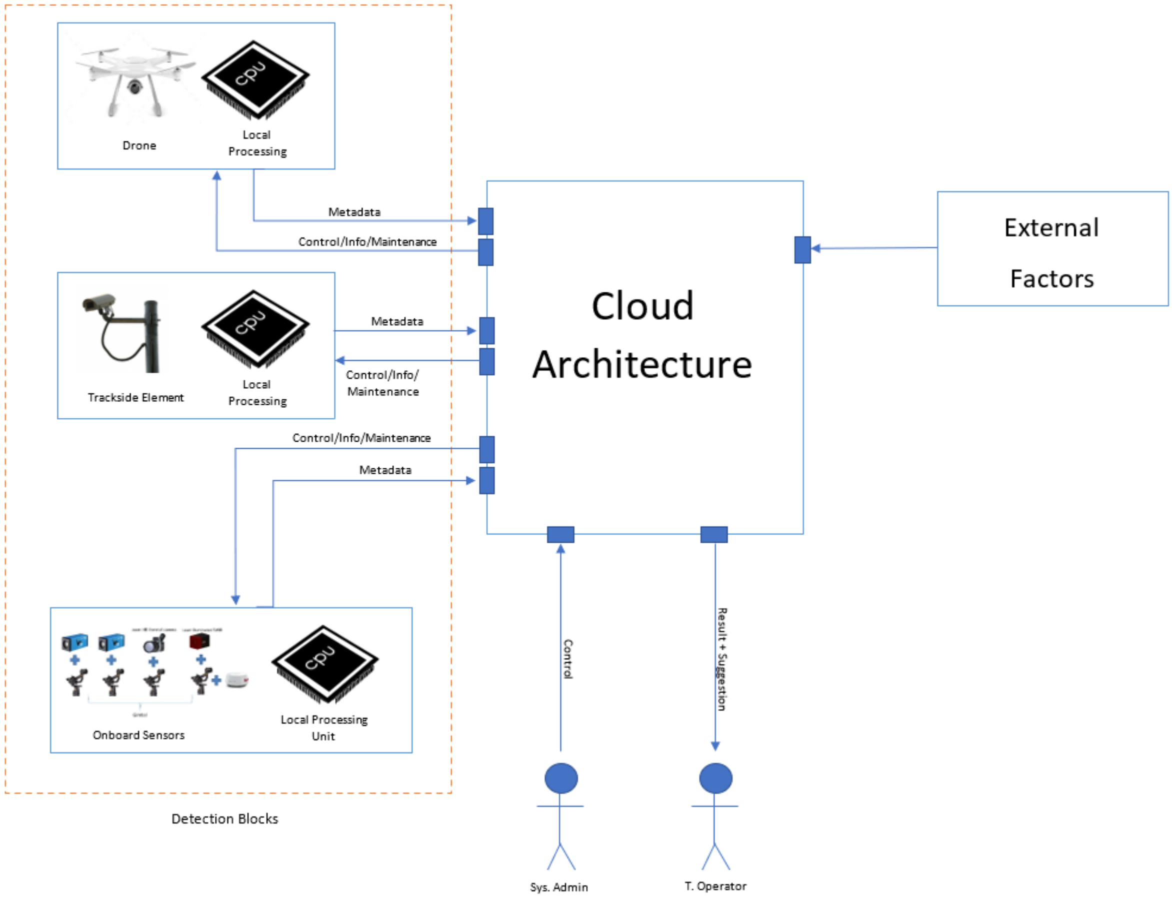

Figure 2: SMART2 architecture. High-level representation of communication of locally implemented OD&TID blocks and cloud implemented DSS.

Once obstacle has been detected by the locally implemented detection block(s), the result of the obstacle detection local processing will be forwarded to the cloud implemented DSS System in the form of metadata, which will be stored in *the Cloud Storage*. According to the selected cloud provider direct communication between a local computer and the cloud will be established using a standard network protocol. Besides the stored data from the detection blocks, in order to make decisions concerning the OD&TID system control and management actions required, the cloud implemented DSS will consider also the data coming from external factors. The "External factors" module in Figure 2 would enable the integration and interfacing of OD&TID systems with route knowledge and route settings from the infrastructure management systems. This connection involves receiving all data gathered in TMS control centre from different sources regarding the position of the detection systems, train location, speed profile and route, signals, and status of the relevant infrastructure. The outputs of the DSS, which could be transmitted via interfaces to train control and traffic management systems in future integration of the OD&TID system with ATO, would be the processed detection results for the system.

For the development of **on-board OD&TID sub-system** prototype, SMART2 envisages multi-sensory on-board system integrated in a custom-made housing that protects the sensors, holds them in the correct alignment and enables easy mounting/dismounting of the unit to/from a locomotive. A demountable unit removes the need for significant modification of the locomotive and enables it to be set up for different evaluation tests in static and moving conditions, and on different compatible/adaptable vehicles. The multi-sensor SMART2 on-board system will consist of different vision sensors enabling obstacle detection under day and night illumination conditions. The RGB cameras and thermal camera will be accompanied with a novel vision unit LADAR (LAser Detection Active Ranging), to be developed in SMART2 project, based on Short Wave InfraRed (SWIR) vision technology and range gating. The addition of this novel vision sensor to augment the capabilities of the RGB and thermal cameras will significantly increase the performance of the on-board OD&TID system, improving the functional reliability in different illumination and weather conditions, including challenging weather conditions. The performance of the on-board system will be also advanced (relative to the achievements of the SMART project) by mounting the cameras in a gimbal to allow the control of cameras' orientations and their field of view directed to the track ahead of the train, particularly when the track is not directly ahead of the train, such as in curves and at junctions. As part of the gimbal control for the SMART2 cameras, a range sensor, such as radar detection system, will be used to determine the angular relationship between the front of the train and any object on the track. This radar information will be a set-point for the gimbal control module to orient the camera in direction of detected object. Computer Vision software will then perform object classification and object distance estimation based on the images and orientation of the cameras and the range sensor.

The key component of **the trackside OD&TID sub-system** will be an advanced 3D laser optic subsystem. This subsystem will enable optimization of the operational parameters of the OD&TID system (detection range, scanning angles, scanning resolution, and scanning frequency). This type of trackside sub-system to be developed within the scope of the SMART2 project is intended for OD&TID at level crossings.

The SMART2 airborne sub-system prototype will consist of a nested Unmanned Arial Vehicle (UAV) (drone), which will be placed on a pillar next to the rail track at strategic locations such as tight curves, gorges or landslide prone locations. The concept of SMART2 stationary airborne (drone) based OD & TID system is illustrated in Figure 3.

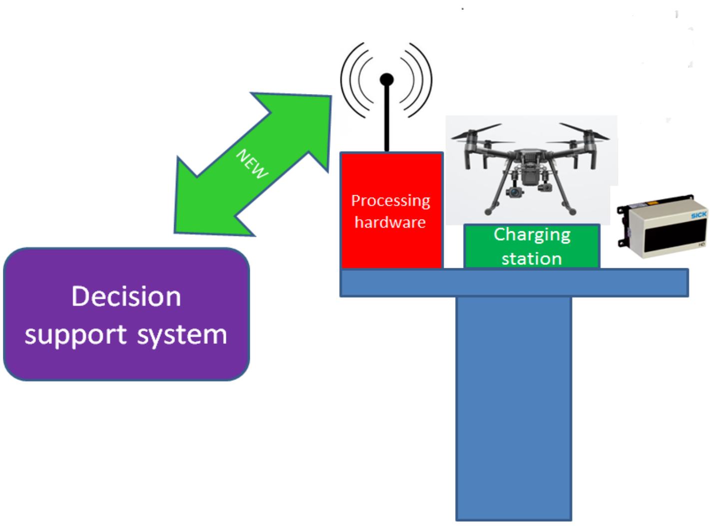

Figure 3: Concept of SMART2 airborne OD&TID sub-system

The drone's nest will have an automatic charging station, hardware for hosting processing algorithms for OD&TID, and a communication station with two sub-modules, one for the communication between the drone and processing hardware and the second one for the communication between the drone-based OD&TID system and the DSS. The UAV (drone) will carry appropriate RGB camera. Upon the command issued by the DSS, the drone will leave the nest and will investigate a section of the rail track and its surroundings as specified by the DSS. In general, the drone will be a flexible OD&TID asset with a number of different operational modes, including charging mode(s) where the drone is docked with the charging station (with or without sending sensor data from its charging location), and active modes where the drone will be airborne and fly as directed by the DSS, sending sensor data back to the processing hardware at the charging station, from where the processed data is sent to the DSS.As explained above, SMART2 OD&TID sub-systems will interface through the DSS. Each sub-system will locally perform sensor-based object and intrusion detection and classification. In addition, each detection sub-system will estimate distance between the detected object and the sub-systems sensors and consequently the distance between the object and the train (based on the known position of local sub-system with respect to current train position). The sub-systems processing results will be sent to DSS as explained in Figure 2 and additionally illustrated in Figure 4.

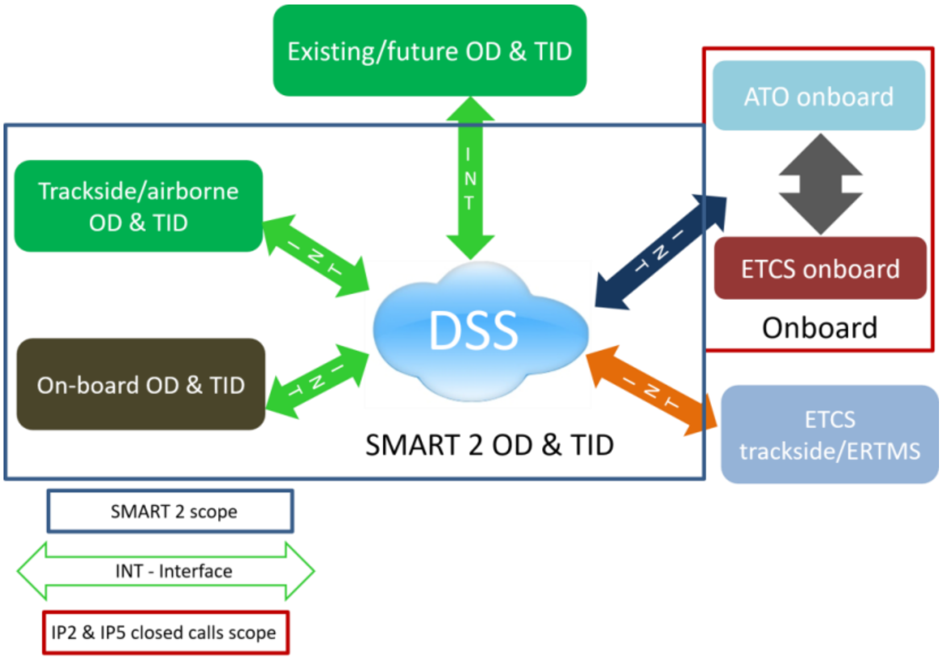

Figure 4: Concept of SMART2 integrated OD&TID system architecture

The blocks framed by a blue rectangle in Figure 4 illustrate the activities/tasks within the scope of the SMART2 project, and the interfaces between different systems and sub-systems are shown in different colours. The interfaces marked with green denote the interfaces to be developed in SMART2, and represent the communication between the sub-systems' processing units and the DSS, which mainly consists of the three OD&TID sub-systems sending the locally obtained processing results to the DSS (with OD&TID sub-system management and control data being sent the other way). The interface marked with dark blue illustrates intended connection between the SMART2 DSS and the train in order for the SMART2 DSS to gather train related data such as the position and speed of the train. Also, this train interface could be used for SMART2 DSS to report OD&TID processing results to ETCS onboard/ATO onboard, for the onboard train control to respond to according to a ruleset determined outside of SMART2. The interface marked with orange colour illustrates the intended connection to the traffic management command centre, and is to be used by SMART2 DSS, on one side, to gather data about trains in the area, such as the direction and path of the trains and possibly data related to authorized persons which might be in the detection area legitimately. On the other side, this connection could be used to send processed OD&TID data to the traffic management system (ETCS trackside/ERTMS). The precise specification or architecture of the interfaces between the SMART2 OD&TID system and the onboard and trackside systems for train control and traffic management, or indeed the precise architecture and mechanisms for applying OD&TID in ATO, have yet to be determined. Based on the analysis of freight specific use-cases of OD&TID in the context of ATO, and inputs received from the IP2 and IP5, SMART2 will determine the OD&TID system requirements, in terms of the detection data to be output by the system, and the train and TMS input data it would require. The scope of SMART2 is to develop and demonstrate the

OD&TID detection technologies to provide reliable OD&TID in the area ahead of trains up to a range of 2km. The architecture of the interfaces with the train control and traffic management systems would be determined in the future when the architecture of the ATO with OD&TID is defined.

5.2 Possibilities for evaluation tests of SMART2 system

This sub-section establishes framework for the dataset generation field tests as well as framework for conformance testing, functional testing end final evaluation tests of both SMART2 OD&TID demonstrator sub-systems and SMART2 OD&TID integrated system. This sub-section is placed before SMART2 requirements section (Section 5.3), as testing during development and final system evaluation depends on available test rail tracks and test vehicles as well as on available and legal and safety regulations that need to be fulfilled. Therefore, this sub-section is important to understand SMART2 requirements & specifications. Different field tests for data generation, sub-system conformance testing and final evaluation of SMART2 integrated prototype for holistic OD&TID will be conducted in real-world environment supported by Serbian Railways Infrastructure (SRI) and two cargo operators (Serbia Cargo and DESPOTIJA). The evaluation scenarios in real environment will be realized for most significant defined use cases.

5.2.1 Test environments

The performance testing of SMART2 technologies under development and integrated prototype will be performed on several sections of railway that are managed by SRI.

The first possible testing environment is the circular railway section that forms the Niš rail junction (Figure 5). This railway section connects and passes through two junction stations, a locomotive depot, and Niš marshalling yard, having a route length of approximately 30 km. this section passes mainly through the urban area with two steel bridges over the river Nišava and numerous level crossings and is a permanently paid corridor for Serbia Cargo from IM – SRI. The circular section is also already used by Serbia Cargo for testing, as well as for testing locomotives after repair/overhaul.

The circular section that forms the Niš rail junction is well suited for validation of OD&TID demonstrator in operational conditions, especially in specific urban environment, and could be used in the SMART2 testing framework for:

- technical validation of SMART2 OD&TID demonstrator in real traffic,
- technical validation of SMART2 OD&TID demonstrator in urban area with numerous level crossings,
- technical validation of SMART2 OD&TID demonstrator in environment where direct view of the track from the front of the train in curves is blocked by objects (for example buildings),
- technical validation of SMART2 OD&TID demonstrator during the crossing of the bridges,

- dataset generation,
- technical validation of SMART2 OD&TID prototype in various weather conditions.

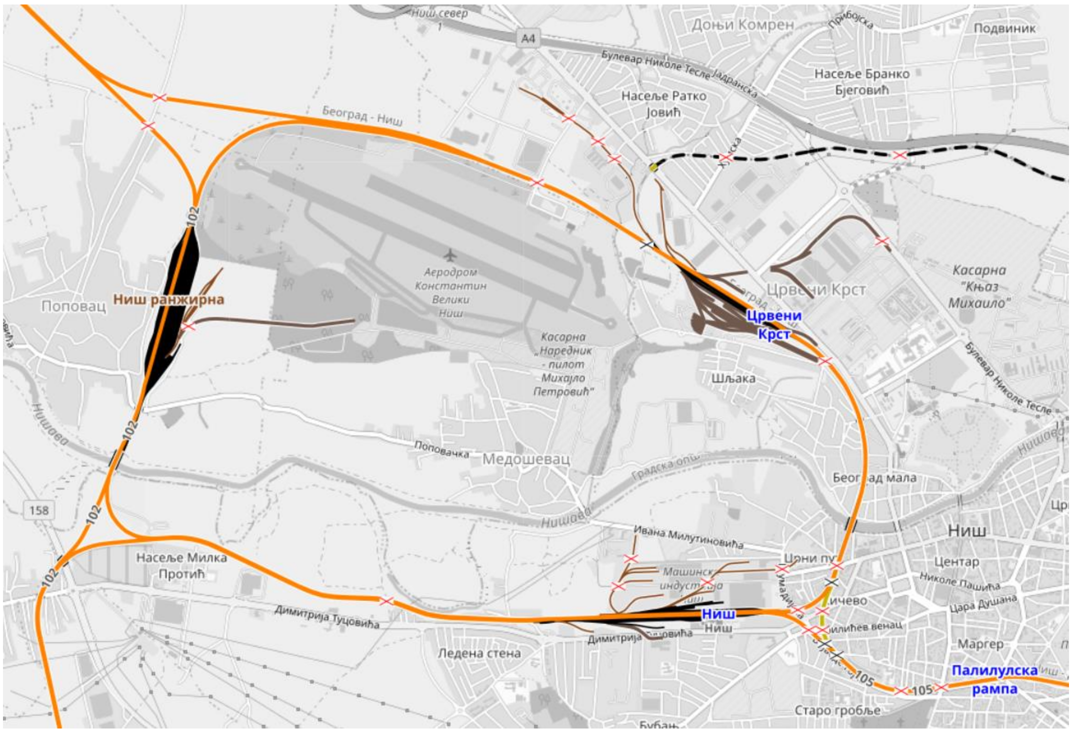

Figure 5: Niš rail junction round rail track

The second possible testing environment is on revenue earning service trains hauling cargo on the route from Niš to North Macedonia boarder (station Ristovac), which has a total length of 120 km and has a specified operating speed of 120 km/h (Figure 6). The route is a part of Pan European corridor X to Thessaloniki and is a particularly challenging corridor due to numerous bridges and tunnels in Grdelica gorge (the length of the section trough the gorge being 30km). The part of the route from Niš to Leskovac contains multiple straight sections that are longer than 2 km. Multiple cargo trains pass along this route every day, so it is appropriate for the evaluation of the SMART2 system under conditions of revenue earning service trains hauling cargo at speeds of 80 km/h and could be used in the SMART2 testing framework for:

- technical validation of SMART2 OD&TID prototype in real cargo haul situation,
- technical validation of SMART2 OD&TID prototype on challenging section with numerous tunnels and bridges,
- technical validation of SMART2 OD&TID prototype where direct view of the track from the front of the train in curves is blocked by vegetation and hills,
- technical validation of SMART2 OD&TID prototype at straight sections longer than 2 km,
- dataset generation,
- technical validation of SMART2 OD&TID prototype in various weather conditions.

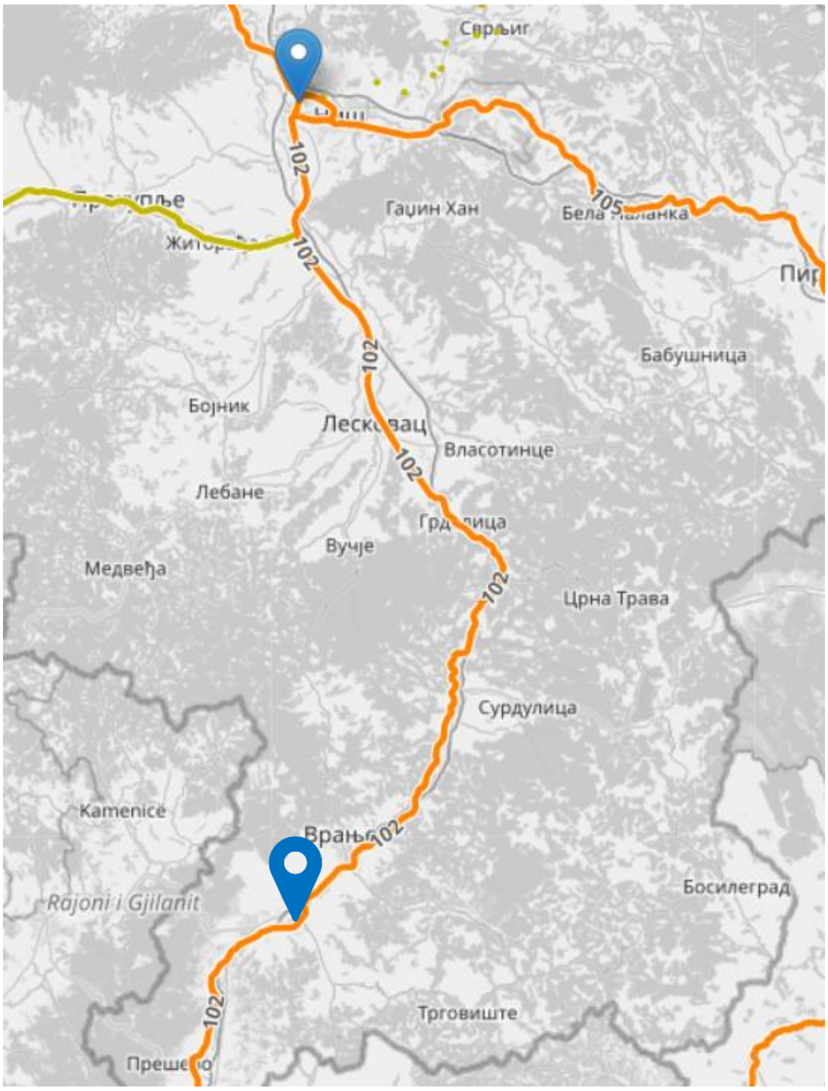

Figure 6: Track Niš - Ristovac

The third possible testing environment is on revenue earning service trains hauling cargo on the route from Markovac to Danube port Pančevo (Figure 7). This route is a part of Pan European corridor X to Budapest which passes through Belgrade junction, which is within a large urban centre and through the multiple towns along the route with multiple crossings and tunnels. Between Markovac and Belgrade, the track passes through hilly landscape with numerous sharp curves where the direct view of the area behind a curve from the front of the train is blocked by vegetation or buildings along the route. There are two possible routes (route 102 and 103, Figure 7) and both are used daily by cargo operator DESPOTIJA. The total length of these routes is 119 km and the specified maximum operating speed on these routes is 120 km/h.

The Markovac Pančevo route is well suited for validation of SMART2 OD&TID demonstrator under conditions of revenue earning service trains hauling cargo in urban and suburban environment and could be used in the SMART 2 testing framework for:

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- technical validation of SMART2 OD&TID prototype in real traffic,
- technical validation of SMART2 OD&TID prototype in urban/suburban area with numerous level crossings,
- technical validation of SMART2 OD&TID prototype where direct view of the track from the front of the train in curves is blocked by vegetation and terrain topology,
- technical validation of SMART2 OD&TID prototype over bridges and in tunnels,
- dataset generation,
- technical validation of SMART2 OD&TID prototype in various weather conditions.

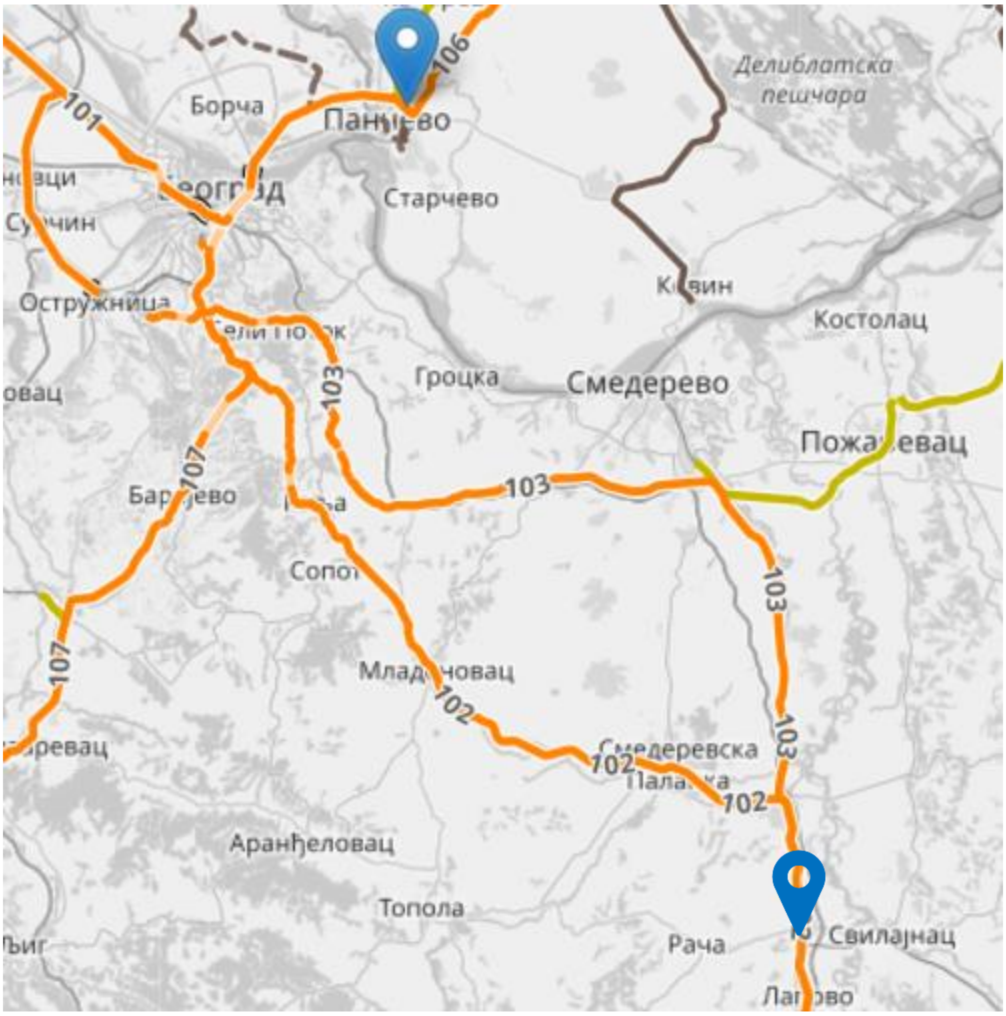


Figure 7: Track Markovac - Pančevo

5.2.2 Test vehicles

The first test vehicle which will be used for SMART2 field tests is Serbia Cargo locomotive ŽS series 444 (former series 441). It is electric locomotive manufactured by corporation Traktion

Union (TU) consisting of the company ASEA from Sweden, Secheron from Switzerland and Elin Union from Austria. In accordance with the license of the TU group, the manufacturer of the locomotives was also the group of firms from former Yugoslavia (Rade Končar from Zagreb, MIN Locomotiva from Niš among others). In 2004, the series 441 was modernised to series 444 by Rade Končar and MIN Lokomotiva. The main technical data of the locomotive are given in Table 1.

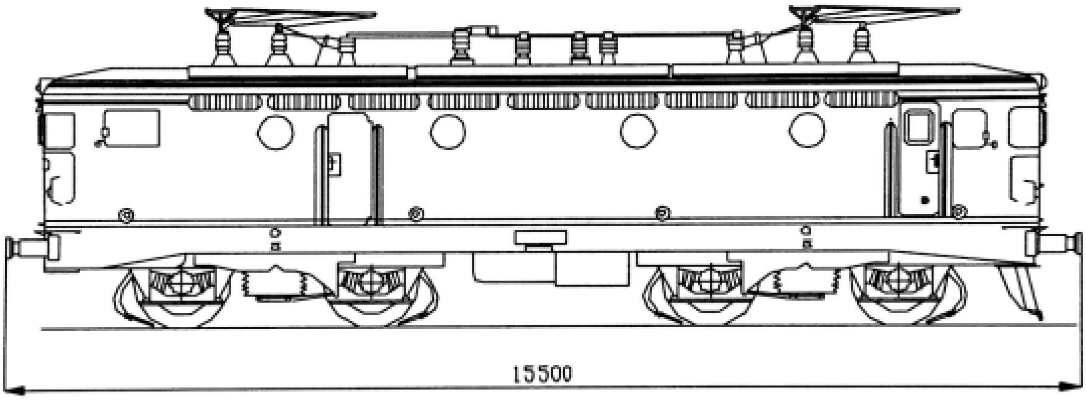
Figure 8: Serbia Cargo electric locomotive ŽS series 444

Table 1 Main technical data of electric locomotive ŽS series 444

Nominal voltage supply	25 kV, 50 Hz
Maximum continuous voltage supply	27,5 kV
Maximum short-term voltage supply	29 kV
Minimal continuous voltage	19 kV
Minimum short-term voltage	17,5 kV
Temperature range	-25º C up to + 40º C
Height above sea level	up to 1200 m
Air humidity	90%
Track gauge width	1435 mm
Minimum curve radius	250 m
Minimum curve radius (5 km/h)	80 m
Maximum speed	120 km/h (140 km/h)
Axle arrangement	Bo' – Bo'
Locomotive mass	78 t (80t with electro-dynamic brake)

Mass per axle		19,5 t (20 t with electro-dynamic brake)
New wheel diameter		1250 mm
Totally worn out wheel diameter		
	with flanges	1170 mm
	with monobloc	1140 mm
Transmission ratio		73 : 20 (87 : 28)
One-hour power		3600 kW
Continuous power		3400 kW
Electro-dynamic brake power		1740 kW
Maximum traction force		280 kN (238 kN)
One-hour traction force		190 kN (160 kN)
Permanent traction force		176 kN (149 kN)
One-hour speed (at 870 V, at full excitation)		77 km/h
Permanent speed (at 870 V at full excitation)		79 km/h
Type of pneumatic brake		extended and direct

Dimensions of the of electric locomotive ŽS series 444 are given in Figure 9.



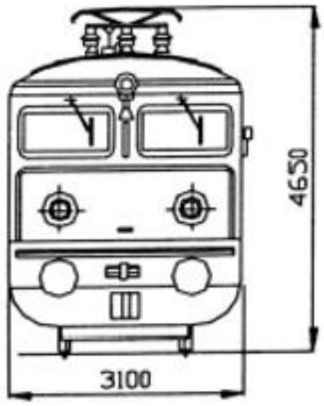


Figure 9: Overall dimension of Serbia Cargo locomotive ŽS series 444

The second test vehicle that will be used for evaluation is DESPOTIJA locomotive ŽS series 461. It is electric locomotive manufactured by Electroputere from Romania. Main technical data of the locomotive is given in Table 2.

Figure 10: Despotija electric locomotive ŽS series 461

Table 2. Main technical data of electric locomotive ŽS series 461

Nominal voltage supply	25 kV, 50 Hz
Maximum continuous voltage supply	27,5 kV
Maximum short-term voltage supply	27,5 kV

Minimal continuous voltage	19 kV
Minimum short-term voltage	17,5 kV
Temperature range	-35º C up to + 40º C
Height above sea level	up to 1200 m
Air humidity	90%
Track gauge width	1435 mm
Minimum curve radius	90 m
Maximum speed	120 km/h
Axle arrangement	C'o – C'o
Locomotive mass	120 t
Mass per axle	20 t (20 t with electro-dynamic brake)
Half worn wheel diameter	1250 mm
Half worn out wheel diameter	1210 mm
Transmission ratio	73 : 20
One-hour power	5400 kW
Continuous power	5100 kW
Electric brake power	2600 kW
Maximum traction force	392 kN (202 kN)
One-hour traction force	280 kN (221 kN)
Permanent traction force	260 kN (202 kN)
One-hour speed (at 870 V, at full excitation)	77 km/h
Permanent speed (at 870 V at full excitation)	79 km/h
Type of pneumatic brake	extended and direct

Dimensions of the locomotive body are given in Figure 11.

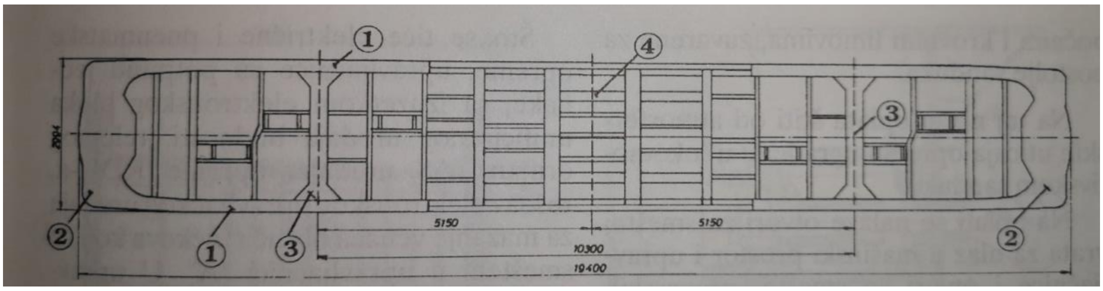


Figure 11: Overall dimension of Despotija locomotive ŽS series 461

5.2.3 Procedural framework for SMART2 field tests

The procedural framework for SMART2 field tests must encompass the following aspects for both SMART2 subsystems and SMART2 integrated system:

1) which permits and certificates are required to be issued by relevant bodies for test vehicle usage and for the usage of devices mounted onto the vehicle;
2) which permits and certificates are required to be issued by relevant bodies for mounting of UAV nest and vision sensors in the railway zone managed by IM;
3) the fulfilment of the prescribed national technical requirements for test vehicles and devices mounted on the test vehicle;
4) possible impact of the on-board OD&TID system on the train operation at selected infrastructure;
5) possibility of emergence of new risks caused by SMART2 OD&TID prototype field tests and their impact to traffic safety;
6) officially given permission to mount the on-board OD&TID system, to use a test vehicle, to use the vehicle with mounted OD&TID in real traffic, as well as to use UAV and track side subsystem in the railway zone managed by IM.
7) the fulfilment of the prescribed national regulative for the usage of UAV in Republic of Serbia, the country where the SMART2 field tests will be done.

1. Legal requirements for obtaining the permits and certification of vehicles and devices, as well as legal requirements for operational testing, are defined by Law on Safety of Railway Traffic of Republic of Serbia (Official Journal of Republic of Serbia, N° 41/2018). In addition to other articles that define approval procedures for vehicles and devices, Articles 113 and 114 define assessment of conformity and suitability for usage for all the structural subsystems.

After SMART2 analysing of above-mentioned articles it was concluded that no permits or certificates need to be issued by Railway Directorate of Republic of Serbia (or from any other government body) because of the following:

- SMART2 testing will be not performed with the aim to obtain assessment of conformity and suitability for usage declaration,
- SMART2 on-board OD&TID prototype will not belong to structural subsystems of used test vehicles,
- SMART2 on-board prototype of OD&TID will not influence locomotive control and functioning of its devices/subsystems.
- SMART2 operational testing will provide a basis for assessment of conformity and suitability for usage if it will be requested by future manufacturer of on-board OD&TID prototype.

2. Legal requirements for obtaining the permits and certification for mounting of UAV nest and track side sensors in the railway zone managed by IM, are defined by Law on Safety of Railway Traffic of Republic of Serbia (Official Journal of Republic of Serbia, N° 41/2018). Article 100 defines the procedure for installation of devices in the protected railway zone. As per noted article, the installation of devices is allowed based on the contract between the IM and device installation investor.

3. The definition of technical requirements for railway vehicles and devices attached to them follows the Article 48 of Law on Safety of Railway Traffic of Republic of Serbia, which states:

"Vehicles on which the national railway technical regulations are applicable, devices and equipment that are installed at railway vehicles, which are essential for the safety of rail traffic (control devices, couplings, systems for stopping the vehicle and for providing light and sound signals) must meet the technical requirements stipulated herein, Serbian and industry standards in the field of railway transport and binding regulations by UIC."

After SMART2 analysing of the above Article, it was concluded that the on-board SMART2 OD&TID prototype will not interfere with systems listed in the article and so will not belong to groups of vehicle systems/subsystems important for vehicle safety. The only requirement which necessarily has to be take into account is one concerning the OD&TID prototype mounting onto the vehicle:

- the on-board OD&TID prototype dimensions must not exceed the prescribed dimensions of the vehicle, i.e. it should not violate its maximum profile,
- the on-board OD&TID prototype must not scientifically influence the vehicle mass.

4. The requirements for locomotive usage on certain infrastructure are defined by Article 30 of Traffic Instructions (Official Journal of Community of Yugoslav Railways N° 6/80, 3/82, 6/83, 2/84, 4/88, 8/88, 9/90, 2/91, 2/94 and 2/01) and the procedure for determining vehicle to track compliance is defined by Rulebook about tracks categorization (former Rulebook of Community of Yugoslav Railways, now an act of SRI). Data necessary for definition of vehicle and track conformity are given in Table 7 of Instruction 52 of Community of Yugoslav Railways (Instruction 52, 1992) (now an act of Serbia Cargo and DESPOTIJA).

The requirements defined by noted acts are referring to maximal axle load and maximal mass of vehicle per meter of length. As mass of OD&TID prototype is negligible with respect to locomotive mass one can conclude that the OD&TID prototype doesn't influence compliance of vehicle to certain infrastructure.

5. Mounting of the OD&TID prototype on a vehicle and usage of UAV in the protected railway zone will certainly represent a change so according to the law and System for safety management of cargo operators Serbia Cargo and DESPOTIJA it is necessary to assess the influence to safety and to define the measures of risk control. The noted procedure is defined in SUB procedure - Risk assessment procedure for implementing changes - P. SUB.18. (SUB.18, 2020).

The analysis was performed by SMART 2 safety experts and the following risks were identified as a consequence of OD&TID prototype mounting and UAV usage in the protected railway zone:

- the on-board OD&TID prototype mounting can block driver track visibility,
- the on-board OD&TID prototype mounting can endanger vehicle structure i.e. structural integrity of vehicle car body,
- the on-board OD&TID prototype can fall of or change position during vehicle usage,
- the on-board and track side OD&TID prototype can electromagnetically interfere with existing vehicle equipment,
- the on-board and track side OD&TID prototype can be incompatible with vehicle existing electrical network,
- the UAV can collide and damage the infrastructure elements,
- the UAV can collide with the moving train.

Based on defined risks the following requirements can be identified:

- the on-board OD&TID prototype mounting must not jeopardize at any circumstances driver track visibility,
- the on-board OD&TID prototype mounting must not jeopardize the vehicle structure i.e. no drilling or cutting of car body is allowed,
- the on-board OD&TID prototype and its mounting must be designed to satisfy requirements by EN 61373:2010 – Rolling stock equipment – Shock and vibration tests for a Category 1 Class B device (equipment in a case mounted directly or under the car body),
- the on-board OD&TID prototype must be designed according to the EN 50155:2007 - Railway applications - Electronic equipment used on rolling stock,
- the UAV usage zone should be outside the railway protected zone
- the UAV should possess its own obstacle detection device and appropriate algorithms.

The OD& TID prototype evaluation will be a change that can influence safety. However, if above mentioned requirements are satisfied it can be concluded that change is not significant and it would be not necessary to carry out the risk assessment procedure according to Common Safety Method (CSM). As a measure of risk control, the standard EN 61373:2010 and EN 50155:2007 will be respected.

6. As already mentioned in point 1, it is unnecessary to have a permit issued by Railway Directorate of Republic of Serbia for the evaluation of on-board OD&TID prototype on track. The legal obligation of Serbian cargo operators is to issue a written consent to mount the OD&TID prototype on the operational train because of the following:

- for mounting as they own the locomotive,
- for operation according to the safety management system of Serbian cargo operators, Security Management System Manual (SMS Manual, 2020).

In order to satisfy all the aspects a commission will be formed by cargo operators, which will confirm that the above noted requirements are satisfied based on documentation supplied by the development team.

7. The prescribed technical requirement national regulative for usage of UAV in Republic of Serbia is defined by Law on Air Traffic of Republic of Serbia (Official Journal of Republic of Serbia, N° 73/10, 57/11, 93/12, 45/15, 66/15 and 83/18) and Bylaw on UAV (Official Journal of Republic of Serbia, N°1/20). By analysing the corresponding documents, the following limitations on UAV usage as a subsystem of the holistic OD&TID can be identified:

- UAV must be registered in the Aircraft records of the Republic of Serbia,
- beyond visual line of sight (BVLOS) is not permitted
- for heights above 100 m, horizontal distance from UAV operator larger than 500 m, night flying, flying in the vicinity if airports, and flying within 500 m to important infrastructure objects the permit from Directorate for Air Traffic must be obtained and the air space must be allocated
- flying within 500 m to railway network managed by SRI is possible only with IM permission
- flying above humans and below 30 m horizontal distance from humans is not permitted,
- for UAV lighter than 25 kg, flying in urban areas is possible only by permission issued by Directorate for Air Traffic.

5.3 SMART2 Technical functional requirements

SMART2 FR-T-01 Detect objects, potential obstacles, in the railway environment and path of trains that are not the part of the railway infrastructure.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: KPI-RAM-03 (a), KPI-RAM-03 (b), KPI-T-01

Detect objects, potential obstacles, on the rail tracks and near the tracks ahead of trains. Targeted potential obstacle is every object found on or near the tracks that are not the part of the railway infrastructure. For the evaluation scenarios SMART2 team should use objects, potential obstacles such as humans, cardboard boxes, animals, branches, vehicles, bicycles as defined by the evaluation protocol.

SMART2 FR-T-02 Mounting/dismounting of on-board OD&TID system

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: KPI-RAM-08, KPI-RAM-11, KPI-RAM-14, FR-T-05

The on-board OD&TID system integrated into housing shall be easily mount/dismount onto/from the frontal profile of the locomotive/vehicle so to enable sensor-based perception of the scene ahead of the locomotive/vehicle.

SMART2 FR-T-03 Physical components/subsystems of the OD&TID system robust to environmental conditions

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: KPI-RAM-01, KPI-RAM-07

All SMART2 subsystems should be well protected in order to provide robustness to different environmental conditions such as dust, mud, rain.

SMART2 FR-T-04 Detection functionality of the OD&TID system robust to environmental conditions

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: KPI-RAM-02, KPI-RAM-07, KPI-RAM-09, KPI-T-02

All SMART2 subsystems should be able to provide reliable information of detected objects in spite of different environmental conditions such as dust, mud, rain.

SMART2 FR-T-05 The OD&TID system shall be able for long-range obstacle detection within 2 km ahead the train.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: FR-T-03, FR-T-04, FR-T-06

According to specific SMART2 objectives, SMART2 OD&TID system shall be able to detect objects within 2 km ahead the train and at large speed ranges from 0km/h up to 180 km/h.

SMART2 FR-T-06 OD&TID system shall be able to detect rail tracks.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: FR-T-06

SMART2 OD&TID system (on-board and airborne) shall be able to recognize the rail tracks ahead of the vehicle (ahead of the OD&TID system mounted on the vehicle) to define region of interest for detection of obstacles.

SMART2 FR-T-07 The OD&TID system shall use a fusion of data from different sensors to improve the effectiveness and accuracy of detections and identifications.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: KPI-RAM-09, OR-RAM-06, FR-T-06, OR-SS-01

Provide the integrated system which will choose combination of different sensor data available in particular environment conditions such that the resulting information has less uncertainty than would be possible when these sensors were used individually.

SMART2 FR-T-08 OD&TID shall provide visualization of sensor data on HMI.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

Provide the sensor data to be visualized on Human-Machine Interface (HMI). Data to be displayed: live image of selected vision sensor with overlaid detected object, as well as the distance to the detected object and class of the object.

SMART2 FR-T-09 OD&TID shall provide software implementation.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

To use the software implementation, such as C++ which is compatible to work with ROS (Robot Operating System, https://www.ros.org/), which is environment supporting distribute modules implementation. Implementation of software modules in ROS will enable recording of so-called ragbags during the field tests, which will enable replaying the sensor data. This will enable off-line work with sensor data recorded in real-world experiments. In this way, distributed off-line software development will be supported.

SMART2 FR-T-10 OD&TID system shall provide classification of detected objects.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: FR-SS-07

The OD&TID system is capable to classify the objects/intrusions as belonging to different classes.

SMART2 FR-T-11 OD&TID shall provide tracking of detected objects.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In line with: KPI-RAM-04, FR-T-06

The OD&TID system is capable to track the objects in order to provide reliable information about potential moving obstacles.

SMART2 FR-T-12 On-board OD&TID subsystem shall be able to control of direction of cameras.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: KPI-RAM-03(a), FR-T-01

Control of camera direction in horizontal plane can greatly improve SMART2 on-board OD&TID subsystem capabilities. The main idea behind is to develop the system of human-like performance of changing viewing direction when examining an area for suspicious objects/situations.

SMART2 FR-T-13 The OD&TID system shall provide real-time information to DSS.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: KPI-RAM-04, KPI-RAM-05, KPI-RAM-09

The feedback information from DSS to SMART2 OD&TID system shall be fast enough to be considered as real-time response.

SMART2 FR-T-14 OD&TID system shall have appropriate audio and visual alerts for the diagnosed failures and loss of the sensors' signals.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In line with: FR-SS-05

The installed diagnostic system should continuously monitor vehicles' service conditions and provides the status of all relevant subsystems and components. All collected data is checked and compared to the predefined threshold values. If the thresholds are exceeded, the on-board diagnostic feature warns of malfunctions and the need for performing maintenance activities. The diagnostic system should generate audio/visual alerts and, in some cases, instructions on how the specific failure can be removed.

SMART2 FR-T-15 The image and signal qualities of vision sensors shall be monitored to ensure optimal operational status of cameras and related equipment.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In line with: FR-SS-01

The diagnostic tool diagnoses the most critical faults during working regimes of cameras: operation statuses of cameras, and poor qualities of received pictures. The quality of an acquired image is monitored by evaluating signal-to-noise-ratio (SNR). Industry standards require SNR thresholds of 10:1 for acceptable image quality and 40:1 for excellent quality. Everything below 10:1 could be diagnosed as low quality, and maintenance of problematic cameras should be performed. Additionally, if the camera is not fixed and can rotate around axes, the status of involving motors should also be monitored.

SMART2 FR-T-16 Satisfactory performances and effectiveness of drones' control units, batteries, and external supply sources. Optimal work of drones' sensors and cameras.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In line with: FR-RAM-03

The diagnosis tool detects potential faults of drone's sensors' and signals (audio/visually) observed deficiencies and faults. A gyroscope and accelerometer measurements evaluate a drone's control surface, diagnosing the loss of effectiveness. The quality of an acquired image by a drone is monitored by evaluating signal-to-noise-ratio (SNR). Finally, the diagnosis system monitors a global positioning system (GPS) and its operating performances, as well as the current battery level and electric supply faults.

SMART2 FR-T-17 OD&TID shall use smart diagnosis and intelligent prevention of faults.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In line with: KPI-RAM-10, KPI-RAM-13

Implementation of intelligent algorithms within the diagnostic system to emulate human experience and fulfil tasks related to anomaly and fault detection and prevention. Intelligent diagnosis should be used to efficiently check availability and operational states of sensors and diagnose potential faults and undesirable behaviours.

SMART2 FR-T-18 OD&TID system shall be able to use zoom of specific mounted cameras

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: FR-T-01

Using zoom of specific cameras will provide better possibility for classification and closer investigation of potential obstacles.

SMART2 FR-T-19 OD&TID system shall be able to communicate with ERTMS and to simulate ERTMS data.

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In line with: KPI-T-04

SMART2 OD&TID system shall have possibility to communicate with ERTMS and have software for simulating ERTMS data in order to provide real evaluation conditions.

SMART2 FR-T-20 OD&TID system shall be able to recognize elements of railway infrastructure

Required by: AUT&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In line with: KPI-T-01, FR-T-03, FR-T-06

OD&TID system may have possibility to recognize fixed railway infrastructure elements and use collected data for correction of the estimated position and the distance of the obstacles detected by OD&TID system.

SMART2 FR – T-21 Radar detection of obstacles and track intrusions shall be with high level of reliability and accuracy.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

In line with: FR-T-03

Radar system should be able to reliably detect hazardous objects (e.g. persons, vehicles) larger than 0.5 m in diameter at a distance of minimum up to 2000m ahead of a train with max distance measurement error of +/- 0.25 m, within the braking distance of the train. In the case of Doppler effect functioning, radar should be able to also detect direction and speed of movement of obstacles.

SMART2 FR-T-22 Radar shall operate in the railway environment. All pieces of radar system should be able to operate with full nominal performance in relation to the *environmental conditions: temperature, humidity, dust, smoke, sun exposure, rain, snow, fog.*

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: KPI-RAM-01, KPI-RAM-02, KPI-RAM-07, KPI-RAM-09, KPI-T-09, FR-T-03

Radar system must be resistant to the challenging environmental conditions typical for operating of trains. It should operate with minimum IP66 environment protection class (level 6 dustproof, level 6 waterproof), and environment operating temperature of -15 to +55 °C. Radar system shall identify or disregard flora and fauna which might be in the detection area as appropriate.

SMART2 FR-T-23 The overall health and safety risk to staff, public, property and the environment, from the operation of the radar system (radio waves) shall be at an acceptable level.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: FR-SS-08

It is not possible to entirely eliminate all risks to staff, public, property and the environment, from the operation of the radar system and its radio waves. However, such risks should be minimised through system design and operating/maintenance procedures to an acceptable level.

SMART2 FR-T-24 The OD&TID UAV shall be able to provide sufficient flight performance

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: FR-RAM-03, FR-T-04, FR-T-06

The OD&TID UAV subsystem shall be able to provide sufficient flight performance related to maximal speed, flight time needed for fulfil targeted mission, adequate radius from its' nest. The fulfilment of specific flight performances make it possible to realize all desired functionalities of OD&TID UAV subsystem.

SMART2 FR-T-25 The OD&TID UAV shall be able to provide sufficient availability for performing assigned missions.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: FR-RAM-03

The battery changing capability of OD&TID UAV needs to provide the minimal flight availability of 90% during 24h.

SMART2 FR-T-26 The OD&TID UAV shall be able to perform automatic missions.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: FR-RAM-03, OR-T-10

The OD&TID UAV has to have multiple planning modes capability to provide optimization of the workflow for automatic missions. In that sense, performing patrol missions, inspection of area in front of upcoming area and monitoring marshalling operations can be realized.

SMART2 FR-T-27 The OD&TID UAV shall be able to stabilize vibration of vision sensors and to control direction of vision sensors.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: FR-T-01

Vibration stabilization of OD&TID UAV vision sensors in three axis and control their directions in at least two axis shall be provided. It means that the selected UAV has to be equipped with appropriate gimbal to fulfil this requirement.

SMART2 FR-T-28 The OD&TID UAV shall be able to be transmission resistant to interference.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: KPI-T-06

The OD&TID UAV has to have the minimal transmission distance 2km according to project scope and real time video quality of minimally 1080p.

SMART2 FR-T-29 The OD&TID trackside subsystem shall be able to detect objects that are larger in size than minimum detectable object size.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: FR-T-06

The OD&TID trackside subsystem shall be capable to detect objects larger than minimum detectable object size of 1.0 x 0.5 x 0.5 m.

SMART2 FR-T-30 The OD&TID trackside subsystem shall be able to cover larger detection area than prescribed minimum.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: FR-T-06

The OD&TID trackside subsystem shall be capable to detect objects in area larger than minimal detection area of size 15 m X 11m per track.

5.4 SMART2 Technical operational requirements

SMART2 OR-T-01 SMART2 on-board OD&TID case body shall be supported and isolated of vibration.

Required by: RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: FR-SS-06

The mounting construction should provide support of the SMART2 OD&TID demonstrator case body. The mounting construction should isolate the SMART2 OD&TID demonstrator body from vibrations transmitted from the vehicle. The vibration isolation should be realised by passive isolator for the minimal disturbing frequency of 1 Hz. For successful recognition of obstacles by vision technologies the acquired images from sensors must be free from distortions induced by vibrations. As low frequency vibration (bellow 1 Hz) are easily stabilised by digital image stabilisation, the upper frequencies which cause significant image distortion should be isolated.

SMART2 OR-T-02 All the sensors envisioned for the SMART2 on-board OD&TID demonstrator should be integrated into one case to create a TRL 6/7 SMART2 on-board OD&TID demonstrator.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: FR-SS-06

To enable various evaluation possibilities envisioned it is necessary to create a portable system which would integrate all the hardware necessary for obstacle detection. The case should provide:

- sensor mounting,
- protection of sensors from accidental damage,
- protection of sensor from environmental effects,
- power for the sensors,
- real time sensor connection,
- real time hardware for obstacle detection,
- storage system for data saving.

SMART2 OR-T-03 All the OD&TID subsystems shall be integrated into holistic SMART2 OD&TID demonstrator and connected to DSS.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: FR-SS-06

All SMART2 subsystems should be integrated into the SMART2 holistic OD&TID demonstrator. It means that on-board, trackside and airborne OD&TID subsystems are connected via DSS interfaces with DSS and working as integrated demonstrator.

SMART2 OR-T-04 The SMART2 processing units for DSS, on-board, trackside and UAV subsystems shall have the necessary computational processing and storage capability in a timely manner and make it available for other systems.

Required by: IM (operating mainline TMS), yard management (IM/RU/OTH), RU (operating loco).

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: KPI-RAM-04, KPI-T-03

Each of SMART2 OD&TID subsystems has to have local processing units with necessary speed and storage capability to provide reliable processing results of object detection and recognition in real time to DSS. In addition, cloud based DSS has to provide reliable final processing real time information to be sent to other systems.

SMART2 OR-T-05 Documentation of all SMART2 subsystems

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

The documentation required in order to integrate all subsystems into a complete system, such as:

- Functional specification
- Mechanical design drawings
- User manual

5.5 SMART2 Technical evaluation requirements

The discussion about potential evaluation scenarios imposes new requirements, beside the general ones, as the consequence of evaluation possibilities and procedural framework for OD&TID demonstrator testing during development and final evaluation. Additional requirements for OD &TID are also imposed by owners of the test vehicles (Serbia Cargo and Despotija) in order to ensure a continuity of their business operations.

SMART2 ER-T-01 Mounting of the on-board OD&TID prototype on locomotives to be used on evaluation tests shall be feasible.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

SMART2 ER-T-02 The quick mounting (approx. 30 minutes) of the on-board OD&TID prototype without maintenance specialized work force (electricians and maintenance engineers) must be possible in order to ensure business continuity of operator of test trains.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

SMART2 ER-T-03 The on-board OD&TID prototype mounting shall not impair the drivers' view of the track ahead of vehicle.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

SMART2 ER-T-04 The on-board OD&TID prototype mounting has to be done without any interference with vehicle structure by removing or cutting material.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

SMART2 ER-T-05 The on-board OD&TID prototype must not exceed the prescribed dimensions of the vehicle and the fitting of it should not cause the vehicle to exceed mass and axle load limits.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

SMART2 ER-T-06 The on-board OD&TID prototype must satisfy standards EN 61373:2010 and EN 50155:2007 to obtain permit for mounting on the vehicle in real traffic conditions or tests on the open track.

Required by: IM&RU.

<u>The requirement is relevant/applicable to:</u> all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator:</u> Mandatory.

SMART2 ER-T-07 The on-board OD&TID prototype must be easily transportable to enable development and evaluation at different locations.

<u>Required by:</u> IM&RU.

<u>The requirement is relevant/applicable to:</u> all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator:</u> Mandatory.

SMART2 ER-T-08 The SMART2 OD&TID prototype must be able to determine position and odometry of the train equipped with on-board in the same coordinate system as used by the train.

<u>Required by:</u> IM&RU.

<u>The requirement is relevant/applicable to:</u> all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator:</u> Mandatory.

SMART2 ER-T-09 The SMART2 OD&TID prototype must function as a stand-alone system, independent from on-board and track side Traffic and/or train control modules, or command and control systems of the vehicle.

<u>Required by:</u> IM&RU.

<u>The requirement is relevant/applicable to:</u> all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator:</u> Mandatory.

SMART2 ER-T-10 ECTS data must be supplied to SMART2 OD&TID demonstrator independently from the train communication system.

<u>Required by:</u> IM&RU.

<u>The requirement is relevant/applicable to:</u> all mainline and yard operation (all use cases).

<u>Level of obligation for SMART2 demonstrator:</u> Mandatory.

SMART2 ER-T-11 The SMART2 airborne subsystem (UAV) must be lighter than 25 kg to enable its use in urban areas.

<u>Required by:</u> AUT&IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

SMART2 ER-T-12 The SMART2 airborne subsystem (UAV) must possess its own obstacle avoidance system so to avoid collisions when flying.

Required by: AUT&IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

SMART2 ER-T-13 The prototype SMART2 airborne subsystem (UAV) must be in the visual sight of the operator.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

SMART2 ER-T-14 The SMART2 airborne subsystem (UAV) should only use the airspace above railway zone at heights lower than 100m.

Required by: IM&RU.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended.

5.6 SMART2 Safety and security requirements

SMART2-SS-01 SMART2 OD&TID system shall be able to detect and quantify loss of performance of operation on a subsystem and/or component level, whether on-board or trackside considering various factors.

Required by: IM, RU and OTH evaluate the output with respect to different scenarios.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

In line with: KPI-SS-01

SMART2-SS-02 The hazard rates of the SMART2 OD&TDI system shall be acceptable according to selected established safety principles and standards.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Recommended

In line with: KPI-SS-03

SMART2-SS-03 The SMART2 OD&TID system shall produce an alert when failures of one or more subsystems are detected, and output the diagnosis of the source of the failures.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory

In line with: KPI-SS-04

SMART2-SS-04 The SMART2 system shall comply with data privacy requirements of GDPR (General Data Protection Regulation)

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: CR-SS-04

SMART2-SS-05 SMART2 on-board OD&TID system shall comply with radar frequency regulation ETSI TR 102 704 v1.2.1 :2012-03.

Required by: IM, RU, AUT and OTH.

The requirement is relevant/applicable to: all mainline and yard operation (all use cases).

Level of obligation for SMART2 demonstrator: Mandatory.

In line with: CR-SS-05

This requirement is due to the need for radar equipment specifications to be compliant with the relevant regulations.

6. Technical specification of SMART2 OD&TID system

In this section technical specifications of the detection sub-systems of the OD&TID system prototype to be developed in SMART2 project are given.

6.1 SMART2 on-board OD&TID subsystem

As it stated in previous chapters, SMART2 on-board OD&TID subsystem consists of set of sensors, the technical specification for each of selected type of sensors has been given below. The sensors of SMART2 on-board OD&TID subsystem are: RGB cameras, SWIR camera, thermal camera and RADAR. In addition, technical specification of integrated on-board OD&TID subsystem is given in this section.

6.1.1 SMART2 on-board OD&TID subsystem - RGB cameras specification

As already mentioned, SMART2 on-board OD&TID system builds on SMART on-board OD system (SMART, 2016-2019). In particular, SMART2 on-board OD&TID system will use SMART zoom RGB cameras, which were selected in order to meet the main requirements to develop a sensory system for reliable multi range, mid (up to 200 m) and long range (up to 1000 m), obstacle detection ahead of the train.

The zoom color cameras from the imaging source (TIS) were selected for SMART obstacle detection (OD) system due to their long range and high resolution. The zoom camera DFK Z12GP031 (Fig.12) are categorized as GigE interface cameras which provides high data transfer rate, high bandwidth and Power over Ethernet (PoE) features which, in comparison to USB interface or FireWork interface, allows the transmission of images that are twice the size to the processing unit.

Figure 12: DFK Z12GP031 from the Imaging Source (T.I.S.E. GmbH, online)

The main features of DFK Z12GP031 zoom GigE camera are listed in the table below.

Table 3 The main features of DFK Z12GP031 zoom GigE camera.

Specification

Resolution	2,592×1,944 (5 MP)
Frame rate	15 FPS (Maximum)
Pixel Size	H: 2.2 µm, V: 2.2 µm
Focal length	4.8 mm (wide) to 57.6 mm (tele)
Interface	GigE
Supply voltage	11 VDC to 13 VDC or POE: 48 VDC to 56 VDC
Trigger	Software and Hardware
I/Os	Yes
Dimension	H: 50 mm, W: 50 mm, L: 103 mm
Weight	330 g
Shutter	$^{1}/_{20,000}$ s to 30 s
Gain	0 dB to 12 dB
White balance	-2 dB to 6 dB

Considering that SMART2 requirements for long-range obstacle detection of up to 2000 m are above the SMART requirements for long-range obstacle detection of up to 1000 m, the SMART2 OD&TID on-board system includes one additional RGB cameras with larger zoom. The additional zoom color cameras selected are from the same manufacturer as the SMART RGB cameras, imaging source (TIS), these were selected for compatibility with already existing SMART RGB cameras. The Imaging Source DFK Z30GP031 color camera (T.I.S.E. GmbH, online) was chosen.

Table 4 The main features of DFK Z30GP031 zoom GigE camera.

Specification	
Resolution	2,592×1,944 (5 MP)
Frame rate	15 FPS (Maximum)
Pixel Size	H: 2.2 µm, V: 2.2 µm
Focal length	4.3 mm (wide) to 129 mm (tele)
Interface	GigE
Supply voltage	11 VDC to 13 VDC or POE: 48 VDC to 56 VDC
Trigger	Software and Hardware
I/Os	Yes
Dimension	H: 60 mm, W: 60 mm, L: 116 mm

Weight	330 g
Shutter	$^{1}/_{20,000}$ s to 30; rolling
Gain	0 dB to 12 dB
White balance	-2 dB to 6 dB

Suitability of selected vision sensors for the SMART2 OD&TID demonstrator

The choice of RGB cameras, to be used for SMART2 OD&TID demonstrator, was done so to make the trade-off between the cost efficiency and fulfillment of functional and technical requirements as defined in Section 5. The chosen sensors fulfill the technical and functional requirements as follows:

- (*SMART2 FR-T-01*, *SMART2 FR-T-02, SMART2 ER-T-01*) the chosen sensors are appropriate for integration to a sensors' housing for easy *mounting/dismounting of on-board OD&TID system* on the locomotive so to enable *detection of objects, potential obstacles, in the railway environment and path of trains that are not the part of the railway infrastructure*
- (*SMART2 FR-T-05, SMART2 FR-T-018*) the chosen sensors are of high resolution which is a basis for reliable and accurate *object recognition at long range distances*; the chosen sensors have variable focal length f, which will enable testing of different zooming factors of individual vision sensor to cover different distance ranges including long distance ranges.
- (*SMART2 FR-T-08*) the selected GigE interface will enable fast communication between sensor and computer/embedded system

6.1.2 SMART2 on-board OD&TID subsystem - SWIR camera specification

Based on the analysis of the state-of-the-art of SWIR sensors (Appendix A1.1.2), the following minimum requirements that the SWIR camera of the SMART2 on-board OD&TID prototype should meet, have been defined:

- Image format: ≥ 640x512 pixels
- Pixel size: ≤ 15x15 µm
- Spectral range: lower limit < 800 nm / upper limit > 1600 nm
- Raw output data resolution: ≥ 14 bits
- Interface: Camera Link or GigaEthernet interface.
- Frame rate: > 150 Hz
- Readout: Global shutter
- Dynamic range: ≥ 50dB (gated mode)

- Sensor noise: < 150 e- (gated mode)
- The power supply: 12V DC nominal

The image sensor should be cooled and its temperature will be controlled by Peltier element.

The camera should have GATED mode, and the trigger delay should be selectable. The integration time should be at least 200 µs. The trigger should be Transistor-Transistor Logic (TTL) signal.

The partial reading of the sensor (ROI) should be possible, and the frame rate should increase when reading a small ROI.

Automatic exposure time should automatically calculate the exposure time depending on the mean histogram. The camera should have non gated logarithmic and high gain CDS mode, and gated low and high gain mode. Bad pixel correction and NUC correction should be calibrated in the factory.

The camera will be compatible with SWIR objective (with focal length 200-300mm)

Among the state-of-the-art SWIR cameras that meet the basic criteria (Resolution: ≥ 640x512 & Pixel size: ≤ 15x15 µm), a camera WIDY SenS 640M-STPE manufactured by New Image Technologies [NIT, online], was chosen. This camera was chosen because of the most acceptable price-quality ratio, delivery time and comprehensive technical support.

Figure 13: WIDY SenS 640M-STPE camera

Table 5 The main features of WIDY SenS 640M-STPE camera.

Specification	
Resolution	640(H)x512(V)
Interface	CameraLink
Sensor format	1 inch
Pixel pitch	15µm
Partial reading mode	Possible to integer just a part of the sensor

	(ROI) and display only this window on the video output. This option allows a frame rate increase on the ROI
TEC	3 modes Low current < 1W Middle current < 1.5W High current < 3.2W
Cooling capacity	ΔT = 30°C
Exposure time	**Gated mode:** 100ns to 9us **Standard mode:** See more details WiDy SenS 640M-ST
Spectral response	0.9 to 1.7um
Dynamic range	**Gated mode:** Low Gain : 58 dB High Gain : 44 dB **Standard mode:** See more details WiDy SenS 640M-ST
Full well capacity (in CTIA)	**Gated mode** Low Gain > 230 ke- High Gain > 17ke- **Standard mode:** See WiDy SenS 640M-ST
ADC	14 bits
Sensor Noise	**Gated mode:** Low Gain < 290e- High Gain < 125e- **Standard mode:** See WiDy SenS 640V-ST
Frame rate	Up to 230fps full frame
Trigger	IN/OUT (LVTTL), selectable delay
Consumption	Camera power consumption (Gated mode) < 3.8W TEC power consumption < 3.2W **Standard mode:** See WiDy SenS 640M-ST
Dimension	46x46x57mm
Mount	C-Mount native
Weight	< 215g
Temperature Range	-10°C to +71°C

Suitability of selected vision sensor for the SMART2 OD&TID demonstrator

The choice of SWIR camera, to be used for SMART2 OD&TID demonstrator, was done so to make the trade-off between the cost efficiency and fulfillment of functional and technical requirements as defined in Section 5. The chosen sensor fulfills the technical and functional requirements as follows:

- (*SMART2 FR-T-01, SMART2 FR-T-02, SMART2 ER-T-01*) the chosen sensors are appropriate for integration to a sensors' housing for easy *mounting/dismounting of on-board OD&TID system* on the locomotive so to enable *detection of objects, potential obstacles, in the railway environment and path of trains that are not the part of the railway infrastructure*
- (*SMART2 FR-T-04*) the selected cooled sensor will enable testing of long range object recognition in various environmental condition independently of lighting conditions (day & nightlight conditions) so that it is *robust to environmental/illumination conditions*
- (*SMART2 FR-T-05, SMART2 FR-T-018*) the chosen sensors is of resolution adequate for reliable and accurate *object recognition at long range distances*; the chosen sensors have variable focal length f, which will enable testing of different zooming factors of individual vision sensor to cover different distance ranges including long distance ranges.
- (*SMART2 FR-T-08*) the selected Camera Link or GigaEthernet interface will enable fast communication between sensor and computer/embedded system

6.1.3 SMART2 on-board OD&TID subsystem – thermal camera specification

Thermal camera chosen for the SMART2 on-board OD&TID subsystem is the FLIR TAU2 model with a resolution of 640x480 pixels and 100mm objective lens (FLIR Tau2, online). Its small size and the fact that sensor requires no cooling, together with possibility to expand it with adapter for gigabit Ethernet communication, make it suitable for SMART2 project.

<u>Objective lens</u>

Specific needs of SMART2 make it necessary to use narrow field lens with long focal distance to achieve enough magnification for detection of distant obstacles.

Figure 14: Thermal camera objective lens

FLIR lens of 100mm focal length and f- number 1.6 fulfils all requirements for this sensor channel, as one of on-board sensors as detailed in Sections 4 and 5. Total length of lens is 100mm which is short enough to place it inside OD&TID sensors' housing. When placed in the housing, separate germanium glass is to be used in the housing aperture for this sensor in front of the lens for mechanical protection during use.

<u>Camera sensor</u>
TAU 2 640x480 is uncooled vanadium oxide microbolometer sensor with 17µm pixel size which, together with 100mm lens gives field of view 6.2° x 5° and intrinsic field of view of 0.17mrad. Equivalently, on 1000m distance, each pixel covers 17cm x 17cm square.

<u>Gigabit Ethernet adapter</u>
In order to use data from TAU 2 camera, it is necessary to convert it from one of the available output formats to GigE vision format. This was achieved by Workswell GigE adapter which connects to the 50pin Hirose connector on the rear side of TAU 2 camera. It is also fixed to camera by 4 screws so they form one solid and robust body that can be further used as one piece. This adapter also allows Power Over Ethernet (POE) to provide power for both camera and adapter, so there is no need for separate power cables. The only disadvantage is that it doesn't allow for hardware triggering, as such software triggering solution will be used in SMART2.

Figure 15: Workswell GigE adapter

Suitability of selected vision sensor for the SMART2 OD&TID demonstrator

The choice of Thermal camera, to be used for SMART2 OD&TID demonstrator, was done so to make the trade-off between the cost efficiency and fulfillment of functional and technical requirements as defined in Section 5. The chosen sensor fulfills the technical and functional requirements as follows:

- (*SMART2 FR-T-01*, *SMART2 FR-T-02, SMART2 ER-T-01*) the chosen sensors are appropriate for integration to a sensors' housing for easy *mounting/dismounting of on-board OD&TID system* on the locomotive so to enable *detection of objects, potential obstacles, in the railway environment and path of trains that are not the part of the railway infrastructure*
- (*SMART2 FR-T-04*) the selected cooled sensor will enable testing of long range object recognition in various environmental condition independently of lighting conditions (day & nightlight conditions) so that it is *robust to environmental/illumination conditions* (*SMART2 FR-T-05, SMART2 FR-T-018*) the chosen sensor is of resolution adequate for reliable and accurate *object recognition at long distance ranges* and the chosen sensor has fixed focal length which will enable reliable and accurate object recognition at long distance ranges
- (*SMART2 FR-T-08*) the selected Gigabit Ethernet adapter will enable fast communication between sensor and computer/embedded system

6.1.4 SMART2 on-board OD&TID subsystem – RADAR specification

According to the requirements related to detection of obstacles and track intrusion by radar to be fulfilled, the selection of Raymarine Quantum 2 radar was performed due its exceptional operating range (6 m to 45 km) and advanced technologies in object tracking.

Figure 16: Raymarine Quantum 2 radar

The Quantum 2 (Figure16) is new generation CHIRP pulse compression radar which provides possible obstacle awareness at both long and extremely short ranges. The radar uses advanced Doppler processing, which enables the system to instantly acquire moving radar contacts and indicate their movement direction. The Quantum 2 is also equipped with Mini-Automatic Radar Plotting Aid (MARPA) which enables OD&TID system to assign radar targets for tracking. Table 6 gives the technical specification of the Quantum 2 radar (Raymarine, 2020). The important feature of Quantum 2 is safe emissions and non-ionising radiation which do not penetrate the human body. Nevertheless, the system will have shielding which will prevent emissions to reach driver cab during field tests and evaluation of the SMART 2 prototype.

Table 6 On-board OD&TID demonstrator gimbal specifications (Raymarine, 2020)

General specifications	
Dimensions	ϕ541 x 209.5 mm
Weight	5.6 kg
Supply voltage	Either 12 V dc or 24 V dc nominal Minimum: 10.8 V dc | Maximum: 31.2 V dc
Power consumption	Transmit mode (maximum): 17 W | Standby mode: 7 W | Sleep mode (applies only to radars connected via Wi-Fi): 2 W
IP protection	IPX6
Operating temperature range	-10°C to +55°C
Maximal wind speed	185 km/h
Transmitter	
Type	X-band solid-state transmitter with pulse compression technology
Transmit frequency	9354 MHz to 9446 MHz
Peak power output	20W
Duplexer	Circulator
Pulse widths (3 dB)	40 ns to 14.7 us
Chirp lengths	Chirp lengths: 400 ns to 20 us
Pulse repetition frequency	1200 Hz to 4800 Hz
Chirp bandwidth	Up to 32MHz
Antenna	
Type	Patch array
Beamwidth (nominal)	Horizontal: 4.9° | Vertical: 20°
Polarization	Horizontal
Rotation speed	24 rpm nominal
Doppler	
Target Tracking	Tracking of 25 simultaneous MARPA and / or ARPA targets
Target Filtering	True Motion mode identifies only objects that are moving relative to vessel

Connectivity	
WiFi	Yes
1G Ethernet	Yes

Suitability of selected radar for the SMART2 OD&TID demonstrator

The chosen radar fulfills the technical and functional requirements as follows:

- (*SMART2 FR-T-01*, *SMART2 FR-T-02, SMART2 ER-T-01*) the chosen radar due to compact dimensions and low mass is appropriate for integration to a sensors' housing for easy mounting on the locomotive so to enable *Detect objects, potential obstacles, in the railway environment and path of trains that are not the part of the railway infrastructure* and *on-board obstacle detection and track intrusion detection, Mounting/dismounting of on-board OD&TID system* and *Mounting of the on-board OD&TID prototype on locomotives to be used on evaluation tests shall be feasible.*
- (SMART2 FR-T-04, SMART2 FR-T-017, SMART2 FR – T-21) the chosen radar has a wide operational range between 6 m and 45 km advanced Doppler processing and target tracking & filtering which is a basis for reliable and accurate object recognition at long range distances;
- (SMART2 FR-T-22) the chosen radar has an IPX6 certification and wide temperature operation range which enables its use challenging environmental conditions.
- (SMART2 FR-T-25) the chosen radar technology and low power emission at high frequencies thus making it safe for personnel directly standing by the radar.
- (SMART2 FR-T-07) the GigE interface will enable fast communication between radar and OD&TI computer/embedded system.

6.1.5 SMART2 on-board OD&TID subsystem-gimbal specification

As one of the mandatory requirements for an onboard OD&TID systems is ability to control the direction of vision sensors (SMART2 FR-T-12: Control of direction of cameras of on-board OD&TID system). To satisfy the noted requirement, all the vision sensors will be mounted on the triaxial gimbals. The selected gimbals for SMART 2 onboard OD&TI are DJI Ronin S model (Fig. 17) and its specifications are given in Table 7 (DJI, 2020).

Figure 17: DJI Ronin S triaxial gimbal, (DJI, 2020)

Table 7 On-board OD&TID demonstrator gimbal specifications (DJI, 2020)

Peripheral	
Camera Tray Dimensions	Maximum depth from the centre of gravity on the camera base plate: 98 mm Max. height (from top of the camera base plate): 150 mm Maximum width: 205 mm
Accessory Port	Mechanical: 1/4"-20, 3/8"-16 Mounting Hole, M4 Mounting Hole Electrical: 12V/2A Power Accessory Port, Camera Control Port, 8-pin Port
Input Power	14.4V
Working Performance	
Load Weight (Reference Value)	3.6 kg (Handheld)
Angular Vibration Range	±0.02°
Maximum Controlled Rotation Speed	Pan axis: 360°/s Tilt axis: 360°/s Roll axis: 360°/s
Mechanical Endpoint Range	Pan axis: 360° continuous rotation Tilt axis: + 205° to - 115° Roll axis: + 230° to - 90°
Controlled Rotation Range	Pan axis: 360° continuous rotation (Roll 360 mode) Tilt axis: +180° to -90° (Upright Mode), +90° to -135° (Underslung and Flashlight Mode) Roll axis: ±30°, 360° continuous rotation
Mechanical & Electrical Characteristics	
Working Current	Static current: ≈0.16 A

Operating Temperature	-20℃ to 45℃
Weight	Approx. 1.5 kg
Dimensions	Approx. 202×185×486 mm

Suitability of selected gimbal for the SMART2 OD&TID demonstrator

Besides enabling the adjustment of camera direction, the selected gimbals isolate sensors from vibrations origination from the moving vehicle thus preventing the occurrence of the motion blur.
The chosen sensors fulfill the technical and functional requirements as follows:

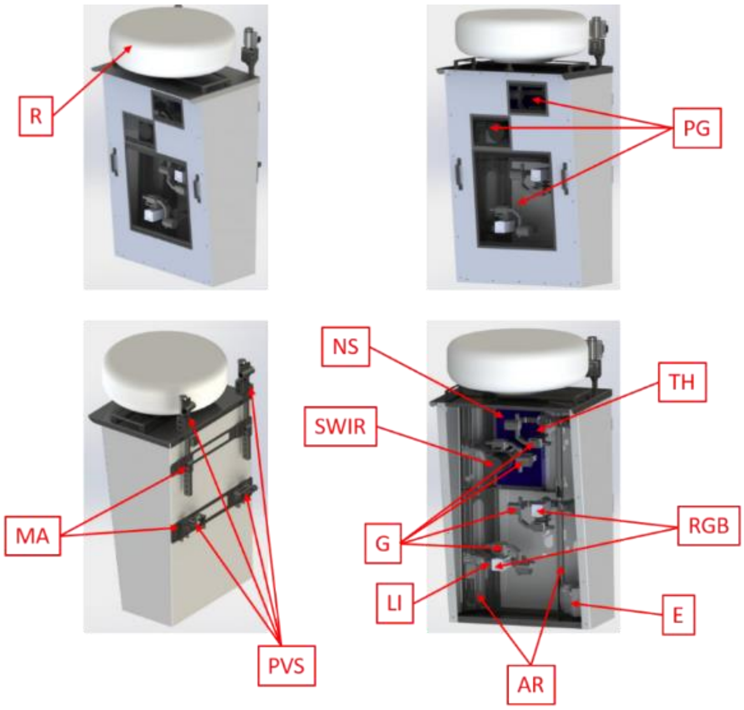
- (*SMART2 FR-T-01*, *SMART2 FR-T-02, SMART2 ER-T-01*) the chosen gimbal due to payload which can support all the vision sensors, wide range of motion in all three axis, compact dimensions and low mass is appropriate for integration to a sensors' housing for easy mounting on the locomotive so to enable *Detect objects, potential obstacles, in the railway environment and path of trains that are not the part of the railway infrastructure* and *on-board obstacle detection and track intrusion detection, Mounting/dismounting of on-board OD&TID system* and *Mounting of the on-board OD&TID prototype on locomotives to be used on evaluation tests shall be feasible.*

6.1.6 Integrated SMART2 on-board OD&TID subsystem

According to the requirements related to the on-board system integration detailed in Chapter 5, the design of the on-board OD&TID demonstrator has been performed. SMART2 on-board OD&TID is based on combination of different vision technologies including thermal camera, SWIR sensor, multi RGB cameras, and RADAR. The idea behind is to create a multi-sensor system for long range (up to 2000 m) obstacle detection, which is independent of light and weather conditions.

Figure 18: On-board SMART2 OD&TID system mounting on different locomotives - SERBIA KARGO series 444 (top), Bombardier TRAXX (bottom left) and Siemens VECTRON (bottom right)

The housing design was is such that it can be located between the headlights of typical freight locomotives below the level of the driver's windows, which enables housing mounting on different vehicles as shown in Figure 18. The sensor housing integrates all the sensors within the SMART2 on-board OD&TID demonstrator, as well as other components necessary for sensor operation and successful obstacle recognition such as network and power components, the detail CAD design of the housing, including the components is shown in Figure 19. Furthermore, detailed information on interconnections between subcomponents and their power supply is illustrated in Figure 20.



LI - laser illuminator
RGB - RGB camera
SWIR - SWIR camera
TH - thermal camera
R - radar
G - triaxial gimabl
E - electronics
NS - 10 G network switch
PG - protective glass
AR - adjusting rails
MA - mounting adapters
PVS - passive vibration suppression

Figure 19 CAD model of the integrated SMART 2 onboard ODS

The dimensions of housing are 600x500x1200 mm, which enables its mounting to different types of locomotives as the dimensions fit in the space generally available between the headlights, windshield and draw hook of most locomotives, and is available on the types of locomotive which are available for SMART2 field tests. Inside the main sensors' housing, the mounting of the triaxial gimbals, which hold the sensors, onto the standardised profiles is enabled using special adapters designed for attaching of gimbals to profiles. The connection of the gimbals onto the profile with standard sliding elements enables the quick positioning of the sensors and reconfiguration of the sensor position if needed. The front panel of the housing is detachable and provides easy access to the sensors. The sections of the front panel are made from plan parallel tempered glass which provides protection for the camera sensors while maintaining the visibility. The thermal camera is protected by rectangular shaped Germanium glass which is transparent for infrared radiation. The radar is mounted on the top of the housing and a protective sheet of aluminium is placed between the radar and the locomotive to protect locomotive and human operators from radar radiation. The front panel is inclined at approximately 80° with respect to the horizontal plane to avoid/reduce reflection from camera shooting through the glass. The reflection is further avoided by a lens hood attached between the cameras body and the protective glass. At a later stage, the inside of the housing will be heated to avoid condensation and enable its functioning during cold weather. Furthermore, wipers will be introduced to front panel to clean the protective glass and enable the sensors to have a good, undistorted/unobstructed, view during rain and snowfall.

The schematic of SMART2 on-board OD&TID prototype can be viewed in Figure 200. Sensor data will go to the OD&TID processing and data storage elements located in the locomotive drive cabin via a network switch (NS). The on-board system will be equipped with RTK GPS system which will give precise location of the train in the global coordinate system and odometry data. The on-board OD&TID will communicate with DSS by 4G/LTE network independently from train communication system. The OD&TID processing hardware will also provide control of gimbal orientation based on recognised track data or based on GPS position of the train. Based on commands issued by the DSS, it will be possible to adjust the gimbal orientation by OD&TID processing hardware in order to investigate objects in the trackside environment which might jeopardise the train. The zoom of some of cameras will also be controlled by OD&TID processing hardware on a command from DSS with the same goal as for gimbal orientation.

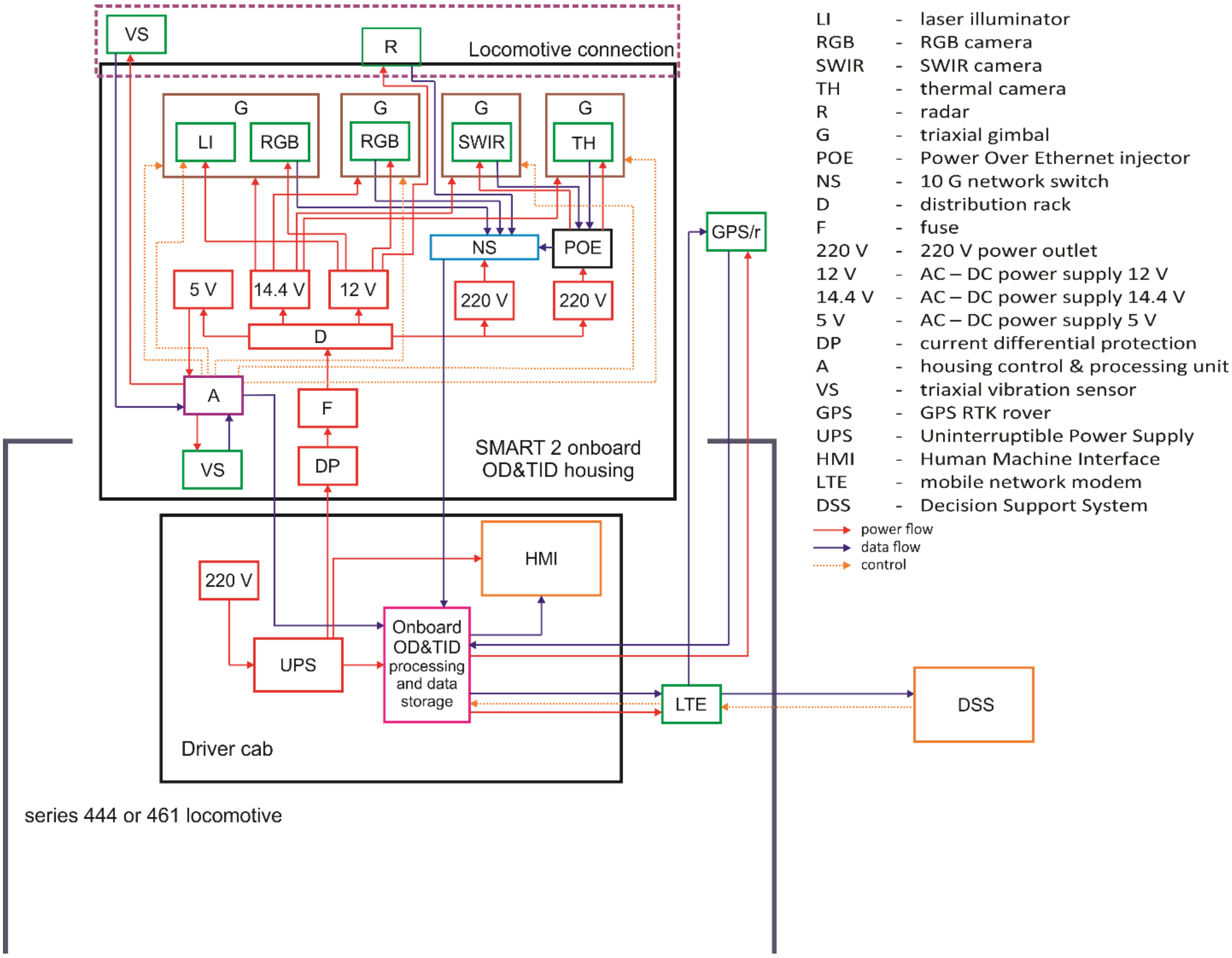


Figure 20 Schematics of the integrated SMART2 on-board OD&TID system

The gimbal motors are controlled by PWM (Pulse Width Modulation) signal from housing control and processing unit which also acquires signal from vibration sensors located in the housing and on the locomotive body. The Arduino MEGA microcontroller board (based on the ATmega2560) has been chosen as the housing control and processing unit (Figure 211). It has 54 digital input/output pins (of which 15 can provide PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator and a USB connection. The board is connected with USB cable to the SMART2 OD&TID processing and data storage and receives control inputs from it.

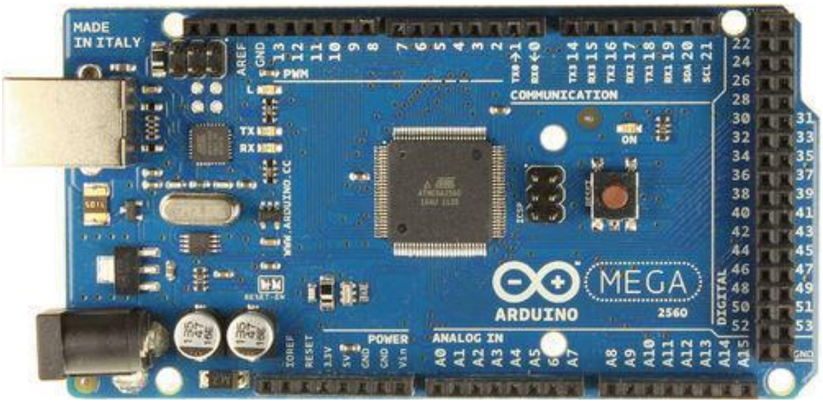


Figure 21 Housing control & processing unit - Arduino MEGA microcontroller board, (Arduino, 2020)

The connectivity of the OD&TID sensors to the SMART2 OD&TID processing and data storage computer is provided by 10 G network switch NETGEAR XS708T to enable real time acquisition of sensor data., and its specifications are given in Table 8, (NETGEAR, 2020)

Table 8 Specifications for network switch of on-board OD&TID demonstrator (NETGEAR, 2020)

Technology	
Standards	IEEE 802.3 Ethernet IEEE 802.3u 100BASE-T (XS708T/XS716T only) IEEE 802.3ab 1000BASE-T IEEE 802.3an 10GBASE-T 10Gbps Ethernet Over Copper Twisted Pair Cable IEEE 802.3ae 10-Gigabit Ethernet Over Fiber (10GBASE-LRM) - XS708T/ XS716T only IEEE 802.3ae 10-Gigabit Ethernet Over Fiber (10GBASE-SR, 10GBASE-LR, 10GBASE-ER, 10GBASE-LX4) IEEE 802.3z Gigabit Ethernet 1000BASE-SX/LX IEEE 802.3x Full-Duplex Flow Control IEEE 802.1Q VLAN Tagging IEEE 802.3ad Trunking (LACP) IEEE 802.1AB LLDP with ANSI/TIA-1057 (LLDP-MED) IEEE 802.1p Class of Service IEEE 802.1D Spanning Tree (STP) IEEE 802.1s Multiple Spanning Tree (MSTP) IEEE 802.1w Rapid Spanning Tree (RSTP) IEEE 802.1x RADIUS Network Access Control IEEE 802.3az Energy Efficient Ethernet (EEE)
Interface	
Ports	8 10GBASE-T copper

	2 SFP+ 1000/10GBASE-X fiber ports (shared)
Power Requirements	
Input Voltage	Internal 100-240VAC 50-60Hz
Power Consumption	~ 49.5 W
Physical Characteristics	
Housing	Aluminum Shell
IP Rating	-
Dimensions	440 x 204 x 43 mm
Weight	2.61 kg
Installation	Rack mounting
Environmental Limits	
Operating Temperature	-5° to 55 °C
Storage Temperature	–10° to 70 °C
Ambient Relative Humidity	max 95% (non-condensing)
Standards and Certifications	
Electromagnetic emissions and immunity	CE mark, commercial FCC Part 15 Class A, VCCI Class A Class A EN 55022 (CISPR 22) Class A Class A C-Tick EN 55024 CCC 47 CFR FCC Part 15, Subpart B, Class A ICES-003: 2016 Issue 6, Class A ANSI C63.4:2014 IEC 60950-1:2005 (ed.2)+A1:2009+A2:2013 AN/NZS CISPR 22:2009+A1:2010 CLASS A
Safety	CB mark, commercial CSA certified (CSA 22.2 #950) UL listed (UL 1950)/cUL IEC 950/EN 60950 EN 60950-1: 2006 + A11:2009 + A1:2010 + A12:2011 + A2:2013 IEC 60950-1:2005 (ed.2)+A1:2009+A2:2013 AN/NZS 60950.1:2015 CCC (China Compulsory Certificate)
MTBF (mean time between failures)	
Time	276197 h

It is important to note that when selection of switch was made there were no commercial solutions available for 10 GB switches certified for railway applications. The selected switch is certified to short circuit protection and electromagnetic immunity and emissions, so the noted certificates were used to obtain permits for mounting on the vehicle in real traffic conditions. As the SMART2 on-board OD&TID prototype is not an constituent of the interoperability of the locomotive and does not influence locomotive control and functioning of its devices/subsystems the noted certificates will be sufficient to obtain permits for evaluation.

A custom-built PC has been designed and built for SMART2 OD&TID processing and data storage computer the specifications of which are given in Table 9.

Table 9 Specifications for SMART2 on-board OD&TID processing and data storage computer

Hardware setup	
Processor	INTEL Core i9- 7900X
Motherboard	ASUS RAMPAGE VI EXTREME
Memory	KINGSTON DIMM DDR4 64 GB (8x8GB)
GPU	2 x ROG Strix GeForce GTX 1080 Ti OC edition 11GB GDDR5X
Storage	2 x HDD SSD M.2 NVMe Samsung 500GB 960 Pro connected in RAID 0
Power supply	LC Power LC1000 v2.4 80 plus Platinum
Conectivity	Aquantia AQC-107 10G Ethernet Intel I219-V 1G Ethernet 2x2 MU-MIMO 802.11AC Wi-Fi 1x1 802.11AD Wi-Fi USB 3.1 Gen 2 (Type A + Type C) 12 x USB 3.1 Gen 1 ports (4 at front) 2 x USB 2.0 ports
Cooling	COOLER MASTER MasterLiquid ML240L
Software setup	
OS	Ubuntu 20.04 (Focal)
Control software	ROS Noetic Ninjemys
Other software	Qt 4.8.1 CUDA 8.1 OPEN CV

The on-board OD&TID computer is connected with a cloud based DSS via an LTE class 11 modem. The determination of the position of the on-board OD&TID is carried out with centimetre precision by a GPS - RTK rover Emlid REACH M2 which is shown in Figure 22 (Emlid, 2020), which receives RTK corrections via the LTE class 11 modem. The GPS - RTK rover is connected via USB connection with OD&TID computer. The specifications of the GPS - RTK rover are given in Table 10.

Figure 22 GPS - RTK rover Emlid REACH M2, (Emlid, 2020)

Table 10 GPS - RTK rover specifications

Positioning	
Static horizontal	4 mm + 0.5 ppm
Static vertical	8 mm + 1 ppm
Kinematic horizontal	7 mm + 1 ppm
Kinematic vertical	14 mm + 1 ppm
Mechanical	
Dimensions	56.4 x 45.3 x 14.6 mm
Weight	35 g
Operating temperature	-20…+65 ºC
Electrical	
Input voltage on USB and JST GH	4.75 - 5.5 V
Antenna DC bias	3.3 V
Avg. consumption @5V	200 mA
Connectivity	
LoRa radio	Frequency range868/915 MHz Distance up to 8 km
Wi-Fi	802.11b/g/n
Bluetooth	4.0/2.1 EDR
Ports	USB, UART, Event
Data	
Corrections	NTRIP, VRS, RTCM3
Position output	NMEA, LLH/XYZ
Data logging	RINEX with events with update rate up to 20 Hz
Internal storage	16 GB

GNSS	
Signal tracked	GPS/QZSS L1C/A, L2C GLONASS L1OF, L2OF BeiDou B1I, B2I Galileo E1-B/C, E5b
Number of channels	184
Update rates	20 Hz GPS / 10 Hz GNSS
IMU	9DOF

The whole SMART2 on-board OD&TID system is powered by UPS (APC SMT2200IC) which is certified for electromagnetic immunity and emissions. Besides adding a layer of equipment protection, the UPS also adds another layer of protection as it has a control logic which protects from power surges and short circuit. The UPS is located in driver cab and it is connected to a 220 V power outlet of locomotive. As selected sensors and other electronics require different voltage supply, three AC-DC power supplies are installed in on-board OD&TID housing. The AC-DC power supplies are certified by EN 50155:2007 (Railway applications. Electronic equipment used on rolling stock). To power the switch and POE injector for thermal camera it is envisaged that a DIN rail 220 V power outlet will be installed into the housing. To prevent possible short circuit and safety issues, additional fuses and current differential protection is positioned before the power supply elements located in the housing.

The certification of power supply to railway standards enables the satisfaction of requirements regarding the Electric & electromagnetic compatibility. The only connection to locomotive electric system will be a 220V power supply cable which is connected into the driver cab outlet which is protected from short circuits. The system has a position determination system (GPS RTK) independent from the vehicle positioning system. This configuration allows the fulfilment of the requirements that no connection to the control & command systems of the vehicle is made (*SMART2 ER-T-09*) as it enables the on-board OD&TID system to determine its position independently of the locomotive systems. As the overall mass of the sensors housing with all the sensors and additional equipment will be approximately 60 kg, it can be considered that the on-board OD&TID demonstrator mass is negligible in comparison to the locomotive mass, thus fulfilling the requirement (*SMART2 ER-T-05*). The overall sensors housing dimensions and planed positioning bellow the windshield, is such that it will not hinder the driver's field of view (*SMART2 ER-T-03*). The sensors housing of the OD&TID demonstrator will be made of high strength steel with sufficient cross section of structural elements to stiffen the housing body, which was checked by the Finite Element Analysis (FEA) method. Additional stiffening elements will be integrated onto the longer sheet metal spans to increase the system vibration resistance. Natural frequency of the sensors housing is significantly above the dominant frequencies of the locomotive car body vibrations. Furthermore, the sensors housing will be vibration isolated. Such design will enable fulfilment of the requirements regarding the vibration resistance (*SMART2 ER-T-06*). The vibration resistance will be tested according to EN 61373:2010 (Rolling stock equipment – Shock and vibration tests for a Category 1 Class B device) after the manufacturing of the sensor housing. The sensor housing will be powder coated after the manufacturing so that it is resistant to corrosion. The presented design of the integrated system enables the fulfilment of all the requirements defined in Chapter 5.

6.2 SMART2 trackside OD&TID subsystem

Based on the state-of-the-art analysis and requirements related to trackside OD&TID, the selected system for the SMART2 trackside OD&TID subsystem is Fokus SALVIS X (SALVIS X, online), with the laser scanner as the main sensor component, to meet the requirements, with the basic specification given in Table 11.

Table 11 Technical specification for SMART2 trackside OD&TID subsystem

Laser sensor	
Horizontal field of view	60 °
Vertical field of view	30 °
Detection range	2 to 40 m
Distance measurement accuracy	± 5 cm
Minimum resolution	0,2 m
Detection area	> 15 x 11 m
Detectable object size	>1,0 m x 0,5 m x 0,5 m
Frame rate	> 2 Hz
Detection response time	200 ms
Laser safety	Class 1
Electrical	
Operating voltage	24 V DC ± 10 %
Power consumption	100 W
Environmental	
Operating temperature range	0 °C to + 25 °C
IP rating	IPX6
Connectivity	
Interface	Ethernet 100BASE-TX

The trackside system is connected with wired ethernet connection to SMART2 trackside OD&TID processing and data storage computer. A custom-built PC has been designed and built for SMART2 trackside OD&TID processing and data storage computer with the specifications given in Table 14.

Suitability of selected trackside system for the SMART2 OD&TID demonstrator

- (*SMART2 FR-T-01*) the chosen laser scanner system has broad field of view, detection range, high point resolution, low object reflectance which is a basis for reliable and accurate object recognition at level crossings.
- (*SMART2 FR-T-29, SMART2 FR-T-30*) the selected laser scanner has larger detection area than required and can detect objects with dimensions lower than required.
- (*SMART2 FR-T-03, SMART2 FR-T-04*) the laser scanner has an IPX6 certification and due to underlying technology it is suitable for reliable and safe operation in harsh railway environments (dirt, dust, vibrations, rain, snow, high temperature, immunity to direct and reflected sunlight);
- (*SMART2 FR-T-07*) the ethernet interface will enable fast communication between SALVIS X and OD&TI computer/embedded system.

6.3 Technical specification of SMART2 airborne OD&TID subsystem

Based on the state-of-the-art analysis and requirements related to UAV OD & TID presented in previous sections, the UAV selected for the SMART2 trackside OD&TID subsystem is DJI Phantom 4 RTK (Fig.23), with RGB camera as the main sensor component. The main features of the SMART2 UAV OD&TID are given in Table 12.

Figure 23: DJI Phantom 4 RTK UAV (DJI, 2020)

Table 12 The main features of SMART2 UAV OD&TID subsystem

Aircraft	
Takeoff Weight	1391 g
Diagonal Distance	350 mm
Max Service Ceiling Above Sea Level	6000 m

Max Ascent Speed	6 m/s (automatic flight); 5 m/s (manual control)
Max Descent Speed	3 m/s
Max Speed	58 km/h (50 km/h with integrated obstacle detection functioning)
Max Flight Time	30 minutes
Operating Temperature Range	0° to 40°C
Operating Frequency	2.400 GHz to 2.483 GHz (Europe)
Transmission Power (EIRP)	2.4 GHz CE (Europe)： < 20 dBm
Hover Accuracy Range	RTK enabled and functioning properly： Vertical： ±0.1 m； Horizontal： ±0.1 m
Image Position Offset	The position of the camera center is relative to the phase center of the onboard D-RTK antenna under the aircraft body's axis:(36, 0, and 192 mm) already applied to the image coordinates in Exif data. The positive x, y, and z axes of the aircraft body point to the forward, rightward, and downward of the aircraft, respectively.
GNSS	
Single-Frequency, High-Sensitivity GNSS Module	GPS+GLONASS+Galileo
Multi-Frequency Multi-System High-Precision RTK GNSS	Frequency Used： GPS： L1/L2； GLONASS： L1/L2； BeiDou： B1/B2； Galileo： E1/E5a First-Fixed Time： < 50 s Positioning Accuracy: Vertical 1.5 cm + 1 ppm（RMS； Horizontal 1 cm + 1 ppm（RMS） 1 ppm means the error has a 1mm increase for every 1 km of movement from the aircraft.
Obstacle detection	
Infrared	Obstacle Sensing Range: 0.2 - 7 m FOV: 70°(Horizontal), ±10°(Vertical) Measuring Frequency: 10 Hz Operating Environment: Surface with diffuse reflection material, and reflectivity＞ 8%（such as wall, trees, humans, etc.)
Vision	Obstacle Sensing Range: 0.7-30 m FOV: Forward/Rear: 60° (horizontal), ±27° (vertical), Downward: 70° (front and rear), 50° (left and right) Measuring Frequency: Forward/Rear ： 10 Hz;

	Downward： 20 Hz Operating Environment: Surfaces with clear patterns and adequate lighting (＞ 15 lux)
RGB camera	
Sensor	1" CMOS; Effective pixels: 20 M
Lens	FOV 84°； 8.8 mm / 24 mm (35 mm format equivalent:24 mm)；f/2.8 - f/11, auto focus at 1 m - ∞
ISO Range	Video:100-3200(Auto) 100-6400(Manual)
Mechanical Shutter Speed	8 - 1/2000 s
Electronic Shutter Speed	8 - 1/8000 s
Video Recording Modes	H.264， 4K： 3840×2160 30p
Supported File Systems	FAT32（≤ 32 GB） exFAT（> 32 GB）
Storage	MicroSD, Max Capacity: 128 GB. Class 10 or UHS-1 rating required Write speed≥15 MB/s
Operating Temperature Range	0° to 40°C
Gimbal	
Stabilization	3-axis (tilt, roll, yaw)
Pitch	-90° to +30°
Max Controllable Angular Speed	90°/s
Angular Vibration Range	±0.02°
Transmission System	
Transmission standard	Occusync 2.0
Video Resolution	1080p
Maximum Transmission Distance	6 km
Video Download Speed	40Mb/s
Live View Video Quality	720p@30fps, 1080@p30fps
Transmission Modes	2.4 GHz and 5.8 GHz, auto-switch between these two frequencies
Latency	120-130ms
Connectivity	
Wireless	4G/LTE dongle, WiFI
Wired	USB 2.0

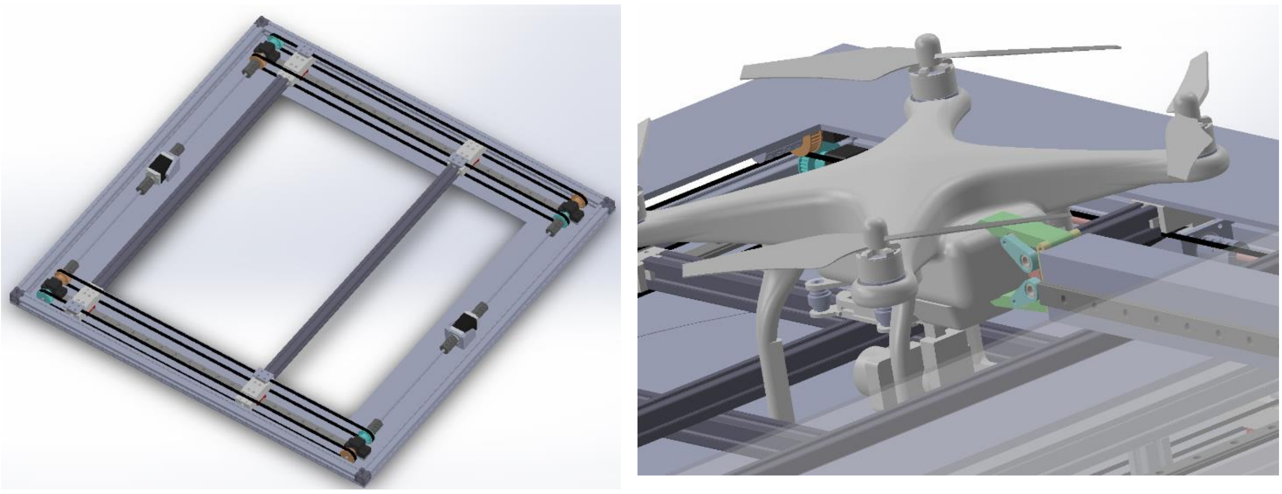
The selected UAV does not have automatic charging capability, so it was necessary to specify the automatic charging station for the selected UAV. Considering all the charging procedures available for the drone (DJI Phantom 4 RTK) SMART 2 team put the focus to an analytic process analysis in order to determine the optimal charging concept and perform the design of the charging system. SMART 2 approach involved an analysis using AHP method (Analytic Hierarchy Process) in order to determine the weight of each decision criterion involved in the process of designing of each charging system available. The result of the AHP analysis (Figure 24) showed that the best option is a battery swap system because it fulfils three most desired criterions (Minimal risk factor, Minimal invasive modifications to the drone and Minimal modifications to the battery). Furthermore, the noted battery swap system enables maximal possible availability of the drone for the mission related to OD&TID.

	VOC4 ...	VOC3 ...	VOC2 ...	VOC10...	VOC5 ...	VOC8 ...	VOC1 ...	VOC6 ...	VOC7 ...	VOC9 ...	Importance in Gr...
VOC4 (BT) Build Time	1	1/3	1/3	1/5	1/5	1/3	1/5	1/5	1/5	1/5	2%
VOC3 (PT) Programming Time	3	1	1	1/3	1/5	1/3	1/5	1/5	1/5	1/5	3%
VOC2 (DT) Design Time	3	1	1	1/3	1/5	1/3	1/5	1/5	1/5	1/5	3%
VOC10 (P) Price	5	3	3	1	1/3	1/3	1/3	1/5	1/5	1/7	5%
VOC5 (CPI) Cross Platform Integrability	5	5	5	3	1	1/2	1/3	1/3	1/3	1/2	9%
VOC8 (EU) Ease-of-Use	3	3	3	3	2	1	1	1/3	1/3	1/3	9%
VOC1 (CT) Charge Time	5	5	5	3	3	1	1	1/2	1/2	1/2	12%
VOC6 (IMD) Invasive Modifications to the Drone	5	5	5	5	3	3	2	1	1	1	19%
VOC7 (IMB) Invasive Modifications to the Battery	5	5	5	5	3	3	2	1	1	1	19%
VOC9 (RF) Risk Factor	5	5	5	7	2	3	2	1	1	1	19%
Consistency (Lamda - N):	0,79										

Importance in Group

0% 12,5% 25% 37,5%

Figure 24: AHP Analysis for a UAV charging system



a) b)

Figure 25: CAD model of the UAV charging system

The design for the charging system consists of two subassemblies (1) landing and take-off zone equipped with positioning mechanism and 2) battery swap mechanism) designed in such way that the overall time between the landing ant the take-off process is minimal. The proposed solution involves a subassembly designed for the landing zone equipped with two mobile actuated axis in order to position the landed UAV (Fig. 25 a). Each axis is actuated by two stepper motors equipped with belt transmissions, assembled in such manner that it allows a single stepper motor to actuate upon it's assigned positioning beam (Fig.25, a). Regarding the swapping station, the robotic arm is designed in order to remove the battery, insert it into the charging pad, take another fully charged battery and reinsert it into the UAV (Fig. 25, b). The specifications of the battery swapping system are given in Table 13.

Table 13 Technical specification for SMART2 UAV charging station

Mechanical & performance	
Overall dimensions	1500 x 750 x 250 mm
Landing area	approx. 500 x 500 mm
Positioning time	max. 60 s
Battery swap time	max. 60 s
Repositioning time	max. 60 s
Electrical specifications	
Primary voltage	220-230 V
Control voltages	24 V, 5V
Charging voltage	15.2 (V)
Power Consumption	max. 2000 W
Communication	
Network interface	1G Ethernet

The schematic of SMART2 UAV OD&TID prototype can be viewed in Fig.26. The stepper motors in the battery swapping pad are controlled by Arduino MEGA microcontroller board. The board is connected with USB cable to the SMART2 UAV OD&TID processing and data storage and receives control inputs from it. The UAV sensor data will go to the OD&TID UAV processing and data storage elements located in the UAV nest via Occusync 2.0 transmission system. The UAV is equipped with RTK GPS system which will give precise location of the UAV in the global coordinate system and odometry data. The UAV OD&TID will communicate with DSS by 4G/LTE network independently from existing trackside communication systems. The UAV OD&TID processing hardware will also provide control of UAV missions, gimbal orientation and camera zoom based on commands issued by the DSS. The RTC corrections will be received by a 4G/LTE dongle on the UAV.

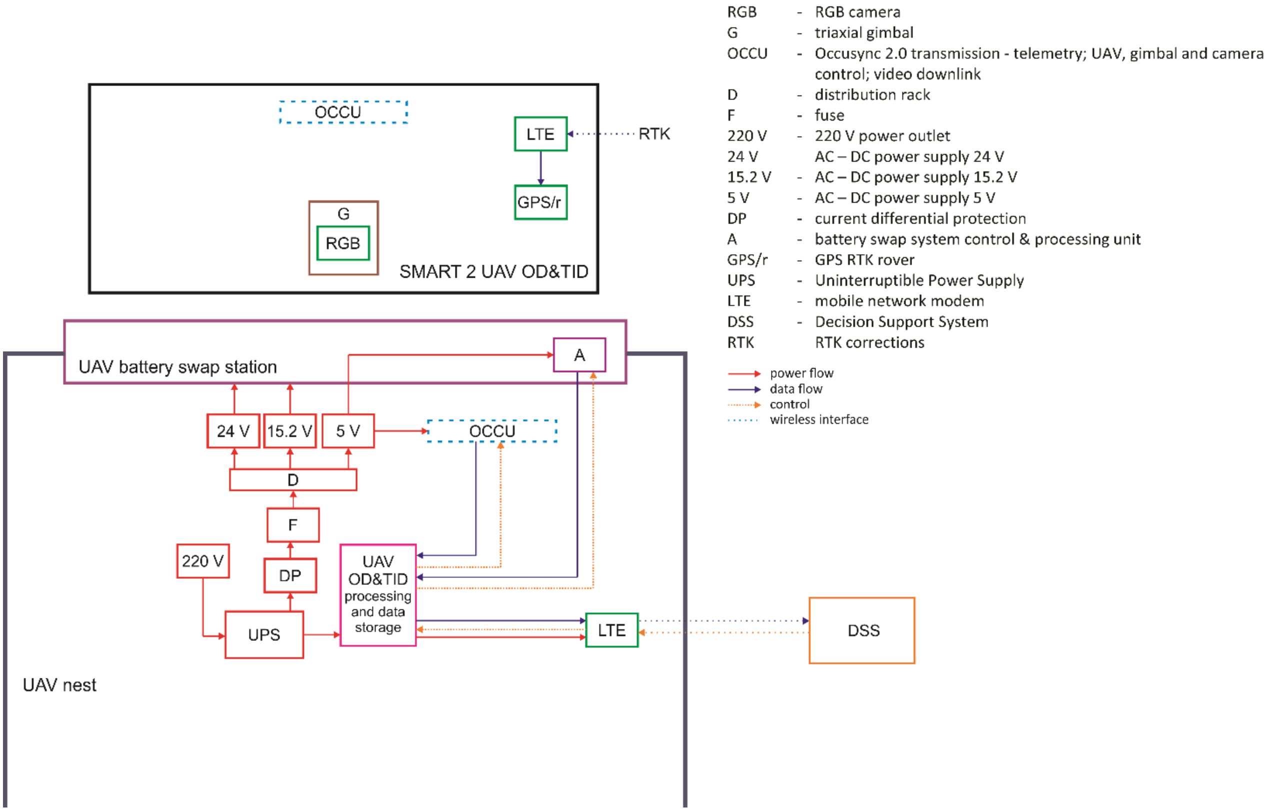


Figure 26: The scheme of the power and data flow for SMART2 UAV

A custom-built PC has been designed and built for SMART2 UAV OD&TID processing and data storage computer the specifications of which are given in Table 14.

Table 14 Specifications for SMART2 UAV OD&TID processing and data storage computer

Hardware setup	
Processor	INTEL Core i9-10900
Motherboard	ASUS ROG STRIX Z490-F
Memory	G.Skill DIMM DDR4 64 GB (4x16GB)
GPU	1 x GIGABYTE GeForce RTX 2070 SUPER GAMING OC
Storage	1 x HDD SSD M.2 NVMe Samsung 1TB 970 EVO
Power supply	SHARK WPM Gold ZERO 750W
Conectivity	Intel® I225-V 2.5Gb Ethernet 4 x USB 3.2 Gen 2 (3 x Type-A+1 x USB Type-C) 2 x USB 3.2 Gen 1 2 x USB 2.0 ports
Cooling	1200 BOX Intel cooler
Software setup	

OS	Ubuntu 20.04 (Focal)
Control software	ROS Noetic Ninjemys
Other software	Qt 4.8.1 CUDA 8.1 OPEN CV

Suitability of selected SMART2 UAV for the SMART2 OD&TID demonstrator

The choice of SMART 2 UAV, to be used for SMART2 OD&TI demonstrator, was done so to make the trade-off between the cost efficiency and fulfilment of functional and technical requirements defined in Section 5.

- (*SMART2 FR-T-03*) The selected UAV cannot operate at temperatures below 0 °C and cannot be sent to OD&TID related missions at wind speeds higher than 10 m/s. There are UAVs on the market that can successfully satisfy requested requirement (operating temperature above -20 °C, wind speeds below 30 m/s) but their price does not justify their use at this stage of development.
- (*SMART2 FR-T-05, SMART2 FR-T-018*) the chosen sensor has high resolution which is a basis for reliable and accurate *object recognition at long range distances*; the chosen sensor have variable focal length f, which will enable testing of different zooming factors of individual vision sensor to cover different distance ranges including long distance ranges; mechanical shutter makes data capture seamless as the Phantom 4 RTK can move while taking pictures without the risk of rolling shutter blur; camera lens goes through a rigorous calibration process, with parameters saved into each image's metadata, letting post-processing software adjust and increase accuracy.
- (*SMART2 FR-T-24*) the chosen UAV has maximal speed of 50 km/h and flight time of 30 minutes which enables it to perform missions in radius of up to 12,5 km from it's nest or even 25 km with UAV nest change strategy with multiple UAV.
- (*SMART2 FR-T-25*) the chosen UAV with the battery changing capability has minimal flight availability above 90% during 24 h which can be even larger with intelligent mission planning by DSS based on data supplied by TMS.
- (*SMART2 FR-T-26*) the selected UAV has multiple planning modes capability, including the Waypoint Flight, Terrain Awareness, Block Segmentation and possibility to import KML/KMZ (Keyhole Markup Language/Keyhole Markup Language compressed) which enables optimization of the workflow for automatic missions thus provides ability to the UAV to perform patrol missions, to inspect area in front of the upcoming train and monitor marshaling operations.

- (*SMART2 FR-T-27*) the selected UAV is equipped with high performance triaxial gimbal which provides suppression of vibrations originating from aircraft and precise adjustment of camera direction
- (*SMART2 FR-T-28*) the selected UAV possesses Occusync 2.0 transmission technology which enables control of the UAV and real time video transmission to the OD&TI UAV of high quality resistant to interference with automatic switching between transmission frequencies; the transmission distance is up to 7 km which is well above required range and area coverage for a holistic OD&TI approach.

6.4 Technical specification of Cloud based interfaces and DSS

6.4.1 Cloud Service Providers – selection criteria

There are many cloud service providers on the market – some of them are multi-purposes platforms of major IT companies, while others offer only very specialised services, aiming to cover a niche of the Cloud Services market. In this analysis, all three main Cloud Platforms on the market, Amazon AWS, Google Cloud Platform and Microsoft Azure, will be considered as potential candidates for the SMART2 prototype DSS.

All three considered platforms can be shortly described by following remarks:

- **Amazon AWS**: a subsidiary of Amazon which provides on-demand cloud computing services for individuals, companies and governments. These services are charged on a "pay-for-what-you-use" basis. They offer several cloud-based services to their users, such as Virtual Machines, Aurora (MySQL Database), EC2 (Cloud Computing) to name a few. Their current market share (as of 2019) is roughly 48% of the market.
- **Microsoft Azure**: this is a Cloud Computing Service created and offered by Microsoft. Their stated goal is to create, build, test, deploy and manage applications through Microsoft-managed data centers. Microsoft Azure was launched in 2010 and some of the most important features it offers are: Virtual Machines, Cloud Storage (both Blob and with a file system), Virtual Machines, Serverless Computing. Microsoft Azure is the second largest Cloud Service Provider after Amazon AWS, with a 28,4% market share as of 2019.
- **Google Cloud Services**: This is a suite of cloud services offered by Google. It has a set of management tools, along a series of modular cloud services such as storage, computing, data analytics and machine learning. Some of the most notable are : App Engine, Compute Engine (Cloud computing solutions), Cloud Storage, BigTable (storage) and Virtual Machines. The platform is the third largest provider according to their market share, evaluated at roughly 5% as of 2019.

Several aspects must be considered when choosing a cloud service provider for a system. On one side, it must be determined what services are needed, and whether or in what form the Cloud Platform offers them. On the other side, there are certain platform-specific parameters (such as latency, download and upload speed, reliability, security, etc.) that should be taken into consideration as well.

For this purpose, papers such as (Glosh et al., 2015) and (Sundaraawaran et al., 2012) proposed different approaches which can be used to rank the cloud service providers based on the needs of the user. Ghosh et al. (2015) proposed a method which can be used to calculate a parameter called "Risk of Interaction" for every cloud service provider; in order to do so, a thorough analysis of the Service Level Agreement (SLA) for each cloud service provider is proposed. This is due to the fact that, while the major cloud platforms sell basically identical services (the name varies from platform to platform), the platform-specific parameters (such as reliability or data protection for example) vary greatly from one Platform to another. Comparing the data in the SLA to the real data (which can be measured), the "Risk of Interaction" is then calculated based on the "competence" of the platform and its "trustworthiness".

(Sundareswaran et al., 2012)

proposed a more pragmatic framework, by introducing the concept of a "Cloud Broker" – this is an algorithm which is designed to continuously monitor the essential, platform-specific parameters for the cloud service providers and rank them accordingly.

However, for the SMART2 project, implementing a complex framework in order to select a service provider is not required. Of particular interest for the scope of SMART2 project, the chose of cloud service provider for prototype OD&TID system relays on the reliability and latency of each platform, which can be taken from the SLA (in the case of reliability) and measured (in the case of the latency). As such, the service provider with the highest reliability and lowest latency will be chosen.

Additionally, there are several subjective criteria which play a significant role in the decision-making process, which aren not mentioned in either (Ghosh et al., 2015) or (Sundareswaran et al., 2012) – the costs of the services offered by each platform and the available know-how of the developers. The platform with the lowest costs and the highest developer knowledge is clearly desirable.

6.4.2 Data usage specification

Before selecting a cloud service provider, it is important to estimate how much data is expected to be handled throughout the system in average, in order to estimate the costs and the expected performance of the system. It was already stated that the goal is to deliver metadata files to the cloud only, which are the results of processing carried out locally, and then these data will then be fed into the DSS alongside the external data inputs. However, the factor that has the most significant impact on the amount of data is the sensor data sampling rate. Four different rates have been considered: 100ms, 200ms, 500ms and 1000ms.

Some other constraints must be considered as well:

- It is assumed that all the trains are operated almost continuously – namely, we assumed that the train operates for 1340 minutes per day.
- The speed of the train is irrelevant in this case, as the amount of storage needed is impacted by the sampling rate and the operation time.
- A 20% buffer to the estimated storage space has been applied in order to account for unexpected situations.
- All the cloud service providers charge the user for the number of read/write processes that we use. Those are generally sold in batches of 10000.
- Low latency and overall reliability will be the deciding factors in whether a cloud service provider is adequate or not.

Taking all these considerations into account, the average expected data flow can be seen in the following table, based on the variable acquisition rate:

Table 15 Multi-modal OD&TID System Data Usage Estimate

Acquisition Rate(ms)	Operation Time (sec per day)	Metadata files per day (includes 20% buffer)	Total size per day (Gb)	Total Size + Buffer(20%) (in Gb)	Total size + buffer (Gb, Entire Month)	Read-Write Processes (in batches of 10000) includes buffer per month
100	80400	804880	3,83	4,6	138	161
200	80400	402880	1,92	2,3	70	81
500	80400	161680	0,78	0,94	28,2	33
1000	80400	81280	0,39	0,47	14,2	17

6.4.3 Provider Specifications

Amazon AWS

The main services of interest offered by Amazon AWS are Amazon SimpleDB (the equivalent of table storage) and Amazon Lambda (a serverless computing environment). According to the AWS Service Level Agreement (AWS service, online), the provider is making "commercially reasonable efforts" to provide the highest possible platform reliability. For the services of interest (Amazon SimpleDB and Amazon Lambda), the reliability was on average 99,99%. So Amazon AWS offers the promising technologies for the SMART2 OD&TID system.

In order to estimate the latency of the platform, the Amazon AWS Ping Test provided by the freelance platform cloudpingtest.com (AWS ping, online) can be used. The quality of the connection (the upload and download speed basically) can be estimated using (AWS network, online). However, these vary greatly with the quality of the connection available at the test site. For this reason, as well, download speed was not measured, since there are too many variables to take into account and any result that could be obtained is irrelevant if the test conditions are changed even slightly. Regarding the ping test, it tells us what the delay between a local command and the response from the AWS Cloud is. Since there are many data centres available around the world, only those near our location will be considered (Europe 1 to 6, namely Frankfurt, Ireland, London, Milan, Paris, Stockholm). Obviously, for the result, only the closest will be considered, which is Frankfurt.

Table 16 Amazon AWS Overall Estimated Parameters

Sampling rate	100 ms	200 ms	500 ms	1000 ms
Latency (Frankfurt)	50 ms	50 ms	50 ms	50 ms
Latency (Ireland)	139 ms	139 ms	139 ms	139 ms
Latency (London)	105 ms	105 ms	105 ms	105 ms
Latency (Milan)	94 ms	94 ms	94 ms	94 ms
Latency (Paris)	86 ms	86 ms	86 ms	86 ms
Latency (Stockholm)	149 ms	149 ms	149 ms	149 ms
Total platform latency (5*Best latency)	250 ms	250 ms	250 ms	250 ms
Average Upload Speed	1 Mb/s	1 Mb/s	1 Mb/s	1 Mb/s
Reliability	99,99%	99,99%	99,99%	99,99%

The total platform latency represents the total time that the platform needs in order to process a request i.e., the data transfer from the Detection Block to the Cloud Storage (1x), the forwarding of the data to the DSS (2x), the input from the external factors (3x), the generation of the result (4x), the forwarding of the result to the Cabin UI(5x), thus, the platform latency should be considered as 5 times.

To conclude the analysis of Amazon AWS, we have noticed the following: the average processing time is around 4,25 seconds and the average reliability is 99,99%. With a relatively good platform latency of 50 ms (to the closest datacentre) Amazon AWS is a solid choice for DSS Implementation.

Google Cloud Services

In order to assess the potential of the Google Cloud Services platform, the following tool is available to us: the Google Cloud Platform Network Test (Google Cloud NT, online). The tool (Google Cloud NT, online) can be used to estimate the latency of the platform, alongside the upload and download speed. However, such tests are very inconclusive, as the results vary greatly if even a tiny parameter is changed (for example, the quality of the internet connection at the test site, the distance of the test site to the data centre, the type of internet plan available to the tester, the quality of the network infrastructure – and this refers to the infrastructure of the network outside the Google Datacentre).

When considering latency, it is worth noting that Google has several data centres around the world and in Europe, there are lots of candidate data centre for the latency testing. Depending on the distance between our location and a data centre, the latency will increase. For this test, we shall not consider any data centres outside of Europe; for the best results, we shall consider the data centre in Frankfurt.

The services that we are interested in are BigQuery, which is a table-based data storage service and the Serverless Computing platform that Google Cloud has, namely Google Cloud Functions. The Serverless Computing is needed to run the DSS in a cloud environment, while BigQuery will be used to store our data.

The reliability of the Google Cloud Platform is presented in the Service Level Agreement is roughly 99,95% on average (Google Cloud LA, online) for the services of interest to this project.

All the parameters of the Google Cloud Platform (prices, latency, processing time etc...) have been summarised in the following table. As an additional note, the total platform latency is calculated in the same approach as it was calculated for Amazon AWS.

Table 17 Google Cloud Services Performance and Cost Estimates

Sampling rate	100 ms	200 ms	500 ms	1000 ms
Latency (west3-c)	20 ms	20 ms	20 ms	20 ms
Latency (west4-b)	24 ms	24 ms	24 ms	24 ms
Latency (west3)	35 ms	35 ms	35 ms	35 ms
Latency (west2-a)	36 ms	36 ms	36 ms	36 ms
Latency (north1-b)	50 ms	50 ms	50 ms	50 ms
Latency (west1-c)	30 ms	30 ms	30 ms	30 ms
Latency (west6-b)	30 ms	30 ms	30 ms	30 ms
Latency (west2)	55 ms	55 ms	55 ms	55 ms
Latency (west1)	53 ms	53 ms	53 ms	53 ms
Latency (west6)	37 ms	37 ms	37 ms	37 ms
Latency (north1)	75 ms	75 ms	75 ms	75 ms
Latency (west4)	47 ms	47 ms	47 ms	47 ms
Total platform latency (5*Best latency)	100 ms	100 ms	100 ms	100 ms

Average Upload Speed	1,2 Mb/s	1,2 Mb/s	1,2 Mb/s	1,2 Mb/s
Reliability	99,95%	99,95%	99,95%	99,95%

The conclusion here is that Google Cloud Services offers services which fulfil the needs of the OD&TID System, with good latency values and good reliability values.

Microsoft Azure

The last platform that we will analyse is Microsoft Azure. To assess its performance, the following tool is available: Azure Networking Test offered by CloudHarmony (Microsoft Azure SLA, online). . While the upload and download speed were measured as well by this test tool (Microsoft Azure SLA, online), alongside the platform latency, these tests are relatively inconclusive as even a small change in the parameters will result in a big change in the result. For example, upload and download speed can be greatly influenced by the network infrastructure available in the area where the test is performed, the distance to the data centre or the data plan of the user performing the test. Thus, none of the two tests will offer identical results and the numbers presented in the table below are only used as a reference of what we can expect.

Regarding Latency, it is worth mentioning that Microsoft has several data centres across the world and in Europe. For this particular test, we will present the expected values for all the European data centres. The data centre in Frankfurt will offer the best result when it comes to system latency.

The services that Microsoft Azure offers and are particularly interesting to us are Azure Table Storage, which can be reliably used to store the metadata produced by the local processing elements and Azure Functions, a serverless computing environment in the cloud which can be used to implement and run the DSS.

The reliability of the Microsoft Azure services which are of interest to this project is presented in the Microsoft Azure Service Level Agreement. The average value of this reliability is 99,995%, the highest among the three considered platforms (Microsoft Azure SLA, online).

All the parameters used to describe the Microsoft Azure Platform have been summarised below:

Table 18 Microsoft Azure Performance and Costs Estimate

Sampling Rate	100 ms	200 ms	500 ms	1000 ms
Latency (Germany North)	20 ms	20 ms	20 ms	20 ms
Latency (Switzerland West)	24 ms	24 ms	24 ms	24 ms
Latency (France South)	37 ms	37 ms	37 ms	37 ms
Latency (UK South)	39 ms	39 ms	39 ms	39 ms
Latency	41,5 ms	41,5 ms	41,5 ms	41,5 ms

(Norway West)				
Latency (Switzerland North)	29 ms	29 ms	29 ms	29 ms
Latency (EU West)	34 ms	34 ms	34 ms	34 ms
Latency (UK West)	45 ms	45 ms	45 ms	45 ms
Latency (EU North)	49 ms	49 ms	49 ms	49 ms
Latency (Norway East)	41 ms	41 ms	41 ms	41 ms
Total platform latency (5*Best latency)	100 ms	100 ms	100 ms	100 ms
Average Upload Speed	1,3 Mb/s	1,3 Mb/s	1,3 Mb/s	1,3 Mb/s
Reliability	99,995%	99,995%	99,995%	99,995%

All the big Cloud Service Providers offer a "pay-for-what-you-use" pricing model. Exactly how the prices are calculated and what services one must pay for is detailed in the Pricing Calculator that each platform offers. Overall, taking into consideration which services are of interest in every case and the 100ms sampling rate case (which has the highest quantity of data which must be handled, thus it is the most expensive), the following table, which contains all the parameters relevant for the final decision, has been created:

Table 19 Cloud Platforms Summary

Provider Name	Amazon AWS	Google Cloud Services	**Microsoft Azure**
Availability	99,99%	99,95%	**99,995%**
Latency	20ms	50ms	**20ms**
Total Latency	100ms	250ms	**100ms**
Total Monthly Price (100ms)	156,5$	26$	**8,95$**
Verdict	**Acceptable**	**Acceptable**	**Best**

Based on the data from Table 19, but also on the experience that the developers from partner OHB-DS have with Microsoft Azure, the best choice for the DSS Implementation would be the Microsoft Azure platform, as it has the lowest latency among the three considered platforms and the lowest prices for the services.

7. Conclusions

This document presents analysis and definition of requirements and specifications for railway OD&TID systems.

The detailed specification of use cases for OD&TID in railways was presented in (SMART2 D1.1, 2020). In this deliverable D1.2, a brief review of defined use cases is given. The listed use cases were used as the base for defining requirements and specification of OD&TID system.

The outcome of the analysis of the use case requirements by SMART2 is the proposal of a set of requirements for OD&TID systems for all use cases, with emphasis on freight use cases. These proposed overall requirements have been specified, defined, and classified in terms of the functional requirements, operational requirements, and capability features of the OD&TID systems. In this way, a common framework for considering the requirements for all use cases, identifying common areas and areas of difference, allowing harmonisation and integration of OD&TID systems has been defined.

In order to provide high-level requirements and specification for OD&TID systems, four types of requirements have been considered, analysed and defined: performance, functional, operational, and compliance with regulation and standards. All these types of requirements have been divided into three categories: RAM – related to reliability, availability and maintainability (RAM) aspects; Safety & Security (S&S) – related to safety and security; and Technical – those tackling technical features of the system, meant to be directly addressed by specifications of subsystems and interfaces.

The performance/KPI-related requirements describe how well the system and its subsystems will perform certain functions. The speed of response, interface throughput, execution time, storage capability, and detection capability, while equipment reliability are considered in RAM performance requirements. The S&S performance requirements mainly relate to the SIL standard which the system should comply with, and the compliance with regulation and standards requirements deal with the regulations and standards the system should comply with in order to be considered suitable for use as part of the railway system and within the overall environment.

The functional requirements relate to functions of the entire system or its subsystems, which shall determine the response of the system in different scenarios. The RAM related functional requirements take into consideration time/distance-based failure rate and mean time between maintenance of the system and subsystem. The S&S functional requirements relate to the capability of the system to resist hazardous incidents in its operational circumstances.

Operational requirements relate to the needs of train operators, railway operators and yard operators, and consider aspects such as failure diagnose and maintenance, risk forecast and data generation and analysis. Compliance requirements benchmark the compliance of the OD& TID system to existing standards and regulation, which ensure the interoperability of railway operation across the EU countries.

These overall requirements have been initial inputs for defining specific SMART2 detailed requirements in section 5.

As it is stated in SMART2 project scope and objectives, the holistic approach would be used for obstacle detection and track intrusion detection. A holistic approach to autonomous obstacle detection for railways using the input from multiple sensor sub-systems would enable the detection area ahead of the train to be increased in many situations, compared to systems solely mounted on the front of the train. In that sense, some specific outcomes from used holistic approach have been considered in defining detailed SMART2 technical requirements.

As the field tests during development and final SMART2 OD&TID prototype system evaluation will depend on available test rail tracks and test vehicles as well as on legal and safety regulations to be fulfilled, it was necessary to include and define evaluation possibilities for SMART2 OD&TID demonstrator to understand SMART2 requirements & specifications. Different field tests for data generation, sub-system conformance testing and final evaluation of SMART2 integrated prototype for holistic OD&TID will be conducted in real-world environment supported by Serbian Railways Infrastructure (SRI) and two cargo operators (Serbia CARGO and DESPOTIJA). The evaluation scenarios in real environment will be realized for most significant defined use cases.

On the basis of defined SMART2 concept of OD&TID system, evaluation possibilities and overall requirements, specific technical requirements for SMART2 OD&TID system have been separately defined. These SMART2 requirements have been divided into three categories: functional, operational and evaluation. These requirements have been the base for defining technical specification.

Technical specifications of SMART2 OD&TID system needed to fulfil the requirements are identified in section 6. Authors reviewed and analysed potential equipment and technologies for object detection and cloud computing for the OD&TID system and DSS, respectively. For the on-board subsystem, WIDY SenS 640M-STPE SWIR camera, DFK Z30GP031 RGB camera and TAU 2 thermal camera are chosen as the key sensors, and these sensors will be centrally controlled by an Arduino MEGA controller and mounted into a sensor housing. Furthermore, the power supply and communication solution for on-board OD&TID subsystem are also discussed regarding the interface and space constraints. The trackside OD&TID will be serviced like a 'watch towel' or 'sentry' in specific location such as: level crossing, stations, tunnels, and etc., and 3D laser scanner will be used as the main sensor component. For the airborne OD&TID subsystem, the key action will be achieved by a drone fleet nested in specific service areas. A drone RGB camera will be used as the key component, and the camera will be mounted on a gimbal that will enable the control of camera's the viewing direction of the camera. Furthermore, the potential cloud service providers are reviewed and compared with respect to proposed selection criteria, i.e.: system availability, system latency and subscribe price; and finally, Microsoft Azure is viewed as the best choice for the DSS of the SMART2 OD&TID system as it has the lowest latency among the three considered platforms and the lowest prices for the services.

This deliverable D1.2 elaborates the first set of requirements. These would be continuously updated with respect to inputs from S2R members working on relevant ongoing projects in IP2 and IP5. A constant exchange with complementarity project S2R-CFM-IP2-01-2019 will be established so as to ensure that the requirements developed in that project are considered for the proposed system. A milestone is defined at M18 to align with and take into account the first official release of the requirements and specifications from the complementarity project S2R-CFM-IP2-01-2019.

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Appendix

A.1 State of the art of technologies relevant to SMART2 subsystems

As it is described in Section §5, SMART2 solution will have four subsystems: on-board OD&TID subsystem as counterpart of loco, trackside OD&TID subsystem, airborne (drone-based) OD&TID subsystem and DSS for collecting data from OD&TID subsystems, decision making and send adequate response to ETCS related to detected obstacles and track intrusions. In (SMART2 D1.1, 2020), the state of the art of existing integrated OD&TID systems has been presented. Here, the state of the art for different technologies that will be used in individual sub-systems is given. Also, the state of the art in vision-based methods for obstacle detection is given, as vision sensors will be primary sensors of on-board and drone-based detection sub-systems.

A.1.1 State of the art of on-board OD&TID systems

In recent years, there has been a rapid expansion in research and development of on-board obstacle detection for road transport. Although railways are the other principal means of transport over land, research and development of obstacle detection in railways has to date lagged behind that for road transport. Consequently, on-board obstacle detection for railways follows research in automotive. Initially, researchers and developers applied and tested techniques, known from the car driver assistance systems, to support on-board obstacle detection for rail transport.

Regarding the hardware, the on-board sensors typically used for obstacle detection in automotive are also used as on-board sensors for obstacle detection in railways. An overview of the on-board sensors for obstacle detection in railways is given in (Gebauer et al., 2012). The analysed sensors are active sensors, LiDAR, radar and ultrasonic, as well as passive sensors, stereo- and mono- cameras as well as infrared (IR) cameras. Different sensors are analysed with respect to usefulness of sensor types depending on weather/light conditions as well as distance (i.e. detection/image capture range) and cost. Active sensors are used for direct precise measurements of obstacle distances. The advantages of cameras over LiDARs and radars are high data density, the possibility of object boundary and multiclass classification for higher number of classes. In order to use the positive characteristics of individual sensors, as well as to overcome the shortcomings of individual sensors, sensor fusion is a common solution for on-board obstacle detection (OD). One of the first OD systems consisting infrared camera and laser rangefinder installed inside the train is presented in (Yamashita et al., 1996). In (Ukai et al., 2011), obstacle detection on railway track by fusing radar and camera sensor is presented. The same fusion of radar and camera is used in (Kruse et al., 2003) where the multi sensor system comprising a tele-camera, far distance radar, a survey camera and a near distance radar network were used for practical testing. A multi-sensor set consisting of three video cameras and an infrared radar system, which monitors the track in front of a train, is presented in (Ruder et al., 2003). Different combination of sensors, such as stereo vision, mono cameras, radar and laser, were implemented in the system presented in (Weichselbaum et al., 2013). The paper focuses on the multi-camera system as one of the sensor subsystems. In order to fulfil accuracy requirements for reliable obstacle detection within 80 m ahead of the train, and to provide sufficient depth resolution to differentiate whether distant obstacles are on track or only nearby, the outer two cameras form a stereo camera system with a baseline of 1.4 m. The third, middle, colour camera primarily serves as source for colour information. A railway object-detection system that can be installed on a locomotive to automatically detect objects in front of the train in the shunting mode is used in (Ye et al., 2018), (Ye et al., 2020). The system consists of on-board camera that captures images for the proposed detection algorithm, the distances between the detected object and train are measured using millimetre-wave radar. In (Gleichauf et al., 2020), an 8-layer laser scanner, an RGB and a thermal camera were fused to allow a robust wagon and obstacle detection for the automation of a shunting locomotive. A multi-sensor system consisting of look-ahead sensors, video cameras (optical passive) and LiDAR (optical active) is presented in (Mockel et al. 2003). More precisely, the system consists of a fixed short distance LiDAR (also called near LiDAR) and a two-dimensionally scanning long distance LiDAR (also called far LiDAR). These sensors are using the time-of-flight principle and therefore provide a high longitudinal precision. The passive sensor unit is a multi-focal assembly of one survey fixed camera (also called short-range or near camera) and two far-range cameras (also called long distance or far cameras) with a pan device enabling the viewing angle control. The viewing angle is controlled via a mirror that is rotated by a stepper motor.

As obvious from above mentioned in related papers, vision sensors are in practice essential sensors in multi-sensor on-board OD systems. This is because only vision sensors can provide explicit rich visual information about the scene in front of the train. Also, the fact that using a camera sensor is the least expensive variant of the considered technical OD solutions influenced the significant amount of research and development of vision-based on-board obstacle detection systems. Advances in computational platforms and vision algorithms, enabled use of low-cost vision sensors to capture images in real-time and perceive surroundings of a rail vehicle leading so to number of purely vision-based on-board OD systems. There are various possibilities for the usage of front cameras in trains published in recent literature. The methods based on using of single cameras, attached in the front of the train, are presented in (Uribe et al., 2012), (Wang et al., 2017), and (Wang et al., 2019). Research in (Ross, 2010) and (Ross, 2012) present the application of a monofocal video camera, mounted behind the wind shield of the train, to improve the track localization quality. Train front cameras are also used in (Qi et al., 2013) and (Nanosone et al., 2017). In (Wohlfeil et al., 2011) a cost-efficient vision system consisting of camera that observes the area in front of a railroad vehicle is used for the rail tracks detection in real-time. In (Berg et al., 2015), a vision system consisting of a monocular thermal camera is mounted on a train is presented for detecting the rails in the imagery, as well as a way to detect anomalies on the railway. In some of published works, single camera systems are augmented to improve their limited data recording capability. A system in which a camera with zoom lens mounted on a pan–tilt unit so that the camera always points to the rails is used is presented in (Nassu et al., 2012). A prototype system installed in the cab of a train, consisting of single camera that acquires images of the railway scene in front of the train and a near infrared laser which is mainly used to add illumination to the area the camera is directed at when the light is insufficient for railway object detection (Ye et al., 2020).

A number of authors present the application of multi-camera systems to advance environment perception performances. In (Nassu et al., 2011), various on-board camera models and lenses were used to identify rail tracks at short as well as at long distances. A vision-based system consisting of a high-resolution camera capable of detecting relevant objects within a distance of 500 meters mounted on the car body of the locomotive to have a clear view of the scene in front of the train is presented in (Athira et al., 2019). Ukai, (2004) considers an optical arrangement of ultra-telephoto lens camera mounted on train which monitors the status of the track for 600m (braking distance) or over ahead of the train.

A.1.1.1 Vision-based on-board obstacle detection in railways

In principle all methods for vision-based on-board obstacle detection can be divided into two main groups: methods based on traditional Computer Vision (CV) and methods based on Artificial Intelligence (AI).

Traditional CV methods

Bearing in mind that the main goal of OD in railways is detection of objects, possible obstacles, on and near the rail tracks, almost all traditional CV methods contain rail track detection for the purpose of detecting image Region of Interest (ROI), within which the search for the objects that are hazardous to train should be performed. However, some of the methods presented in the literature, as described in section below, contain only rail tracks detection and do not consider obstacle detection at all. This is because those methods assume that finding the obstacle-free rail tracks region in front of the train is sufficient for defining the collision free region.

Rail track detection

Starting from the rail track geometry as consisting of two parallel lines, a number of published works exploit the methods for lane detection, which is a fundamental yet challenging task in autonomous driving and intelligent road traffic systems. Those published works extended the line detection methods using the geometric characteristics specific to rail tracks. For example, method proposed in (Kudinov et al., 2020) is based on the fact that the distance between the rails of the railway track is fixed and a prior known for each country. Also, the presented method uses the fact that the points belonging to the rails which are on the perpendicular erected to one of the rails, can be analogues to the base markers for determining spatial coordinates as part of a Perspective-2-Point (P2P) solution. Method for rail detection presented in (Wang et al., 2017) is based on four hypotheses: the gap between the rails at the initialization stage is constant, in the bird's-eye view the rails are parallel and the pair of rails has to come to a vanishing point in projectively distorted image. The paper (Ross, 2010) presents the approach for recursive estimation of the tracks in the on-board mono-focal camera pictures, which are then tracked from bottom upwards by means of a discrete Kalman filter. The geometry of rail tracks is exploited also in (Maitre et al., 2010) in the method for rail track detection for the purpose of obstacle-free range determination for the rail track maintenance vehicles. The presented method consists of warping the camera image into an image where the rails are parallel through a projective transform, and of tracking the two rail curves simultaneously by evaluating small parallel segments. The idea behind the projective transformation-based method is to get the bird's-eye view on the rail tracks that is not as much distorted by perspective as an observer in the driver cabin of the train. Besides the parallel rail tracks, the bird's-eye view enables also exploitation of the fact that the sleepers between the parallel rails are spaced regularly.

Some of the published papers present the methods which are based on extraction of image features which are consequences of the rail tracks characteristics such as the sharp edges that have as a consequence a large image gradient. For example, the paper (Qi et al., 2013) presents a railway tracks detection and turnouts recognition method using Histogram of Oriented Gradients (HOG) features. As first, the presented system computes HOG features and establishes integral images, and then extracts railway tracks by region-growing algorithm. The method is based on the fact that the variance of the HOG features corresponding to the image blocks that contain rail track is relatively large since such block always contains a prominent edge. Evaluation results showed that the method proposed in (Qi et al., 2013) was superior to other related methods, (Wohlfeil et al., 2011), Nassu et al., 2011) and (Kaleli et al., 2009). In (Wohlfeil et al., 2011), gradient-based edge detection is used for rail tracks extraction. Extracted rail tracks are then tracked for the purpose of switch recognition. In (Nassu et al., 2011) an approach that performs rail extraction by matching edge features to candidate rail patterns modelled as sequences of parabola segments is presented. Patterns are pre-computed for the rail areas near the camera and generated on the fly for more distant regions. The proposed approach also addresses the challenges posed by the open and complex environment, such as bad visibility, shadows, motion blur, clutter and occlusion. An approach representing the advancement of (Nassu et al., 2011) is presented in (Nassu et al., 2012). The improvements include a semiautomatic method for generating rail patterns for the short distance and multiple extractors for increasing robustness in the long distance. The sequential nature of the input is explored for making rail extraction faster and more robust as in consecutive frames the rails should have similar position and curvature. In (Kaleli et al., 2009), an algorithm to extract the train course and railroad track space in front of the train using dynamic programming is presented. As first, railroad features, the railroad vanishing point and track width parameter are extracted from an input image using gradient-based edge detection followed by Hough transformation for line detection and then dynamic programming is used to compute the optimal path which gives the minimum cost to extract the railroad track space. The proposed algorithm extracts the left and right rails using dynamic programming simultaneously and does not need any static calibration process. Hough transformation as widely used CV method for detection of simple shapes such as straight lines is used also in (Wang et al., 2015), however not on the original input onboard camera image, rather on a transformed bird-view image in which the parallel characteristics of rail tracks are kept and also dimension information such as the gauge width between two rail tracks is known. Bird-view image is obtained using inverse projective mapping (IPM). Then the IPM image is segmented using a modified edge-based image segmentation. In order to extract the rail track, a Hough transformation is used to detect the line segments in the edge map. Combined with some geometric constraints from the prior knowledge, the rail track is robustly extracted. The continuation of work (Wang et al., 2015) is presented in (Wang et al., 2016) where a method that extracts rails by matching the edge features of the real IPM image to the candidate parametrically modelled rail patterns is introduced. In addition, the geometric constraints of the rail pattern are taken into consideration during the pattern generation. A distance transform is used as the similarity measurement between the template pattern and the extracted edge map with the same size as the pattern. IPM method was used also in (Gschwandtner et al., 2010). Presented method actually uses lane detection techniques - known from driver assistance systems - to assist in rail track detection for autonomous trains and also uses geometric constraints of the rails. Once the IPM image has been created a smoothing filter known as Difference of Gaussian (DoG) is applied with rather big kernel sizes to account for the motion blur and for the probably wrong focus of the x-focus camera. This DoG filtered image is binarized using global thresholding to create a binary image which is then split vertically into 10 equally sized slices. This breaks up longer lines and allows extraction of parallel line segments. (Mockel et al., 2003) also follows method of rail tracks detection in order to establish an image ROI. This is done by the two track funding modules, one that transforms database (infrastructure) information into standard track description and the other one that extracts the track by conventional camera image processing approaches. If no database information is available, the track must be extracted at least as far as the obstacle detection is demanded (up to 500 m). Study (Seber et al., 2016) presents a robust approach that partitions a video frame into four regions, each of which is filtered by two-dimensional Gabor wavelets at different scales. Considering the size and the orientation range of the rails at each partition, responses of the Gabor wavelets that are tuned to specific frequencies, enable rail edge enhancement together with noise filtering. One of assumptions is that the complete cabin view can be divided into 4 sub-regions as near, far, remote and horizon, and the horizon does not contain any railway information. In near to remote field, the visual appearance of the thickness of the rails decreases while their directionality (i.e. orientation spectrum) increases. Being a method in frequency domain, the proposed method for automatic extraction of the railways is insensitive to fine tuning of parameters, which is usual problem of methods based on image processing methods in (image) spatial domain.

In contrast to the studies mentioned above that use presumed knowledge and assumptions about the geometry of railway tracks in (Seber et al., 2016), a statistical analysis of railway track relies on various video records to quantify the margins of variations is provided. Moreover, based on the results of those statistical analyses, this study introduces a method to predict the railway tracks by means of polynomial approximation followed by multilayer perceptron networks.

The performance of all mentioned traditional CV methods for rail track extraction, however, may suffer due to varying lighting conditions and complex backgrounds. Traditional methods that use the line or edge features to detect railroad maybe have a good performance in a fixed scene, but their performance decreases rapidly when the scene changes. This is especially the case when the train is moving along the track, since the background is constantly changing, and the hand-crafted features of traditional CV method cannot meet the requirements. Also, the particular challenge is the condition of the onboard camera during the train journey, as vibrations of the locomotive cause blurring effects. In order to cope with these real-world problems, the so-called Structure from Motion (SfM) pipeline was specifically designed to support the monitoring operations of the railway infrastructure using a monocular camera mounted on the train's locomotive (Fioretti et al., 2020).

Detection of obstacles on the rail tracks

The majority of published obstacle detection methods are based on searching along the detected rail tracks or on searching within the image ROI defined upon rail track detection. In (Ukai, 2004), once the image ROI is extracted through rail extraction, two detection methods are applied for moving and stationary objects. Optical flow method is applied for moving obstacle detection within ROI while the stationary objects are detected using Sobel edge detection followed by Morphological processing of edge detected image. The method presented in (Fonseca et al., 2014) deals with the railway identification also using the Hough transform (applying several criteria like length and position the lines that more likely represent the rails are selected) and initiation of the obstacle detection using artificial vision algorithms. On this area a systematic search is done for finding and delimiting possible obstacles. In relation with the obstacle detection stage the first task is to use the Canny algorithm. A closer follows and then the contours in the image are identified and stressed. Small and disconnected objects are then eliminated. After filling the contours a systematic search is started using the rails as guide. Using digital added obstacles the algorithm detects mostly all of them and warns if the objects over the rail can create a danger to the safety travel of the train. The continuation of (Fonseca et al., 2014) work is presented in (Uribe et al., 2012) where Hough transform for detecting the rails was used. Once rail tracks are detected, on every rail a systematic search is done bottom-up detecting obstacles that can be dangerous for the train course. This method was effective in detecting fixed objects in front the train and obstacles just near the rails. The paper presents different method for dynamic obstacles. It is based on the optical flow between frames which discards background moving elements and finds candidate dangerous objects, tracks their trajectories and foresees their paths for determining if exist risks to collision. Bottom-up adaptive windows are used to find obstacles along detected rails which is presented in (Wang et al., 2017). After getting the gradient image, the start of the rails is located in order to create bottom-up windows and to check for obstacles. However, the authors claim that there are very rare cases of obstacles on railways and because of that the videos have been modified adding digital obstacles of different nature, shape and obstruction trajectory.

In (Mukojima et al., 2016) a method for detecting obstacles by comparing input and reference train frontal view camera images was proposed. This is a background subtraction method that can be applied to moving cameras. Firstly, the proposed method computes frame-by-frame correspondences between the current and the reference (database) image sequences. Then, obstacles are detected by applying image subtraction to the corresponding frames. The proposed method first finds a reference frame captured at the most similar location to the current frame by image sequence matching. Then, it performs pixel-wise registration between the current frame and its corresponding reference frame. Finally, multiple image subtraction methods are applied to compute the image difference between the two frames, and obstacles are detected by integrating their outputs. Method based on background subtraction is presented in (Nanasone et al., 2017), that is on comparing the live images from onboard camera with images that other trains operating earlier at the same route. In (Vazquez et al., 2001) a new strategy to detect dynamic object in railway is presented, using vision and Principal Components Analysis (PCA). For this purpose, a set of images of the railway static environment is first captured to obtain the transformation matrix that used in PCA. By means of this matrix, the successive images are projected in the transformation space and recovered. The motion detection is performed, evaluating the Euclidean distance between the original and recovered images. The image regions, whose Euclidean distances are greater than a threshold, are considered like belonging to dynamic objects.

Distance estimation

Even though the estimation of distances between the detected objects and on-board vision sensors (distance between the obstacle and the train) is crucial for obstacle detection to react early enough, the majority of published CV works do not consider distance estimation at all, or consider it through enabling long ROI along the rail tracks only.

Ukai, (2004) presents a method of detecting obstacles with an image sequence taken by an ultra telephoto lens camera mounted on train which monitors the status of the track for 600m (brake distance) or over ahead of the train. However, there are no details on estimation of distances to individual objects. (Kudinov et al., 2020) considered an algorithm for solving the problem of indirectly measuring the distance to a wagon by reducing it to solving the Perspective-2-Point problem for the purpose of automatic docking of a locomotive with a train. Because of the application, the considered distances are short-range. Evaluation results showed that on a straight section of a railway track at distances up to 50 meters, an absolute error of measuring the distance to a locomotive or wagon is no more than 1.2 meters. In (Maitre et al., 2010) the vision algorithm instead of obstacle distance estimation detects reliably the obstacle-free zone to more than 100 metres. This is sufficient as a prototype anti-collision system for rail track maintenance vehicles that monitors the space ahead of the train for obstacles. This system can help maintain a safe distance between maintenance trains. Method of detecting the railroad track space at high distance and rails at longer distance are presented in (Kaleli et al., 2009) and Nassu et al., 2012), respectively. However, neither of them provided any discussion of distance estimation.

Some of the systems primarily based on vision sensors use additional range sensors to support distance estimation. (Yamashita et al., 1996) presented system where laser rangefinder is combined with camera for distance estimation. If the distance is critical in relation to the sum of the braking distance, idle running distance and spare distance (total distance 1km), an alarm is issued to the driver. (Mockel et al., 2003) presented a multi-sensor system consisting of look-ahead sensors, video cameras (optical passive) and LiDAR (optical active) having an up to 400 m look-ahead range under typical operating conditions. The prototype was evaluated out on a test vehicle (Train Control TestCar) driving up to 120 km/h over long distances across German. The presented work followed as one of the requirements: Objects at a position ahead of the vehicle that will be reached in 10s time must be detected with “high probability. (E.g. if the vehicle goes 100 km/h an obstacle must be detected with “high probability at 300 m distance). The braking distance of the train was not considered.

In (Gebauer et al., 2012), an on-board multi-sensor obstacle recognition system is presented that satisfy the following requirements: (1) Detect all relevant obstacles to assure safe operation inside the railway track clearance in a distance of less than 80m within direction of movement; (2) Any object larger than 40×40 cm is a relevant obstacle; (3) The reason for the determination of 80m distance range is that the system was developed for regional trains that never go faster than approximately on straight tracks of regional lines; (4) The assumed emergency braking performance is the 2.73m/s^2 according to the German electric tramway edict. The same maximal distance range was considered in (Weichselbaum et al., 2013) where the system was presented that satisfy requirement that detection of obstacles inside the tracks clearance volume with at least a size of 0.3 m x 0.3 m x 0.3 m at a distance from 10 m up to 80 m ahead. The results of the system depend strongly on the accuracy of the delivered track information. When the track information is inaccurate, the system may fail in certain situations.

AI-based methods

Recently, because of the achievements of neural networks, object detection based on AI has made great achievements in the field of road traffic, though research regarding rail transport has lagged behind. So far published works are presented in the following.

Rail track detection

AI-Based rail track detection methods, in principle, converted the railway detection task from railway line detection or edge detection problems to segmentation problems. In (Wang et al., 2018) an efficient rail area detection method based on Convolutional Neural Network (CNN) was presented. The method consists of two parts, extraction of the rail area and further optimization. Further optimization consists of optimizing the contour of the extracted rail area using polygon fitting method, and thus getting a more elegant outline of the rail region. Established CNN achieves pixel level extraction of the rail area. The used network was inspired by SegNet (Badrinarayanan et al., 2015) which is an encoder-decoder architecture for image segmentation. The self-recorded dataset was annotated according to cityscape dataset standards, i.e., the pixel level labeling for the rail region and the non-rail region was used. The dataset was collected from Beijing metro Yanfang line and Shanghai metro line 6 with resolution of 1280*720. BHrail-dataset include representative real scenarios, it contains datasets in tunnel environments and datasets in elevated environments with 5617 annotated images.

In (Wang et al., 2019) a deep learning segmentation algorithm for railroad (named RailNet) is presented. RailNet, is an end-to-end deep learning-based railroad track segmentation algorithm that consists of a feature extraction network and a segmentation network. The feature extraction network uses a pyramid structure to propagate features from top to bottom to obtain a hybrid feature vector. The segmentation network is a convolutional network for generating the segmentation map of the railroad. In order to train and test RailNet network, authors built a railroad datasets called the Railroad Segmentation Dataset (RSDS) for segmentation that include 3000 images, 2500 images for training, 200 images for validation and 300 images for test. All images come from a real train's driving environment. When labeling the ground truth of the datasets, the railroad is defined as all pixels between two rail lines. During training, the authors also applied the data augmentation algorithm to enhance training samples but no details were given. The weights of RailNet backbone network (which is ResNet50) were initialized using the weights trained by the ImageNet Dataset.

Obstacle detection

In (Ye et al., 2018), the dataset of outdoor public image-resource of railway scenes was used. The objects found in the images were divided into three categories: train, people and animal. The size of training set was 15000 images and the test set 5000 images. Region Based Convolutional Neural Networks (R-CNN) was trained and well trained model is evaluated on test images showing the correct rate of warning of 94,85%. Railway Object Dataset built by authors of (Ye et al., 2020), was used for development and evaluation of the method that can detect seven different types of objects: bullet train, railway straight, railway left, railway right, pedestrian, helmet, and spanner. The proposed object-detection method uses a Differential Feature Fusion convolutional neural network (DFF-Net). This method is improvement of the system proposed by the same authors in (Ye et al., 2018), which is based on CNN called Feature Fusion Refine neural network (FR-Net).

Feature-Enhanced Single-Shot Detector FE-SSD, a deep learning-based railway traffic object detection method was proposed in (Ye et al., 2020). The proposed method inherits the merits of the RON and FB-Net methods and involves the application of an enhanced receptive field, which can balance the accuracy and real-time performance for object detection and significantly improve the small-object detection performance. An obstacle detection algorithm which consists of two steps: main network and feature fusion is presented in (Xu et al., 2019). In the first step, the input image is converted into multi-scale feature maps based on the Residual Neural Network. Next, a series of convolution layers are added to extract features, and the network outputs a confidence score and bounding boxes for possible obstacles. Authors made a dataset which contains a large-scale urban rail transit video frames taken by on-board HD camera. The dataset was gathered from Hongkong MTR Tsuen Wan Line, Beijing Metro Yanfang line and Shanghai metro line 6 with resolution of 1280*720 pixels. A total of 6384 images constituted the dataset and the authors divided them into two groups: 5107 images for training and 1277 for testing. Dataset contains images in daytime and night, sunny and rainy days manually annotated the coordinates of the obstacles appearing in the image.

In (Guo et al., 2019) a high-speed railway clearance intrusion detection method with image object classification and recognition was presented. The method is based on improved Single Shot multibox Detector (SSD) algorithm as original SSD can not be used to detect small intruding objects. The improvement consists of high-level features deconvolved to low-level and fused with original low-level features to enhance their semantic information and improve the detection accuracy. The deconvolution structure is introduced into the SSD network to improve the detection ability of small objects. The low-level feature maps have better edge information, and high-level feature maps have stronger semantic information. In order to improve the small object detection ability, feature maps should not only have a high resolution to detect small objects, but also have stronger semantic information to detect the location and category information. In total, 14,760 image frames with 21,053 pedestrian samples and 9321 train samples (bullet trains) were labeled.

In publications (Haseeb et al., 2018), (Haseeb et al., CSCS 2018), (Haseeb et al., ICVS 2019) and (Ristic et al., 2020), a novel machine-learning based method named DisNet developed in SMART project to support the on-board cameras in detected objects, possible obstacles, in front of the train is presented. This system will be the starting point for SMART2 as SMART2 on-board system will built on results achieved in SMART. The DisNet consists of two parts; the first part is deep learning-based object detection, and the second part is neural network-based distance estimation. The object detector can be any bounding box-based deep learning method which extracts the bounding box of an object detected in the input image as well as the object class. In the SMART project, one of the state-of-the-art deep learning-based methods for the prediction of detected objects bounding boxes named YOLOv3 (Redmon et al., 2018) was used. The main advantage of YOLO is its speed, making it appropriate for real-time applications, which was the main reason for its selection for the SMART OD system. The distance estimator is a feedforward artificial neural network named DisNet. It was developed in the project SMART and it consists of 3 hidden layers, each containing 100 hidden units. The DisNet estimates distance between each detected object and the on-board camera based on the features of the object Bounding Box (BB) extracted by the YOLO-based object detector.

The YOLO model used was originally trained with the Microsoft COCO dataset (COCO, online) of images of everyday scenes containing common objects in their natural context, consisting of 328000 images of 91 easily recognizable objects classes. In total, 2.5 million object s are labeled in the images of the dataset, and about 3500 images of railway scenes are labelled with the object class “train”. However, COCO dataset does not contain images of explicit railway scenes of objects on the rail tracks and, moreover, it does not contain images of distant objects. In order to enable the YOLO model to detect objects in railway scenes, with particular focus on distant objects, the original YOLO model was re-trained on SMART data. In total, 998 images captured with SMART RGB cameras were used, with 2238 labeled objects of classes human, car, bicycle and animal. These images were recorded in the dataset generation field tests performed during the SMART project. All dataset generation field tests were performed in operational conditions where the integrated on-board system was mounted on the operational locomotive owned by Serbia Cargo and running on Serbian part of pan-European Corridor X. The evaluation tests performed also in operational environment at different time point. The evaluation tests showed that SMART on-board obstacle detection system fulfilled functional requirements:

- Frontal obstacle detection – Detection of objects on and near the rail tracks ahead of the train. Targeted potential obstacles were objects that were not the part of the railway infrastructure, which could be a hazard to the train such as humans, vehicles, and large animals;
- Object Detection across a range of environmental conditions – Detection of objects in the train’s path under different light and weather conditions.

Distance estimation

Even though in (Ye et al., 2020), it is said that beside the on-board camera that captures images system contains also millimeter-wave radar for measuring distances between the detected object and train, there is no detail provided on the measurement of distance to detected objects. However, as the application is “shunting mode” the distances are short-range as typical for shunting operations.

(Redmon et al., 2018) presented RailNet railroad segmentation method considering the railroad detection task of low-speed autonomous trains according to the design specifications of low-speed trains in China. The maximum design speed is 80km/h, and the operating running speed is less than 60km/h. Emergency brake deceleration is not less than 1.2m/s2. Therefore, the emergency braking distance is approximately 118 meters. Our algorithm got a processing speed of 20 frames per second. That means the train runs a distance of 0.83 meters after processing one frame. The emergency braking distance is much larger than the train's run distance of processing for one frame. However, the work does not consider range of rail tracks detected.

The main part of the SMART on-board obstacle detection system presented in (Haseeb et al., 2018a), (Haseeb et al., 2018b), (Haseeb et al., 2019) and (Ristic et al., 2020) is the distance estimator named DisNet. It is a feedforward artificial neural network that consists of 3 hidden layers, each containing 100 hidden units. The DisNet estimates distance between each detected object and the on-board camera based on the features of the object Bounding Box (BB) extracted by the YOLO-based object detector. In other words, DisNet learns the relationship between the size of the object BB and the distance of the object to on-board camera.

The evaluation tests performed in operational environment showed that SMART on-board obstacle detection system fulfilled functional requirements of mid- and long-range obstacle detection. SMART system based on DisNet advanced the state-of-the-art methods by long-range object detection and identification of obstacles in the mid-range (from 80 m up to beyond 200 m) and in the long-range (up to 1000 m).

A1.1.2 SWIR vs. visible& thermal

SWIR technology is developed mainly for three applications: hyperspectral imaging, low-light level imaging and active imaging (Feautrier et al., 2015). In SMART2 application, for the detection of an obstacle on the rails at a large distance in front of a moving train, all these three applications play a role.

SWIR **hyperspectral imaging** modality produces clear images in the presence of challenging atmospheric conditions such as rain, fog and mist. As summarized in (Lightweight SWIR, online) with respect to long range SWIR and LWIR micro cameras installed on a UAV: “The SWIR sensor provides rich background details, while the thermal hints highlight scene features-of-interest in a comprehensive, information-rich image. SWIR imaging also allows the soldier to see through battlefield obscurants, to see in very low-light conditions, and to see all the lights and lasers on the battlefield.”

SWIR cameras produce high SNR images under **low light conditions** or at night time, and therefore SWIR is more suitable for long range imaging at night compared to NIR imaging (Surveillance, online).

Active imaging allows the use of illuminating lasers that have a much lower average power, which is important primarily due to the lower cost of the laser, the eye-safe operation and the ability to avoid feedback that occurs on the path due to rain, fog or mist or from the object behind the primarily observed area.

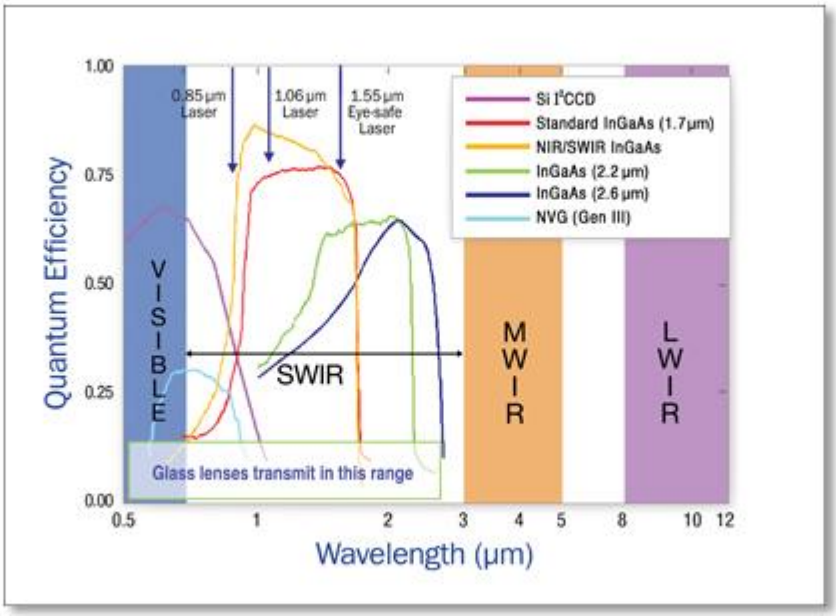


Figure 27: Imaging in infrared

Thermal imagers are another class of camera with good detection abilities and are a good compliment to SWIR. While thermal imaging can detect the presence of a warm object against a cool background, a SWIR camera can actually identify what that object is. That's because thermal imagers do not provide the resolution and dynamic range of imaging possible with an InGaAs SWIR focal plane array.

CMOS and CCD imagers are typically just daylight sensors. However, a single SWIR camera can be used for both day and night imaging. The single SWIR camera can operate over the full duration of typical long day/night driving.

One major benefit of SWIR imaging is the ability to image through the glass. Meaning, a SWIR camera can use conventional, cost-effective visible camera lenses for all but the most demanding applications. For SWIR cameras, special expensive lensing or environmentally hardened housings are mostly unnecessary.This ability also allows for the shortwave IR camera to be mounted inside a protective window, providing extra flexibilty when positioning the camera system on a potential platform.

The main advantages of SWIR are summarized in (Why SWIR, online):

- High sensitivity
- High resolution
- Seeing in the light of night glow or night sky radiance
- Day-to-night imaging
- No cryogenic cooling required

- Conventional, low-cost visible spectrum lenses
- Small size
- Low power
- Possibility of gated detection

SWIR technologies

Among the available SWIR solid state detectors such as PbS, InGaAs, MCT, etc…, InGaAs is and remains the most promising because of its high quantum efficiency and its ability to operate at room temperature. Technical progress is constant on this detection material. The dark current at room temperature, one of the most important parameters, has passed from µA/cm2 to nA/cm2 (Ni et al., 2015) and even to sub-nA/cm2 (Trezza et al., 2015) in a predictable future (Yang et al., 2016).

InGaAs Detector Arrays (Goeff, 2015) (Rouvie et al., 2015)

InGaAs is a semiconductor material which is an alloy of Indium Arsenide (InAs) and Gallium Arsenide (GaAs). Detector arrays are produced by growing an epitaxial layer of InGaAs on an Indium Phosphide (InP) substrate, with a thin passivation layer of InP grown on top of the InGaAs. The doped substrate and InGaAs layer are used to construct a photodiode array (PDA) which delivers photosensitivity, typically for wavelengths between (900 – 1700) nm. The individual pixels of the photodiode array are then bonded to a CMOS ROIC (ReadOut Integrated Circuit), which is used to perform the charge to voltage conversion, A/D conversion and transfer of data from the sensor. Historically Indium bump bonds were used to attach the imaging array to the CMOS ROIC, which imposed some practical limitations on both the physical size and the pixel pitch of commercially available devices.

This hybrid sensor fabrication results in the PDA being illuminated through the substrate layer. Absorption in the (relatively) thick InP substrate layer prevents photons with wavelengths below ≈900nm reaching the PDA, explaining why many InGaAs sensors have poor response to wavelengths below this value. However, some advanced sensors have the bulk of this substrate layer removed (i.e. thinned away), producing a detector with response across visible, NIR and SWIR regions. A broadband AR coating is also applied to the thinned PDA, producing a detector array which has excellent QE across the SWIR and NIR regions and good QE extending into the visible region.

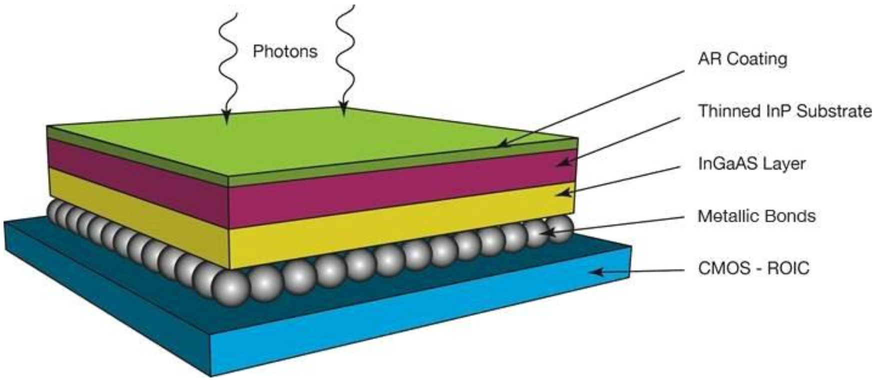


Figure 28: Schematic representation of the main components used in the construction of a VIS-SWIR InGaAs detector array (Goeff, 2015)

These VIS-SWIR detectors can provide high performance imaging capability, enabling the user to observe objects at all wavelengths between approximately 550nm in the visible region and 1700nm in the SWIR regions, using a single camera.

Essentially, InGaAs cameras can be small and use very little power. By using SWIR illumination like 1.55 micron lasers or LEDs, it is possible to eye-safely illuminate a scene.

Other SWIR materials

There are also other cameras that operate in the shortwave infrared range. For instance, sensors constructed from materials like mercury cadmium telluride (HgCdTe) or indium antimonide (InSb) can be very sensitive in the SWIR band. However, in order to increase their signal-to-noise ratio to usable levels, these cameras must be mechanically cooled, often to extremely low temperatures. In large military aircraft designed for surveillance and reconnaissance, cooling is not a problem since these platforms are designed with plenty of space and power to run mechanical cooling systems. In stark contrast, similar sensitivity can be achieved at room temperatures with a InGaAs camera.

MCT APD array (Feautrier et al., 2015)

The MCT (Mercury-Cadmium-Telluride) APD (Avalanche Photo Detector) arrays havebeen designed and fabricated by liquid phase epitaxy (LPE) growth of MCT layers for a 2.55 µm cut-off on lattice-matched, in-house grown CdZnTe substrates. The doping profile has been optimized to allow high biasing for achieving the avalanche multiplication effect. As known, MCT based APDs exhibit a close to constant exponential gain increase and low excess noise for a large range of reverse voltage. The cutoff has been chosen as a tradeoff between achievable APD gain and operating temperature (~150 K) for SWIR Gated-Viewing systems with target distances of about 1000m.

By using MCT IR technology the cut-off wavelength is tuned up to ~2.5µm providing sensitivity in the extended SWIR (eSWIR) spectral range compared to a 1.7µm cut-off wavelength for widely used standard InGaAs detectors. The 2D Gated-Viewing SWIR module for operation together with an e.g. 1.5µm laser illuminator has been developed providing precise timing control by a specific ROIC and high sensitivity by an MCT avalanche photodiode (APD) detector array. With the MCT APD detector array it is also possible to use a laser illuminator with a wavelength of >2µm to be invisible for standard InGaAs detectors.

Scientific grade SWIR MCT camera (Breiter et al., 2019)

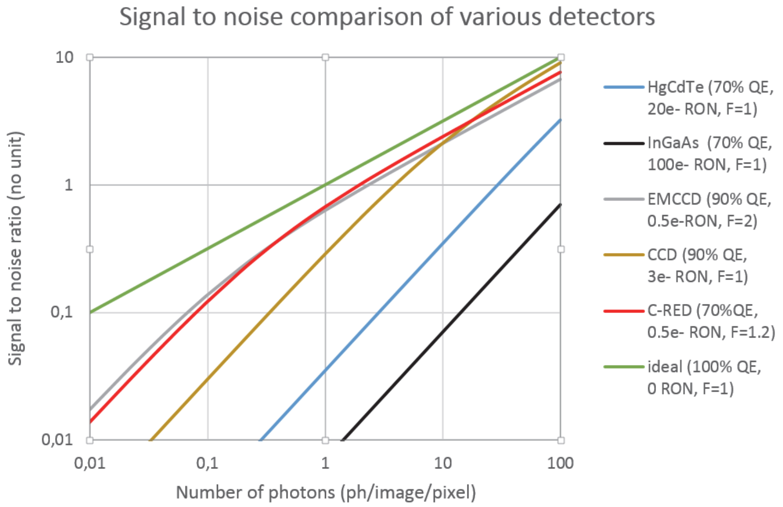


Figure 29: Signal to Noise comparison of various detector technologies. CCD and EMCCD are sensitive in the visible. They are compared with IR detectors (InGaAs, slow scan HgCdTe and the C-RED e-APD camera) (Breiter et al., 2019)

C-RED One camera from Axiom Optics (C-RED, online) is the first commercial company to make e-APD infrared array technology. Using a 320 × 256, 2.5 µm cutoff wavelength HgCdTe e-APD array deeply cooled to 80 K with a highreliability pulse-tube cryocooler (mean-time between failure or MTBF of approximately 90,000 hours), the camera has a high readout speed of 3500 frames/s (full frame) while exhibiting a readout noise below one electron—thanks to the APD gain in the range of 1 to 60. C-RED uses the Selex Saphira 320×256 pixels HgCdTe e-APD array with 24 microns pixel pitch. The sensor cutoff wavelength is 2.5 microns and it allows sub-electron readout noise, taking advantage of the e-APD noise-free multiplication gain and non-destructive readout ability. C-RED is also capable of multiple regions of interest (ROI) readout allowing faster image rate (10s of kHz) while maintaining unprecedented sub-electron readout noise.

Image sensor and camera characteristics

The SWIR camera performance is determined by a combination of the quality of the InGaAs PDA and the performance of the CMOS ROIC, in addition to the design and implementation of the camera electronics and firmware.

Image pixels

Available InGaAs array sizes are small, when compared to CCDs / CMOS imaging devices, the largest, widely available array size is currently 1280 x 1024 pixels. Pixels size usually ranges from 15 µm to 25 µm.

A small number of InGaAs devices with 5 µm pixels are just starting to enter the market, primarily in VGA format (in addition to one SXGA offering). Manufacture of some of these devices has implemented Cu-Cu bonding (instead of Indium bump bonds) for attaching the FPA to the CMOS ROIC. Future generations of these devices could (theoretically) decrease the pixel size further and / or yield larger array sizes, potentially unlocking new applications and market segments for InGaAs image sensors.

The use of a high-performance CMOS ROIC delivers some advantages and disadvantages, analogous to those found on conventional Si CMOS imagers, e.g. high frame rates are achievable, short exposure times down to 1µs can be realized and global shutter (snapshot) operation is implemented on the sensor used within the NINOX camera range. However Non-Uniformity Corrections (NUCs) must be applied to reduce fixed pattern noise (FPN) introduced by the CMOS ROIC.

A 640x512 15µm pitch detector array is an optimum between performance and price (Feautrier et al., 2015). In this moment, almost all manufacturers offer this type of sensor as the main product in their portfolio.

Resolution of Camera

What is the main figure of merit for determine the ability of a camera system to resolve detail contrast in relation to range and luminance, i.e. to see an obstacle on the rails?

According to (Gerken et al., 2014), it is the Minimum Resolvable Contrast (MRC), which comprises all relevant parameters of a camera system. Together with the Effective Contrast (EC) being a function of atmospheric extinction and the specified target contrast, the achievable range of a given camera can be calculated in all scenarios by means of range models like VRM (Visual Range Model). The manufacturer of the camera is per design only responsible for the MRC while EC and target contrast are inherent and given by the scene. Therefore, it is of high interest to quantify the camera performance by means of MRC measurement in the SWIR wavelength band.

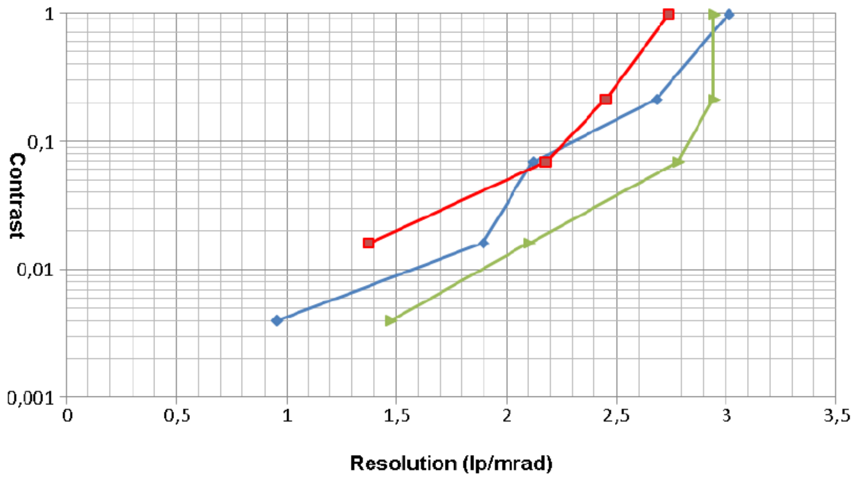


Figure 30: Three InGaAs sensors 640x512 compared in the FOV* of 10 deg at 10000 lx, Pixel Pitch 25, 20 and 15 µm (Gerken et al., 2014)

The table below shows the conditions for detecting, identifying or recognizing objects at a certain distance, according to Johnson's criteria (Ruffini et al., 2010). Detection ranges according to Johnson's criterion and the limits imposed by laser energy and divergence, camera sensitivity, noise and pixel pitch, telescope aperture and transmission, and atmospheric absorption is shown. "Detect" means an object is present; "recognize" means the type of object is discerned (person or car); "identify" means a specific object is discerned (woman or man); "recognize with 90% accuracy" is doubtless identification (Ruffini et al., 2010). According to the test in (Gerken et al., 2014), shown in Figure 8, for targets that have low contrast, such as our case, it is best to use an image sensor with a pixel size of 15 microns. In order to achieve the desired resolutions according to Johnson's criteria, the field of view must be carefully calculated, according to the size of the sensor, and a quality lens must be selected (for a given focal length and aperture aperture).

Table 20 Detection ranges according to Johnson's criterion (Ruffini et al., 2010)

target	width × height of object or character (m × m)	ranges in km; in parenthesis the number of line pairs required by Johnson's criterion to discern the object			
		Detect	Recognize	Identify	Recognize with 90% accuracy
Crawling person	0.6 x 0.2	10 (1)	3.7 (4)	2.1 (7)	1.2 (12)
Standing person	0.6 x 1.7	14 (1.5)	10 (3.8)	5.5 (8)	3.7 (12)
Large vehicle	10 x 3	20 (0.75)	20 (3.5)	18 (7)	10 (12)

Gated or not?

Fundamentally, laser gated imaging uses laser pulses in combination with a synchronized imaging sensor. The laser pulse serves as a source of light to illuminate the scene. Laser pulses are emitted from the source, and pulse durations range from as brief as a few nanoseconds to microseconds.

Depending on the application, laser gated imaging systems have been demonstrated based on different laser wavelengths – visible, near-infrared, and short-wave infrared. Although laser gated systems in near-infrared (based on pulsed lasers, with wavelengths around 850 nm) have become more and more mature recently, there are two main problems:

1. Imaging through atmospheric obscurants (haze, smoke, fog, dust…) requires longer wavelengths, in order to reduce scattering on molecules and particles.

2. High-power lasers in near-infrared (around 850 nm) are not eye-safe.

Lasers in the short-wave infrared (SWIR) range, with wavelength longer than 1.4 µm, are generally considered 'eye-safe'. In this range, water has a high absorption, and photons are absorbed on a human eye's surface before reaching its retina. Most eye-safe lasers operate around 1.55 µm, as this is also the wavelength range commonly used in telecom systems, and for laser range finders. Another advantage of SWIR compared to longer wavelengths in infrared (MWIR and LWIR) is the low thermal background emission in SWIR, resulting in low parasitic light interference. In the SWIR wavelength band different technologies exist for standard imaging. However, when high-sensitivity and gating, i.e. the use of very short exposure times, are required, only a very limited number of detectors or cameras are available on the market (LGI, online).

The potential capabilities and applications of SWIR Gated-Viewing systems have been evaluated in the past (Feautrier et al., 2012) (Finger et al., 2012). The Active Imaging development at AIM focused on demonstration of improved long-range reconnaissance with a dedicated SWIR Gated-Viewing (GV) module (SAS, online).

In GV operating mode, the integration phase is executed first, after then the pixel signals are read out via the analog output channels. The integration time is synchronized to an external gating signal, by sampling the gating signal with an internal clock. The pixel clocks controlling the integration time, are synchronized to the internal clock. The internal clock is generated by an on-chip PLL derived from an external master clock. The maximum frequency of the internal clock is 200 MHz providing a time base of 5 ns for internal gate control (delay and integration) corresponding to a depth in steps of 0.75 meters. Gate control can be either triggered internally by programmable registers or by external signals.

In GV operating mode a maximum framerate of 100Hz can be achieved with the signal readout only and a framerate of 50Hz with readout of signal and reset level which can be used to implement external correlated double sampling (CDS) to reduce noise. The ROIC provides also a standard Integrate Then Read (ITR) imaging mode. However, Integrate While Read (IWR) technique offers higher framerate (ITR, online), which can be very useful in the sense to lowering the laser illuminator peak power and to get higher SNR for the same output framerate, after processing (more pulses and frames averaged).

Based on the above, it is clear that the use of a gated camera, in combination with a pulsed laser illuminator, would be a better solution than continuous lighting. That is why it is necessary to get a camera that has the possibility of synchronized detection based on an external trigger.

Global shuttering

Another requirement in active imaging is global shutter efficiency meaning the pixel should not respond to incident light outside the exposure window. In a traditional CTIA based photodiode interface, the shutter efficiency cannot be 100% at the vicinity of the exposure window. This parasite sensitivity outside the exposure window can affect the active imaging performance. For observation oriented active imaging, it will decrease the efficiency of distance gating effect and for designation oriented active imaging, this can give erroneous results. The reason is that the reset operation in CTIA photodiode interface is made by closing a MOS switch transistor across the integration capacitor (C1 in Fig. 5), (Yang et al., 2016).

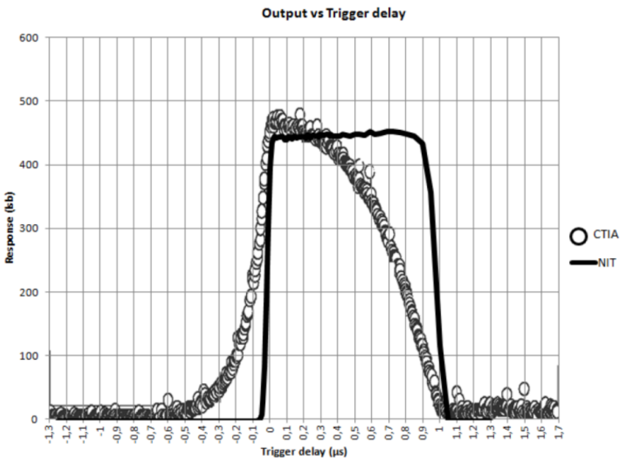


Figure 31: Shutter efficiency comparison between NIT SWIR sensor and a CTIA based SWIR sensor.

When a laser pulse is received by photodiode, the photodiode potential cannot be maintained especially when the bias current of the operational amplifier is low. The shutter efficiency can be tested by using a short pulse laser shining on the sensor and monitoring the sensor output and laser pulse phase shift. An example is shown in Figure 9 where a 4 ns pulse width laser at 1550 nm shines on NIT SWIR sensor and a CTIA traditional SWIR sensor. We can see that the shutter efficiency for CTIA is bad before the exposure window and NIT SWIR gives an almost perfect exposure window with high shutter efficiency.

It is shown in (Yang et al., 2016), that traditional CTIA based photodiode interface is not adequate for active imaging applications. Measured results from newly developed VGA and QVGA SWIR sensors under fast shuttering operation conditions are presented in (Yang et al., 2016), and a considerable improvement compared to CTIA based pixel design for this field of operation is shown. These newly developed SWIR InGaAs sensors (NIT NSC1201 and NSC1401) are currently available for commercial orders.

The efficiency of shuttering is very important, because satisfactory definition of windows cannot be achieved with slow openings. This is especially important for gating that is in the range of 100-200 µs, which is a case that interests us.

Noise and dynamic range

In addition to the increased sensor costs and FPN, the two main disadvantages associated with InGaAs detector arrays have been high readout noise and high dark current.

The readout noise

The readout noise is strongly influenced by the quality / performance of the CMOS ROIC integrated within the detector. Historically ROIC designs provided typical readout noise levels in the range 200 – 700 electrons, depending upon the amount of gain applied. This is acceptable for use in thermal imagers and the detection of 'bright' signals, provided there is sufficient pixel well depth to store signals large enough to overcome the high noise floor and provide an acceptable signal to noise ratio.

However low light detection was not possible with these ROICs and the intra-scene dynamic range was limited. The latest generation of ROIC design has been utilized in the come Raptor and NIT cameras and enables data to be readout via one of two gain modes:

i. High Gain (HG) Mode – offering the lowest readout noise (≈18e-) with limited pixel well depth (>10ke- pixel)

ii. Low Gain (LG) Mode – for maximum dynamic range, offering the maximum pixel well depth (>200ke- per pixel) but with increased readout noise (≈150e-). This provides an intra-scene dynamic range >62dB.

Dark current

The small bandgap of InGaAs (≈0.75eV at room temperature) means that it is much easier to thermally promote electrons from the valance band into the conduction band, compared to silicon for example. This manifests as a significantly higher dark current in InGaAs detectors, when compared to silicon-based detectors with similar pixel sizes. Some early generation devices suffered from dark currents of the order 106e-/pix/sec (≈160fA/pix) at room temperature (+25°C), approximately four orders of magnitude higher than pinned silicon-based detectors. Obviously, this level of dark current severely limits the range of exposure times that could be used for image acquisition, as dark signal and its associated shot noise rapidly became the dominant features in acquired images. Detector manufacture has improved, reducing dark current to the order of ≈104e-/pix/sec (≈1.6fA/pix) at room temperature.

The relatively recent paper (Yeong et al., 2017) proposes a readout integrated circuit (ROIC) for short-wavelength infrared focal plane arrays, which adopts a self-selected capacitor technique to reduce ROICnoise and extend the dynamic range. The self-selected capacitor technique independently operates in each pixel. The proposed readout circuit was designed and fabricated using a 0.35-µm MOS process. The noise measurement result of the fabricated ROIC was 43 e– and the dynamic range was 101 dB.

Cooled or not?

The bandgap of the InGaAs material is temperature dependent and increases as the sensor temperature is decreased. As a result, cooling the device causes the long wavelength cut-off in the response curve to move to shorter wavelengths. Cooling the InGaAs FPA provides a dramatic decrease in the measured dark current per pixel. The calculated dark current doubling temperature is approximately 7°C, which is similar to the dark current temperature dependence observed on Silicon based FPAs (Geoff, 2015).

Some applications may require little or no cooling in order to deliver the required performance, however, more demanding applications may benefit from cooling the InGaAs FPA to temperatures 40°C or 50°C below the ambient, in order to reduce dark current shot noise and increase the accessible dynamic range.

Uncooled systems typically operate with sensor temperatures between +40°C to +50°C, whereas stabilized systems operate with a sensor temperature typically in the range +10°C to +25°C.

Some cameras employ thermoelectric cooling inside a vacuum enclosure to provide a compact and maintenance-free method of cooling the sensor to temperatures of ≤-15°C. The cooling performance of such a camera translates to a dark current reduction of two orders of magnitude, when compared to a room temperature, stabilized system and more than three orders of magnitude, compared to an uncooled system operating at +50°C (Geoff, 2015).

The effect of dark current on the image can be visualized by comparing dark frames of equal exposure time, acquired at different sensor temperatures, as shown in Figure 10.

The higher dark current is clearly visible as speckle in the 2 second dark frame acquired at +30°C. Plotting a horizontal cross section (through the centre of the image) helps to visualize the impact the dark current and associated shot noise will have on any image acquired under these conditions. The presence of relatively high pixel values in this dark frame indicate that a significant fraction of the pixel full well capacity is being wasted, as it is storing dark signal as opposed to any signal the user is attempting to capture. The spikey nature of the image, indicative of a raised noise, in this case due to dark current shot noise, will degrade the final image quality as any detected signal will be superimposed upon this noise floor. The combination of these two effects, reduced useable full well capacity and increased noise floor, will severely limit the maximum signal to noise ratio which can be achieved under these operating conditions.

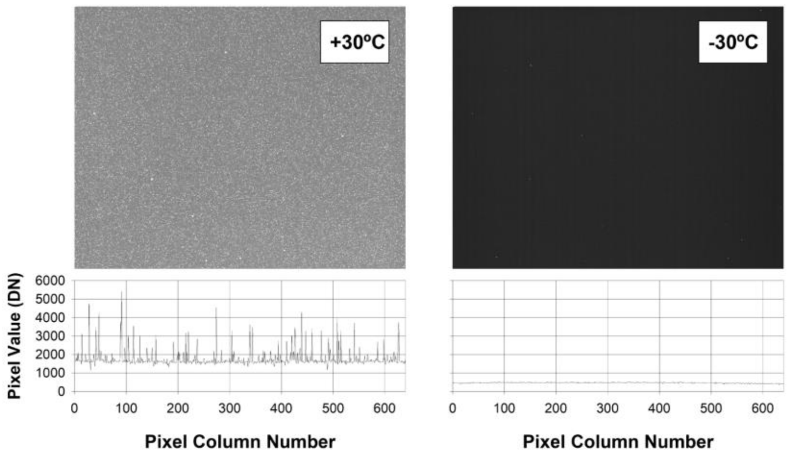


Figure 32: 2 second dark frames acquired at sensor temperatures of +30°C and -30°C. Note the same grayscale is used for both images. The line plots are horizontal cross sections along the central row of each image. (Geoff, 2015)

However, assessing the 2 second image which was acquired at a sensor temperature of -30°C, it is evident that relatively little of the pixel well capacity has been consumed by dark current and also the noise floor is dramatically lower as a result of the reduction in dark current.

The Raptor Photonics cameras utilizes PentaVac™ technology and actively cools the InGaAs FPA to reduce the dark current to approximately 250e-/pix/sec (approx. 0.04fA/pix). This is achieved using only moderate cooling power, attaining a detector temperature of approx. -30°C, thus minimizing the shift in the long wavelength response cut-off and maintaining a compact camera form factor. Figure 11 shows the accessible dynamic range of NINOX 640 II camera, operating with a sensor temperature of -20°C compared to the same sensor operating at a temperature of +20°C.

The graph clearly shows the benefit of cooling the InGaAs FPA, as the accessible dynamic range for both gain modes are preserved for longer exposures, up to a few tens of seconds for the high gain mode and up to several hundred seconds for the low gain mode.

Inferior ROIC architectures and designs can necessitate much deeper cooling of the sensor, e.g. to -80°C or lower, in order to achieve comparable dark current performance. These cryogenic / deep-cooled camera systems are typically physically much larger in size, significantly more expensive and result in much larger shifts in the long wavelength response cut-off.

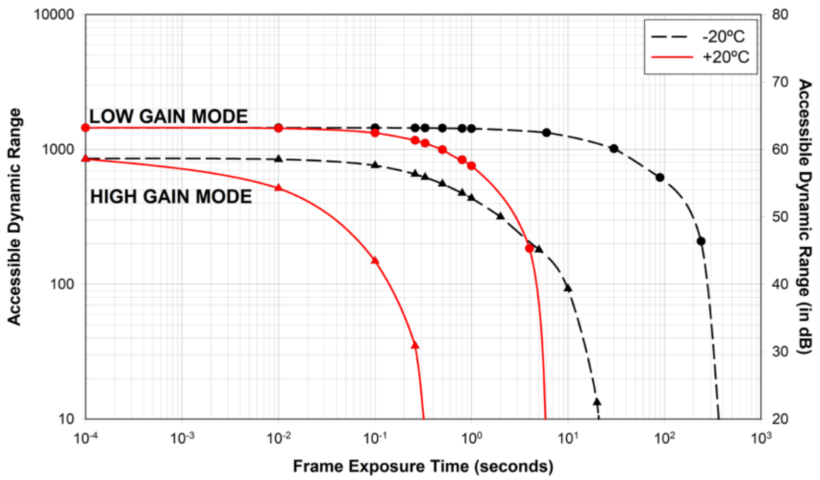


Figure 33: Accessible Dynamic Range versus exposure time for the NINOX 640 InGaAs FPA at two different temperatures. Low gain mode maximizes dynamic range whereas high gain mode minimizes readout noise (Geoff, 2015)

We can conclude that it is obvious that cooling the image sensor is necessary to obtain a quality image. Most camera manufacturers have this feature built-in. Cooling systems that stabilize the temperature at a constant level are more suitable, because they enable stable operation, which does not depend on external conditions. Cooling to very low temperatures, such as liquid nitrogen temperature, is not a required condition, due to the complexity, potential unreliability end the cost of the system.

Do we need the "extended wavelength" InGaAs?

The cut-off at long wavelengths is determined by the bandgap of the InGaAs material from which the sensor is constructed. Unstrained In0.53Ga0.47As is lattice matched to the InP substrate and has a bandgap of approximately 0.75eV at room temperature, corresponding to a cut-off wavelength just below 1700nm. Increasing the fraction of InAs within the alloy reduces the bandgap, shifting the cut-off to longer wavelengths. The material is no longer lattice matched to the substrate and this ‘strained’ or ‘extended’ InGaAs has been used for detection up to ≈2.6µm. However, this extended response does come with some penalties, in particular, higher dark current, more defects per device and increased cost.

Figure 12 shows the quantum efficiency of standard InGaAs in blue together with the quantum efficiencies of two extended wavelength alloys, X=0.74 (green) and X=0.82 (red). The spectral response of silicon is also shown. As we like to say, "InxGa1-xAs starts where silicon leaves off."

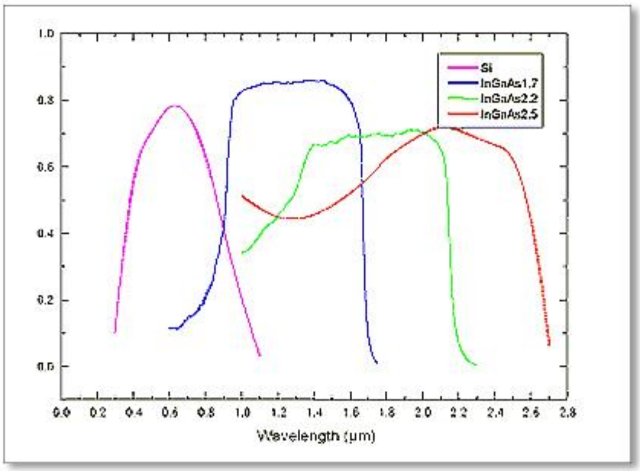


Figure 34: Spectral response of several infrared sensitive materials

Examples of the extended wavelength application is the ability to measure moisture content in agricultural products, by measuring water absorption at 1.9 µm. Another example is "LIDAR" (light detection and ranging), used in airplanes to detect clear air turbulence. LIDAR systems often use lasers that emit light with a wavelength of 2.05 µm. InxGa1-xAs with a longer cutoff is called "extended wavelength InGaAs."

These cameras are very suitable for covert illumination for surveillance, as well as for several other security and military applications, since operation in the spectral range above 1.8 microns cannot be easily detected (except using the same type of the camera!).

The extended wavelength feature, however, does not play a role in our railway application. We have no need for secrecy, and the active illumination that we perform with an eye-safe laser at about 1.6 microns is more efficient on an ordinary InGaAs camera, as can be seen from the graphs in Figure 12.

SWIR in the railway, automotive, maritime and aviation applications

Increasing safety traveling is an objective of mainstream importance for every political institution and great improvement capabilities and is possible with the development of more intelligent devices.

The automotive industry is thus facing this new challenge of detecting vehicle environments in all conditions, and especially in poor visibility conditions, such as night, fog, rain, and snow. The ability to properly analyse the context in which the vehicle is moving, under hard real-time constraints, is strongly influenced by the availability of powerful sensors. Conversely this kind of sensors usually quite expensive and so it makes the development of affordable intelligent vehicles a difficult task. Many research efforts are then spent with the aim to build cheap smart sensors that could provide data to better analyse such a complex environment.

The SWIR sensor is such a kind of smart, low-cost device. Similarly, to what happens with visible light, in standard automotive applications this band is mainly populated by the light reflected by different objects in the scene rather than by their thermal blackbody radiation so that the only applications served by SWIR are those which benefit from reduced scattering effect of longer wavelengths like illumination from invisible sources, as passive illumination provided.

Adverse weather conditions are dangerous for driving. Rain both reduces visibility and makes roadway surfaces dangerous. Wet brakes are less effective too. Snow and ice cause roads to become even more slippery, especially when the temperature is at or below freezing. Slush makes it difficult to steer, hard-packed snow increases the danger of skidding, and black ice makes driving extremely dangerous. Stopping distances on the slippery pavement are from two to ten times farther than on dry pavement. Moreover, usually, anti-brake systems (ABS) are tuned for the most slippery scenario and therefore less effective than can be in normal situations. Therefore, the detection of a general road status or the presence of slippery spots in front of the vehicle can significantly improve driving safety. Most of the proposed solutions to this problem are not based on a true prediction but are focused on the estimation of the road friction, namely, the monitoring of tires slippering. The most promising approach seems to by analysis of the different spectral content of the light reflected from the asphalt in dry, wet, icy, or snow conditions.

More precisely, the Short-Wave Infrared (SWIR 0,9 µm to 1,7µm) bandwidth shows different light reflection patterns depending on road status. According to this result, some solutions based on the use of custom spectrometers have been already implemented, for example, Volvo's Road eye or the Vaisala's Road weather Sensors family. While the use of a spectrometer can be effective, the proposed solutions are not suitable for on-board installation on vehicles.

Israeli startup TriEye (TriEye, online) has secured millions in funding to bring to market its HD shortwave-IR (SWIR) camera that will allow advanced driver-assistance systems (ADASs) and autonomous vehicles to achieve vision capabilities in adverse and challenging low-light conditions. Porsche and DENSO also join this project.

Road conditions assessment is not the only implementation in which SWIR technology could be used. Aviation has evolved to a remarkable level of safety today, thanks to SWIR technology advancement and constant training of pilots and screws. When an accident does occur, it is most commonly due to a reduced situational awareness, especially poor visibility. Darkness, fog, and rain are the primary enemies of flight. But technology is to provide a solution by using short wave infrared SWIR devices. It is also the key to detecting the landing strip runway lights, which have a peak emission in the SWIR band.

The rail transport system is the most widely public transportation system in the world. In Paris, the Réseau Express Régional or Regional Express Network, transporting over three billion passengers per year. To ensure the continuity of the service for the customers, the state-owned operator Régie Autonome des Transports Parisiens, must ensure that the tracks are safe. Since the position of the tracks may vary depending on environmental conditions such as temperature, any changes must be frequently monitored. In the past, this somewhat hazardous task was performed manually by RTP employees. Now, however, an embedded vision system developed by NVT allows this to be performed autonomously. Automating the reading of the rail track position reading is more accurate and safer, while at the same time allowing larger areas of the track to be analyzed. In this way, rail inspectors can respond quickly if any section of the rail should be deformed. The system can also monitor rail expansion during the day and the data collected used to predict future events.

That is not all. In ship traffic, Navy sea force was needed, and America's Seed Found invested in the system for detecting, recognizing, and identifying small, fast, agile boats. Fast-moving boats generate wakes that have very high reflectivity. Electro-Optical systems have been designed for ground-based operations, and do not consider the effect of high reflection from sheep wakes. SWIR technology solved this problem. It makes a difference between intensity signatures from boats and the highly reflective air-bubbled water wake. The imaging system meets the size, weight, performance, reliability of maritime environments like naval aircraft, both fixed and rotary-wing platforms.

Further, The European Union Marine Strategy Framework Directive and Water Framework Directive require the member states to monitor the state of the marine environment, for increasing ship traffic safety. Monitoring of water quality by satellite ocean color data requires high-quality atmospheric correction and especially the accurate quantification of the aerosol contribution to the top of atmosphere radiance. SWIR technology is used to extend existing turbid water atmospheric correction to extremely turbid waters. The atmospheric correction is image-based, and no external measurements are required.

Based on the analysis done in sub-section SWIR state-of-theart (section 3.3.1.3), the following minimum requirements that the camera should meet, have been defined:

- Image format: ≥ 640x512 pixels
- Pixel size: ≤ 15 µm
- Spectral range: lower limit < 800 nm / upper limit > 1600 nm
- Raw output data resolution: ≥ 14 bits
- Interface: Camera Link or GigaEthernet interface.
- Frame rate: > 150 Hz
- Readout: Global shutter
- Dynamic range: ≥ 50dB (gated mode)
- Sensor noise: < 150 e- (gated mode)
- The power supply: 12V DC nominal

The image sensor should be COOLED and its temperature controlled by Peltier element.

The camera should have GATED mode, and the trigger delay should be selectable. The integration time should be at least 200 µs. The trigger should be TTL signal.

The partial reading of the sensor (ROI) should be possible, and the frame rate should increase in small ROI reading.

Automatic exposure time should automatically calculate the exposure time depending on the mean histogram. *The camera should have non gated logarithmic and high gain CDS mode, and gated low and high gain mode. Bad pixel correction and NUC correction should be calibrated in the factory.*

The next few pages provide an overview of SWIR cameras from selected manufacturers. Products that meet the basic criteria are presented:

Resolution: ≥ 640x512 & Pixel size: ≤ 15x15 µm

Xenics, Belgium

https://www.xenics.com/short-wave-infrared-imagers/cheetah-series/

	Cheetah 640 TE1 400 SWIR / vSWIR	**Cheetah 640 TE1 800 SWIR / vSWIR**	**Cheetah 640 TE1 1700 SWIR / vSWIR**	**Cheetah 640 TE3**
Image format [pixels]	640 x 512	640 x 512	640 x 512	640 x 512
Pixel pitch [µm]	20	20	20	20
Detector type	InGaAs photodiode array with CTIA ROIC	InGaAs photodiode array with CTIA ROIC	InGaAs photodiode array with CTIA ROIC	InGaAs photodiode array with CTIA ROIC
Sensor cooling	TE cooler	TE cooler	TE cooler	3-stage TE cooler
Integration type	Snapshot - global shutter	Snapshot - global shutter	Snapshot - global shutter	Snapshot - global shutter
Active area and diagonal [mm]	12.8 x 10.24 [diagonal 16.4]	12.8 x 10.24 [diagonal 16.4]	12.8 x 10.24 [diagonal 16.4]	12.8 x 10.24 [diagonal 16.4]
Optical fill factor	100%	100%	100%	100%
Spectral range [nm]	900 - 1700 [SWIR]; 500 - 1700 [vSWIR]	900 - 1700 [SWIR]; 500 - 1700 [vSWIR]	900 - 1700 [SWIR]; 500 - 1700 [vSWIR]	900 - 1700 [SWIR]
Quantum efficiency	~80% [typical peak value]	~80% [typical peak value]	~80% [typical peak value]	~80% [typical peak value]
Gain modes	High Gain [HG] & High Dynamic Range [HDR]	High Gain [HG] & High Dynamic Range [HDR]	High Gain [HG] & High Dynamic Range [HDR]	High Gain [HG] & High Dynamic Range [HDR]
Full well capacities [electrons]	45k [HG] & 500k [HDR]	45k [HG] & 500k [HDR]	45k [HG] & 500k [HDR]	45k [HG] & 500k [HDR]
Read noise [electrons]	120 [HG] & 500 [HDR]	120 [HG] & 500 [HDR]	120 [HG] & 500 [HDR]	120 [HG] & 500 [HDR]
Dark current [electrons/second]	<100k [at 288K sensor temp and 150 mV reverse bias]; <200k for vSWIR	<100k [at 288K sensor temp and 150 mV reverse bias]; <200k for vSWIR	<100k [at 288K sensor temp and 150 mV reverse bias]; <200k for vSWIR	<1000 [at 233K sensor temp and 150 mV reverse bias]
Read out mode	ITR & IWR	ITR & IWR	ITR & IWR	ITR & IWR
Pixel operability	>99%	>99%	>99%	>99%
Preconfigured exposure time range [ms]	0.1 to 40 in HG, 0.1 to 20 in HDR	0.1 to 40 in HG, 0.1 to 20 in HDR	0.1 to 40 in HG, 0.1 to 20 in HDR	Maximum exposure is up to 20s in HG
Max frame rate [Hz] [full frame]	444	865	1730	111
Region of interest	Yes	Yes	Yes	Yes
Min region size [pixels]	32 x 4 [step 16 x 4]	32 x 4 [step 16 x 4]	32 x 4 [step 16 x 4]	32 x 4 [step 16 x 4]
Max frame rate [Hz] [min region size]	>100000	>100000	>100000	>10000
Analog-to-Digital [ADC] [bits]	14	14	14	14
Command and control	CameraLink	CameraLink	CameraLink	CameraLink
Digital output format	CameraLink [12 bit base] - 1 cable	CameraLink [12 bit medium] - 2 cables	CameraLink [12 bit dual medium] - 4 cables	CameraLink [14 bit base] - 1 cable

Horizon 2020
European Union Funding
for Research & Innovation

New Imaging Technologies (NIT), France

https://new-imaging-technologies.com/swir-products/all-swir-products/

× Category : WiDy SWIR | × Resolution : 640(H)x512(V) | × Gated mode : Yes | × Pixel pitch : 10.6µm² | × Pixel pitch : 15µm² | Clear All

Showing all 3 results

Category 1 | Interface | Resolution 1 | Frame rate | NUC & BPR On-board | Gated mode 1 | Sensor | Pixel pitch 2

MODEL	FRAME RATE	MODE/ SENSOR	RESOLUTION	INTERFACE	GATED MODE	NUC & BPR ON-BOARD
WiDy SWIR 640V-SP	Up to 100Hz	Global shutter NSC1201-SI	640(H)x512(V) 15µm²	USB 3.0	Yes	No
WiDy SWIR 640M-SP	Up to 100Hz	Global shutter NSC1201-SI	640(H)x512(V) 15µm²	CameraLink	Yes	No
WiDy SWIR 640M-SPE	Up to 100Hz	Global shutter NSC1201-SI	640(H)x512(V) 15µm²	CameraLink	Yes	Yes

Raptor Photonics, UK

https://www.raptorphotonics.com/product-type/swir

Owl 640 II

Using a 640 x 512 InGaAs sensor from SCD, the Owl 640 enables high sensitivity imaging from 0.6µm to 1.7µm. The 15µm x 15µm pixel pitch enables the highest resolution VIS-SWIR image and with less than 50 electrons readout noise, the Owl 640 enables the highest SWIR detection limit.

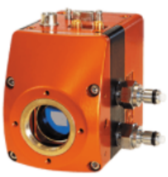
- VIS-SWIR technology
- 15µm x 15µm pixel pitch
- Ultra high intra-scene dynamic range
- Onboard Automated Gain Control (AGC)
- Ultra compact, Low power

Owl 1280

Using a cooled 1280 x 1024 InGaAs sensor from SCD, the Owl 1280 offers a visible response from 0.6µm to 1.7µm, enabling high sensitivity imaging. The 10µm x 10µm pixel pitch enables the highest resolution imaging. The Owl 1280 has a readout noise (rms) specification of <50 electrons and offers a high intra-scene dynamic range of 69dB, enablin simultaneous capture of bright & dark portions of a scene.

- 1280 x 1024, 10µm x 10µm pixel pitch VIS-SWIR technology
- <50 electrons readout noise (rms)
- On-board Automated Gain Control (AGC)
- On-board Intelligent 3 point NUC

Ninox 640 II



The Ninox-640 II is a cooled, high sensitivity digital SWIR camera. Using a 640 x 512 InGaAs sensor, the Ninox 640 enables high sensitivity imaging from 0.4µm to 1.7µm.

- **VIS-SWIR InGaAs technology** I Enables imaging from 0.6µm to 1.7µm
- **Cooled to -15°C** I Allows longer integration avoiding dark current build-up
- **Ultra-Low Noise Sensor: 18e- in High Gain** I Enables ultimate low ligh Vis-SWIR image
- **15µm x 15µm pixel pitch** I Enables the highest resolution SWIR image
- **Ultra high intrascene dynamic range** I Enables simultaneous capture of bright & dark portions of a scene
- **Onboard Automated Gain Control (AGC)** I Enables clear video in all light conditions
- **Ultra compact, Low power** I Ideal for hand-held, mobile or airborne systems

Owl 640 N

Using next-generation technology, Raptor has launched one of the lowest noise VIS-SWIR cameras on the market, perfect for imaging in lov light conditions. Using a 640 x 512 InGaAs sensor, and the sensor stabilised to 15°C, the Owl 640 N offers a visible response from 0.6µm tc 1.7µm to enable a high sensitivity. The camera also offers the lowest readout noise on the market with a typical value of 18 electrons. The camera has a high intra-scene dynamic range of typically 73dB, enabling simultaneous capture of bright and dark portions of a scene.

- **Ultra Low Noise Sensor: 18e- readout noise (rms)** – Enables ultimate night vision VIS-SWIR image
- **VIS-SWIR Technology** – Compatible with VIS-SWIR illuminators, markers & pointers
- **15µm x 15µm Pixel Pitch** – Enables highest resolution VIS-SWIR image
- **On-board Automated Gain Control (AGC)** – Enables clear video in al light conditions
- **Ultra Compact, Low Power** – Ideal for hand-held, mobile or airborne systems

Owl 640 T

- ½" Sensor Format I Better for optical design, ideal for OEM integration into Electro-Optic systems.
- 10µm x 10µm Pixel Pitch I Compatible with VIS-SWIR illuminators, markers & pointers
- <50 Electrons Readout Noise I Enables highest VIS-SWIR detection limi
- On-board Automated Gain Control (AGC) I Enables clear video in all light conditions • On-board Intelligent 3-point NUC I Enables highest quality images

- **½" Sensor Format** I Better for optical design, ideal for OEM integration into Electro-Optic systems.
- **10µm x 10µm Pixel Pitch** I Compatible with VIS-SWIR illuminators, markers & pointers
- **<50 Electrons Readout Noise** I Enables a high VIS-SWIR detection limi
- **On-board Automated Gain Control (AGC)** I Enables clear video in all light conditions
- **On-board Intelligent 3-point NUC** I Enables highest quality photos

Owl 640 A

The Owl 640 A is a variant of the Owl 640 family that offers an analog output. The camera is a rugged, high sensitivity VIS-SWIR camera. Usinç a 640 x 512 InGaAs sensor from SCD, the Owl 640 A enables high sensitivity imaging from 0.4µm to 1.7µm.

- VIS-SWIR technology
- 15µm x 15µm pixel pitch
- Ultra high intra-scene dynamic range
- Onboard automated gain control (AGC)
- Ultra compact, Low power

Photon ETC, Canada

http://www.photonetc.com/zephir-17-ingaas

TECHNICAL SPECIFICATIONS	ZEPHIR 1.7-V			ZEPHIR 1.7-S		
Focal Plane Array (FPA)	InGaAs			InGaAs		
FPA size	640 x 512			640 x 512		
Pixel size	15 µm			15 µm		
Spectral range	0.5 - 1.7 µm (~ 0.5-1.69 µm @ 25 °C) (~ 0.5-1.63 µm @-80 °C)			0.9 - 1.7 µm (~ 0.9-1.69 µm @ 25 °C) (~ 0.9-1.62 µm @-80 °C)		
Dark Current	< 300 - Typ. ~250 e/px/s *(Target at 21°C and sensor at -80°C)* < 150 - Typ. ~ 125 e/px/s *(No thermal emission from target and sensor at -80 °C)*			< 300 - Typ. ~250 e/px/s *(Target at 21°C and sensor at -80°C)* < 150 - Typ. ~ 125 e/px/s *(No thermal emission from target and sensor at -80 °C)*		
	High Gain	*Med Gain*	*Low Gain*	*High Gain*	*Med Gain*	*Low Gain*
Gain Setting (e/ADU)	2.8	28	130	2.1	7.4	89
Readout Noise (e)	50	150	800	30	75	350
Full Well Capacity	12 ke	800 ke	3.5 Me	27 ke	110 ke	1.4 Me
Readout Modes	CDS	ITR	ITR	ITR, IWR, CDS, IMRO		
Digitization	13 bits	15 bits	15 bits	14 bits		
ne Rate with CameraLink (fps)	90	190	190	220		
Peak responsivity	1.1 A/W @ 1660 nm			1.0 A/W @ 1550 nm		
Quantum Efficiency	> 70% from 0.9 to 1.69 µm			> 70% from 1.0 to 1.6 µm		
Operability (typical)	> 99%			> 99.5%		
Integration Time Range	1 µs to 19 minutes (low gain)			1 µs to 19 minutes (low gain)		
Cooling	TEC 4 stages, forced air			TEC 4 stages, forced air		
FPA Operating Temperature	-80 °C			-80 °C		
Cool Down Time	< 10 minutes			< 10 minutes		
Ambient Temperature Range	10 °C to 35 °C			10 °C to 35 °C		
Cold Shield	f#/1.4			f#/1.4		
Software	PHySpec™ control and analysis software included					
Computer Interface	CameraLink™ or USB 3.0			CameraLink™ or USB 3.0		
External Control	On demand			On demand		
Power Supply Requirement	12 VDC @ 5A			12 VDC @ 5A		
Physical Dimensions	169 x 130 x 97.25 mm			169 x 130 x 97.25 mm		
Weight	2.6 kg			2.6 kg		
Certification	CE			CE		

Sensors Unlimited Products, USA

http://www.sensorsinc.com/products/area-cameras/

	Mini-SWIR 1280JSX High Definition Camera	Micro-SWIR 640CSX SWaP Optimized Camera	Micro-SWIR 320CSX SWaP+C Optimized Camera
Weight	≤ 235 g enclosed, ≤ 120 g OEM	≤45 grams enclosed, ≤41 grams OEM	<60 grams enclosed, <55 grams OEM
Lens Mount	M42x1 mount	C-Mount	C-Mount
Camera Link Connector	3M SDR26 Connector enclosed	26 Pin SDR standard connector Board-to-board connector option for OEM model	26 Pin SDR standard connector
Pixel Pitch	12.5 µm	12.5 µm	12.5 µm
Active Area	16.0 mm x 12.8 mm x 20.5 mm diagonal	8.0 mm x 6.4 mm (10.2 mm diagonal)	4.0 mm x 3.2 mm (5.1 mm diagonal)
Operating Case Temperature	-40°C to 70°C	-40°C to 70°C	-5°C to 60°C
Storage Temperature	-54°C to 85°C	-54°C to 85°C	-54°C to 85°C
Humidity	95% relative humidity	95% RH non-condensing	95% RH non-condensing
Power Requirements	DC Voltage: +8-16V Power: ≤ 3.0 W at 20°C (case temperature), ≤ 10.0 W maximum	DC Voltage: +4.5-16 V Power: 1.5 W at 20°C case temperature, max ≤4.25 W	DC Voltage: +4-16 V Power: 1.7 W at 20°C case temperature, max <4 W
Optical Fill Factor	100%	100%	100%
Spectral Response	Standard, 0.9 µm to 1.7 µm NIR/SWIR, 0.7 µm to 1.7 µm VIS/SWIR 0.5 µm to 1.7 µm	Standard, 0.9 µm to 1.7 µm NIR/SWIR, 0.7 µm to 1.7 µm	Standard, 0.9 µm to 1.7 µm
Quantum Efficiency	Standard, ≥ 65% from 1 µm to 1.6 µm NIR/SWIR, ≥ 65% from 0.9 µm to 1.6 µm VIS/SWIR, ≥ 65% from 0.7 µm to 1.6 µm	Standard, ≥ 65 % from 1 µm to 1.6 µm NIR/SWIR, ≥ 65 % from 0.9 µm to 1.6 µm	Standard, > 65 % from 1 µm to 1.6 µm
Mean Detectivity, D*	2.9×10^{13} cm√Hz/W (typical) - 30 fps 2.8×10^{13} cm√Hz/W (typical) - 60 fps	≥ 2.5×10^{13} cm√Hz/W (typical) - 30 fps ≥ 2.8×10^{13} cm√Hz/W (typical) - 60 fps	2.86×10^{13} cm√Hz/W (typical)
Noise (RMS)*	35 electrons (typical) - 30 fps 25 electrons (typical) - 60 fps	≤ 35 electrons (typical) - 30 fps ≤ 25 electrons (typical) - 60 fps	35 electrons (typical)
Dynamic Range**	1700:1 - 30 fps 1850:1 - 60 fps	≥ 2500:1 at low gain, ≥ 800:1 at high gain - 30 fps ≥ 2500:1 at low gain, ≥ 1100:1 at high gain - 60 fps	≥ 2500:1 at low gain, ≥ 800:1 at high gain - 30 fps ≥ 2500:1 at low gain, ≥ 1100:1 at high gain - 60 fps
Image Correction	2-point (offset and gain) pixel by pixel, user selectable	2-point (offset and gain) pixel by pixel, user selectable	2-point (offset and gain) pixel by pixel, user selectable
Digital Output Format	12 bit base Camera Link®	12 bit base Camera Link® Other output options available	12 bit base Camera Link®
Scan Mode	Continuous or 3 externally triggered modes	Continuous with user configurable trigger modes	Continuous

SWIR Vision System, USA

https://www.swirvisionsystems.com/acuros-swir-camera/

eSWIR Cameras

Camera Model	Resolution	Megapixel	Interface	TEC	Shutter	Frame Rate (fps)	Pixels (µm)	Vis-eSWIR (nm)	Lens Mounts
Acuros™ CQD™ 640/640L GigE eSWIR Camera 	640 x 512	0.33	GigE Vision	TEC	Global	380	15 x 15	350 - 2000	C, F, M-42
Acuros™ CQD™ 640/640L USB3 eSWIR Camera 	640 x 512	0.33	USB3 Vision	TEC	Global	380	15 x 15	350 - 2000	C, F, M-42
Acuros™ CQD™ 1280/1280L GigE eSWIR Camera 	1280 x 1024	1.31	GigE Vision	TEC	Global	90	15 x 15	350 - 2000	C, F, M-42
Acuros™ CQD™ 1280/1280L USB3 eSWIR Camera 	1280 x 1024	1.31	USB3 Vision	TEC	Global	90	15 x 15	350 - 2000	C, F, M-42
Acuros™ CQD™ 1920/1920L GigE eSWIR Camera 	1920 x 1080	2.07	GigE Vision	TEC	Global	60	15 x 15	350 - 2000	F, M-42
Acuros™ CQD™ 1920/1920L USB3 eSWIR Camera 	1920 x 1080	2.07	USB3 Vision	TEC	Global	60	15 x 15	350 - 2000	F, M-42

After detailed analysis and consultation with the manufacturers, a camera **WIDY SenS 640M-STPE** manufactured by **New Image Technologies**, was chosen. This camera was chosen because of the most acceptable price-quality ratio, delivery time and comprehensive technical support.

A.1.2 State of the art of trackside OD&TIS system

Remote sensing and 3D object detection is an area that has been very interesting technologically and commercially in recent years. Much of the effort is focused on the development of autonomous driving systems, driver assistance systems, aerial mapping, docking of space crafts, collaborative robots, machine vision, mobile phone applications and the like. There are several different technologies used for the listed applications. New ones are also intensively appearing, trying to solve individual problems in a specific way. Some of these remote 3D object detection technologies that can be used for trackside OD & TID systems are listed below:

- Video imaging cameras (stereo vision),
- Thermal imaging cameras (NIR, SWIR, FLIR etc.),
- 3D Time of flight cameras,

- Radar (FMCW, rotating and solid state array antennas),
- LiDAR (2D/3D laser scanning).

Each of these technologies has its advantages and disadvantages. Therefore, the choice of decision is conditioned by the specific requirements of the application. There are many different interrelated factors that affect the performance of applications and sensing results. For each individual application, an appropriate trade-off must be found between all these factors. It is about finding the optimum between Detection Range, field of view, frame rate, resolution, eye safety, operational conditions, costs etc.

LiDAR technology was selected for SMART2 trackside OD & TID. It is based on measuring the time of flight of a reflected laser beam from an object. Due to high operational frequencies, very short times of flight (picoseconds), strong electromagnetic interferences, noise, difficult operating conditions in the railway environment and strict safety requirements, the development of electronic prototype modules is very demanding. The biggest challenges are controlling the laser optical system, detecting reflected light pulses with high-sensitivity photosensors, measuring of extremely short time intervals and processing data in real time. SW algorithms for identifying obstacles are additional challenges.

The result of the detection with the SALVIS system (SALVIS, online) will be 3D point clouds with vector data on the distance of the detected object. It is assumed that only with the applied LiDAR technology and advanced processing of the obtained measurement data, it will be possible to achieve the required resolution of the object and the Detection Area. Sufficient resolution is urgently needed for further improvement of the SALVIS features in the next phases of development that will follow the completion of SMART2, to recognize the shapes in more detail and to carry out object classification.

For the up to date known solutions for obstacle detection at railway level crossings, it is possible to find online data that scanning of objects is performed with a frequency of 1 Hz up to a maximum of 2 Hz at a relatively low resolution. With our SMART2 solution, we would like to increase the frame rate to at least 3 Hz to 4 Hz with an improved resolution (0.3 °). The results of SALVIS prototype testing and the development of the SW application will show whether such a frame rate can actually be achieved and if it will be sufficient to measure the size, speed and direction of movement of detected objects. This is the basis for determining the degree of their danger.

SALVIS is intended for the control of a limited area on a railway line. The idea is that with one SALVIS sensing unit it will be possible to control one dangerous Detection Area, such as a typical level crossing on an interoperable double-track railway. An example of such a level crossing with a Detection Area of size 15 m X 11m is shown in the Figure 1. The specification of the Detection Area size is taken from the requirements of the British IM Network Rail procurement.[1]

[1] https://networkrail.bravosolution.co.uk/esop/toolkit/opportunity/opportunityDetail.do?opportunityId=29925&oppList=PAST [Accessed: 13-August-2020]

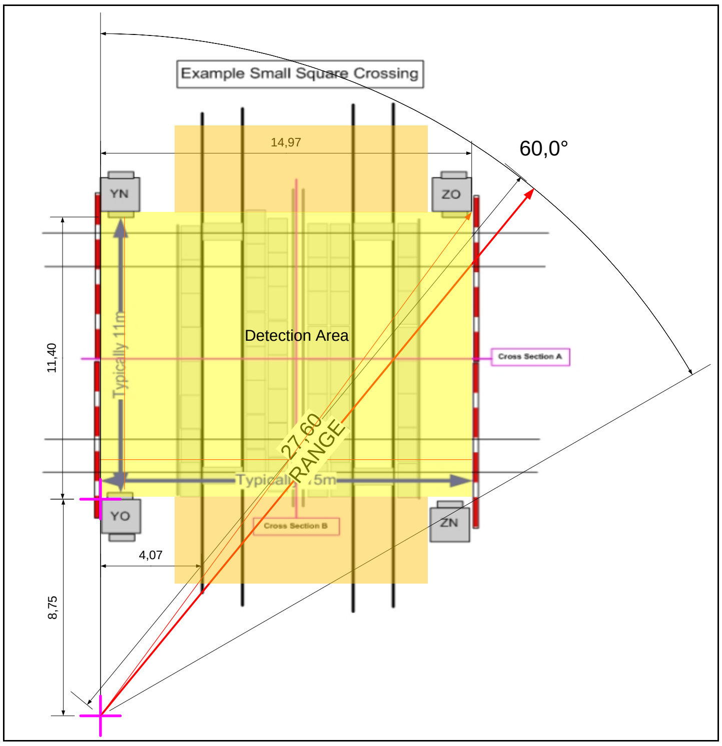


Figure 35: The Detection Area of a typical double-track level crossing

As shown in Figure 13, the SALVIS horizontal field of view is planned to be 60 °. The vertical field of view is planned to be 30 °. The SALVIS horizontal Detection Range is planned to be 40 m at normal weather conditions. The estimated measurement accuracy for distance is ± 5 cm.

Data about the minimum size of the objects that should be detected by the trackside OD & TID in the SMART2 project is taken from the requirements of the Swedish IM Trafikverket (Figure 14). For the Hektor obstacle detection system they set the Minimum Detectable Object Size of 1.0 x 0.5 x 0.5 m. This size corresponds to the approximate size of the scooter and the child. The trackside OD & TID system in SMART2 should detect such an obstacle even if it hangs from a height of 3 m.

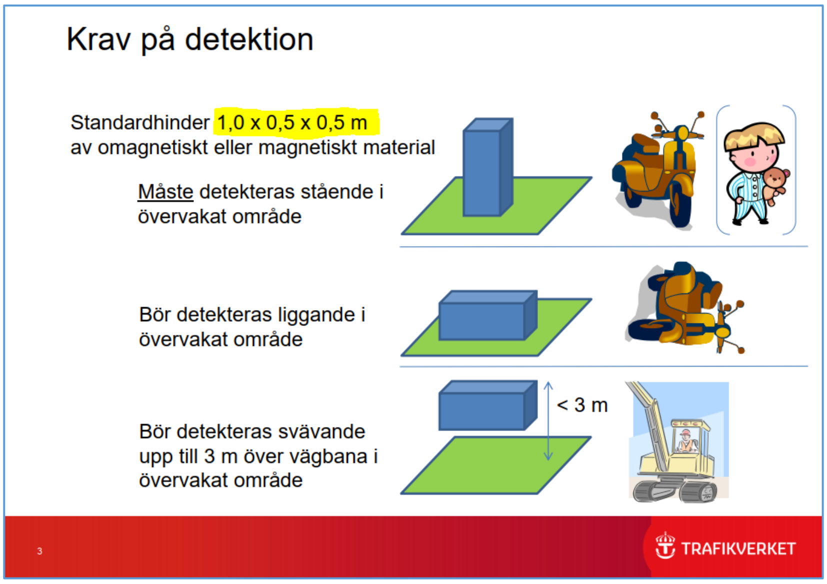


Figure 36: The Minimum Detectable Object Size determined by the Trafikverket[2]

The estimated resolution of the SALVIS system is 20 cm at 40 m horizontal distance.

For more complex situations than the one shown in Figure 13 (for example level crossings at multi-track railway lines, landslide endangered areas, highway underpasses, long station tracks and platforms etc.) additional SALVIS sensing units can be added and connected to the same control system.

SALVIS will be designed in such a way that it will be possible to obtain later a SIL4 safety certificate (after the completion of SMART2 project). Due to the requirements for high processing power, the SALVIS prototype will be realized with embedded processors. Due to limited resources in the SMART2 project, the prototype will run on an operating system which will support real-time applications.

Advanced features of the proposed SALVIS system are shown through its high resolution, long Detection Range, wide field of view and improved frame rate. All these features, which can be further optimized through the SMART2 project, are a good basis for a safe, powerful, and cost-effective trackside OD & TID system.

A.1.3 State of the art of airborne OD&TID system

During the last years, UAV have been extensively developed and they are gaining popularity in recent years due to their technical advantages. Today drones are equipped with cameras and sensors, and they can collect data, images, video, LiDAR surveys and more which could be useful also in different railway applications.

[2] https://www.trafikverket.se/contentassets/b704221b76c94469a4135c76270e1b43/presentation_hektor.pdf [Accessed: 07-March-2018]
https://www.trafikverket.se/for-dig-i-branschen/teknik/anlaggningsteknik/vagskyddsanlaggningar/hektor/ [Accessed: 13-August-2020]

SESAR European Outlook Study (2016) (SESAR, 2016) defined that the infrastructures such as railway may be monitored and kept secure by using drones. Railway inspection is recognised as one of important sectors for use of drones. Railway inspections will be carried out with Long range surveying (primarily BVLOS - beyond the visual line of sight). Europe market potential is that by 2035 can be in use up to 400 000 drones with the majority flying BVLOS and from this number around 180 000 could be used for mapping and surveying where one of the key market segments is railway. Drones could benefit the railway in inspection in which could be monitored approximately 200 000 km on a bi-monthly basis.

Drone market in the last decade has been growing exponentially on a global scale, and in railway applications, in 2019, it reached around 3.5 billion euros, with an annual growth trend of 40% (ESCAP, 2019, p16).

In year 2008, the European Parliament and the Council of the European Union (EU) issued Regulation 216/2008 on the establishment of the EASA – European Union Aviation Safety Agency and gave it legal authority for civil aviation, including UAS (Unmanned Aircraft Systems). EASA has allowed each EU Member State to develop its own laws and regulations for drones of 150 kg or less, Table 1 (globalmasstransit, 2019).

Table 21 Rules governing the operation areas of drones (globalmasstransit, 2019)

Country	Regulatory body	Drone weight	Maximum speed	Maximum flight altitude	Distance from the operator
Europe					
Starting from 31 December 2020 EU and EASA	NAA	Depending from class 1-5	19 m/s or low speed depending from class 1-5	120 m above ground or sea level	Depending from class 1-5
Great Britain	Civilian Aviation Authority (CAA)	≥ 20 kg: private 20 - 150 kg: commercial	Not defined	122 m above ground level	VLOS operations. Commercial BVLOS operations are forbidden
North America					
Canada	Transport Canada	≥ 35 kg: private < 35 kg: commercial	Not defined	90 m above ground level	> 500 m
USA	Federal Aviation Administration (FAA)	≥ 25 kg: commercial	161 km/h	122 m above ground level or structure	VLOS operations

Use of drones per state in rail network

Different European countries are testing or already using drones in their railway networks for monitoring, inspection, testing and maintenance etc. (Table 3 (*globalmasstransit, 2019)*).

Table 22 Determination of the intrinsic GRC (easyaccesrules, 2020)

Max UAS characteristics dimension	1 m	3 m	8 m	> 8 m
Typical kinetic energy expected	< 700 J	< 34 kJ	< 1084 kJ	> 1084 kJ
Operational scenarios				
VLOS/BVLOS over a controlled ground area	1	2	3	4
VLOS in a sparsely populated environment	2	3	4	5
BVLOS in a sparsely populated environment	3	4	5	6
VLOS in a populated environment	4	5	6	8
BVLOS in a populated environment	TBD	TBD	TBD	TBD
VLOS over an assembly of people	7			
BVLOS over an assembly of people	TBD			

Abbreviations: Adif - Administrador de Infraestructuras Ferroviaria, ARCEP - Autorité de Régulation des Communications Électroniques et des Postes, CNIL - Commission Nationale de l'informatique et des Libertés, DGAC - Direction Générale de l'Aviation Civile, ONERA - Office National d'Etudes et de Recherches Aérospatiales.

In railway application, drones are used for:

Topographical surveys

Drones can be used for producing topographical surveys without venturing into the sites concerned. Accuracy of drones derived topographic information showed results that are comparable to the LiDAR and RTK-GPS topographies (Mazzoleni, 2020) and drones can scan particular locations for BIM-type applications (Building Information Modelling) or for use in project studies.

Safety and security functions

Drones can provide support for the teams in charge of surveillance operations on particular parts of the rail line. They can detect the presence of individuals in the area, both by day and at night, using photo and/or video reconnaissance techniques. They could be used for fight with: vandalism; theft; trespassing and suicide attempts; and assault of staff and customers.

The largest rail freight operator in Poland, PKP Cargo, started to use drones in 2015 for crimefighting and decrease thefts by 60 per cent during first years of the drone use. (Zasiadko, 2019) Similar measures were undertaken in 2018 by the British Network Rail. A drone was used there to record and send photos of intrusions and illegal activities. The same year, the Belgian railway company Infrabel implemented drone (BVLOS) for night flights to combat the theft of traction cables.

Metro Trains Melbourne uses drones to detect vandals and intruders. They are equipped with RGB cameras, thermal imaging cameras, and are deployed in specific network sections to respond to incidents.

Inspections of stations and industrial sites

In the Netherlands, rail operator Nederlandse Spoorwegen (NS) will use drones for maintenance inspections at stations. According to their experience use of drones **"causes less nuisance for travellers, leads to lower costs and ensures inspections are completed faster". (**Gompel, 2019)

The Société Nationale des Chemins de fer Français (SNCF) has been using drones for its inspection, surveillance and maintenance work since 2013. The authorities have set up a subsidiary, Altametris, which provides customised drone solutions with a focus on sensors, designs innovative solutions, and processes data. Table 4 shows details of the drones operated by Altametris.

Table 23 Drone system applications on European rail networks

Country	Responsible body/company	Implementation purpose	Key supplier
France	SNCF Réseau	Topographic measurements, network mapping, inspection work, supervision, maintenance	Altametris (subsidiary of SNCF Réseau), ARCEP, CBIL, Delair Tech, DGAC, ONERA
Germany	Deutsche Bahn (DB)	Supervision, inspection and evaluation, construction planning	Microdrones (manufacturer)
Netherlands	ProRail	Control of switch heating systems, control of corrosion protection of steel structures	Arcadis
Norway	Bane NOR	Monitoring and lubrication of point machines by means of autonomous drones	Nordic Unmanned, Total Trafikkhjelp, IRIS Group Nordic
Spain	CAF Signalling	Geolocation of signalling systems on high-speed lines	SigmaRail, UC3M Intelligent Systems Laboratory
	Thales, Adif	Madrid-Seville high-speed line error detection tests (for maintenance work) *Automatic Train Operation* (ATO)	SigmaRail, UC3M Intelligent Systems Laboratory
Great Britain	Department for Transport (DfT)	DfT's Pathfinder tests and trials	SenSat
	Transport for London (TfL)	Measurement and maintenance of the London Underground network	Lanes Rail
	Network Rail (NR)	Inspection work and track	Aecom, Cyberhawk, NR Air

		maintenance	Operations crew

Australia is developing track inspections system with drones due to extensive sixth rail network imposes special requirements, especially in remote areas. Institute of Railway Technology (IRT) in Monash implements drones for support in autonomous track inspection [Both, 2019]. Also, use of technologies that are going to allows identification of visible defects in rails, missing parts such as rail fixations.

Track maintenance

British rail infrastructure firm Network Rail (Margaritoff 2018) start to use drones in 2018 for track inspection. The drones are equipped with thermal-imaging, 4K-resolution cameras that can spot faults and damage to tracks. Advantage of drone use is that it does not require closure of any tracks to train traffic. Intrigued by the Network Rail experience, German rail operator Deutsche Bahn intends to deploy drones, both for track maintenance and infrastructure monitoring.

Norway company Bane NOR uses drone for track maintenance. In 2018, they announced plans to develop a system in which an autonomous drone lubricates point machines. The system is programmed according to the route using map coordinates. Bane NOR is the first authority in the world to introduce drone technology for railway maintenance (Zasiadko, 2019).

British company Lanes Rail uses drones as significant support among other tools for for the maintenance wide range of resources, including tracks, station buildings, bridges and engineering work implementation. British Network Rail has implemented drone systems for: Identification of problems with infrastructure and earthworks; Surveillance of water-related hazards, such as water reservoirs and washouts near rivers; Vegetation growth management and animal intrusion monitoring and Identification and monitoring of violation and suicide spots

Table 5 shows the parameters of the drones used by NR [*globalmasstransit, 2019*].

Table 24 Data of drones operated by Altametris

Parameter	Details
Weight	2–20 kg
Sensors	High-resolution video/photographic equipment, multispectral thermographic cameras (infra-red band) and/or LiDAR (3D environment laser system)
Fleet	12 drones and robots

Train driving

French firm Thales (Thales, 2019) is developing its own specialized four-rotor drones, called rail bots that will move on the track of the train and will be able to run autonomously. These drones will be equipped with thermo-imaging, advanced optronics and custom electronics. With use on Artificial Intelligence, drones will be able to send in real time data and analysis of anomalies that they detect.

Network mapping

Drones make highly accurate 2D and 3D mapping easy and produce ultra-precise, detailed results that can be fed into the Information Systems of the different departments. Their degree of detail is approx.1/1,000 over lengths of 20 to 50 km per day with an accuracy to the centimetre level. Drones are therefore ideal for scanning the railway system to update the GIS (Geographical Information System). [SNCF]

Spanish company SigmaRail in 2017 used drones to perform a survey of the ERTMS Alicante-Murcia high-speed line in south-eastern Spain. The data captured has been used to create an accurate digital model of the rail corridor in order to validate performance and examine engineering priorities. (Railway technology, 2018) SigmaRail solution is to upload data downloaded from UAVs in a format that CAF use for programming ERTMS devices.

Table 6 shows details of the drones used by SigmaRail on Spanish high-speed lines, Table 4 (*globalmasstransit, 2019)*.

Table 25 Parameters of the drones used by NR

Parameter	**Details**
Weight	7 kg (maximum)
Range	A flight of up to 500 metres from the operator is permitted
Flight	Permits flying up to an altitude of 122 m
Flight time before recharging	20 minutes
Crew	At least two people (one operator-in-command and one observer/camera operator)
Camera	4K high resolution video and high resolution image systems
Features	Embedded on-line geospatial environment (GEO) Embedded protocol RTH – *Return to Home* Multiple motors and rotor blades

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Table 7 shows details of the drones used by SigmaRail on Spanish high-speed lines [*globalmasstransit, 2019*].

Table 26 SigmaRail drone parameters

Parameter	Details
Video equipment	RGB or thermal imaging cameras
Location	Each image is geographically located using the on-board GPS system
Survey capacity	Approx. 6 km of the section in less than an hour
Memory	2 GB of data on a 20-minute flight

Rolling stock inspections

SNCF introduce inspection of rolling stock with drones that can inspect roof of TGV. In the Technicentres, drones can record vehicle condition and detect even the most minor defects in real time. [Sncf, 2020]

Inspection of earthworks, construction, bridges and tunnels

For more inaccessible or hard-to-access areas such as tunnels, bridges or construction sites drones are very good solution. They can be used for scanning of defects, damage or monitoring construction in real time.

DB is using drones since 2015 throughout the country to supervise and plan construction, and to check the vegetation around railway lines. DB use 12 types of drones, differentiated on the basis of load capacity, flight time and operational capability. Each drone is equipped with cameras that can record video and make high-resolution digital or thermal images (Sesar, 2016, p. 93).

ProRail, company that maintains the Dutch railway infrastructure, has used drones equipped with thermo-cameras for inspection the turnout heating systems on its tracks. Dutch Arcadis is using drones to control steel infrastructure (bridges and viaducts) (Arcadis, 2017). It visually inspects the condition of corrosion protection, estimates the remaining life cycle of coatings, and advises on maintenance activities.

From July 2018, ProRail has used drones and 3D scans to map trees along the Dutch railway network. The company uses this technology to identify trees at risk of falling or loss of branches, thus enabling preventive measures to be undertaken before the trees cause a risk for movement on the tracks.

USA BNSF Railway Co. is using fully autonomous drones to collect data from extensive railway infrastructure since 2015. They use BVLOS for inspections with programmed drone according to plan. Derailments are also inspected as they allow railway staff to safely and efficiently observe areas that may be inaccessible in emergency situations. In 2016, Union Pacific Railroad used live transmissions from one of its drones to explore the track during the floods in northern Iowa. (SNCF 15).

Australia is developing drones for exploring tunnels capable of safe flight with limited space (no GPS coverage), equipped with laser sensors to enable both the measurement of enclosed spaces and positioning in confined spaces (*globalmasstransit, 2019*).

A.1.4 State of the art of cloud based DSS system

There are many railway applications related to usage of different kind of decision support systems. Regarding to traffic issues, decision support systems and decision-making algorithms are used for rail traffic management, timetable planning and different cases of traffic prediction. The second group of implemented decision-making procedures is related to maintenance of infrastructure (smart maintenance, predictive maintenance, status of infrastructure, asset management). Traditionally, the decisions to perform maintenance have been based on the infrastructure managers' observations, judgments and choices which are derived by available budgets, planned schedules and abrupt failures (Dhillon, 2002). However, maintenance based on these drivers often leads to undue maintenance of increased cost. For this reason, predictive maintenance is considered to be a most effective maintenance policy that suggests performing maintenance only where it is promptly needed (Khan et al., 2003). However, predictive maintenance poses decision-making challenges on the infrastructure managers, particularly for railways whereby the maintenance decision-making is a difficult task due to a widespread network of diverse railway objects, availability demands, possession time, deterioration rate and budget constraints. Such infrastructure maintenance requirements pose decision-making dilemmas to the infrastructure managers, where maintenance planning is challenged by the number of conflicting issues (Liden, 2015). That is why the DESTination RAIL project (http://www.destinationrail.eu/) has developed a holistic decision support tool that provides the solutions for the common infrastructure problems encountered in diverse regions of Europe, e.g. deterioration and scour damage to bridges, slope instability, damage to switches and crossing, etc. As it stated in (http://www.destinationrail.eu/ajax/DownloadHandler.php?file=2006) , it is achieved by developing number of novel techniques and systems for identifying, analysing, predicting and remediating rail infrastructure. The idea of decision support tool is to assist infrastructure managers in assessing the current state of assets, predicting the assets' performance over time, executing diverse maintenance scenarios, and to provide maintenance planning recommendations.

The third group encircles decision-making algorithms for implementation safety procedures in railway environment.

The latest results in that field have achieved in GoSAFE RAIL project (http://www.gosaferail.eu/). The GoSAFE RAIL project will be transformative for asset safety in the rail sector. The objective of this project was to bring together inter-disciplinary experts from Risk based asset assessment of infrastructure, Artificial Intelligence (AI), object detection and data management sectors with leaders in network microsimulation modelling to deliver a Decision Support Tool that will allow a step change for infrastructure safety. The involvement of Infrastructure Managers and Railway Undertakings had a a goal to provide the R&D performers have access to data and through collaboration with the Shift2Rail initiative and complementary H2020 projects, access to demonstration sites necessary to develop the tool and a ready market to commercialise it. Through the development of a Global Safety Framework fed by a Network Decision Support Tool the project provided integrated solutions to issues related to infrastructure safety and planning considering a number of common problems faced by EU infrastructure managers.

The application of decision support system for obstacle and track intrusion system is very novel and there is much more expertise from that field (obstacle detection) in automotive industry [64],[65], [66]. However, it is not so easy to transfer knowledge and expertise from automotive industry to railway because there are some differences between. There are three major challenges using decision making algorithms and decision support tools in solving practical rail problems:

- Reliability of data needed for implementing decision-making algorithms
- Very serious demands regarding safety in general and especially security redundant communication to fulfil
- Reaching sustainable ATO is possible only with optimized integration of ATO on-board and traffic management system (TMS) that reflects very complex procedures for integration to be implemented

In addition, one challenge more particularly for developing obstacle detection and track intrusion system is qualitative risk assessment. In that sense, holistic decision support system that will be developed during SMART 2 project will have to take into account all above issues, provide interfaces for different detection systems to exchange information and give proper risk assessed outputs.

A.1.4.1 Cloud technologies

While it is not a new concept, Cloud Computing has become more popular and widespread in the last decade, mainly thanks to tech giants such as Google, Microsoft or Amazon which launched their cloud computing platforms.

Cloud Computing is the result of mixing several already existing technologies, such as: Virtualization, Parallel Computing and Grid Computing. The result of mixing these technologies was a distributed computing model, whose purpose is to deliver resources (such as CPU power, storage, and access to specialized software) to the users, over the internet (Gajbhiye et al., 2014).

Cloud Computing has been the topic of several research papers over the last years. Some of the earlier papers have focused on defining and understanding the concept and its advantages, rather than exploring its applications. Currently, the official NIST definition of Cloud Computing is the following, proposed by (Mell et al., 2011):

"Cloud Computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (such as networks, servers, storage, applications and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This model is composed of five essential characteristics, three service models and four deployment models."

The services provided by Cloud Computing Platforms can be broadly separated into the following three categories:

- **SaaS (Software as a Service):** the Cloud Provider enables the user to have access to specialized software. The user has no access to the hardware which runs the software, nor do they have the ability to change software configurations. Google Drive (Google drive, online) (cloud storage for personal use) is an example of such a service.

- **PaaS (Platform-as-a-Service):** deliver a development environment to the user, where they can build their individual applications. All the necessary tools to do so (tools for design, programming, testing, deployment) are available. Microsoft Azure over Google AppEngine (Google AppEngine, online) offer such a service.
- **IaaS (Infrastructure-as-a-Service):** provide full environments to the user, in the form of Virtual Machines. The user has full control of everything which happens within the virtual machine and also over what specifications the machine has (CPU Type, RAM Amount, GPU Type, available storage). Amazon EC2 (Amazon, online) is such an example.

As it was already explained by (Gajbhiye et al., 2014), the main purpose that Cloud Computing serves is to be a cheaper, more viable and more versatile replacement for on-premise infrastructure. The biggest advantages it provides to its users are its versatility, alongside a significant reduction in operational costs.

When purchasing infrastructure locally, one must always do so with the worst case scenario in mind – this means that the local infrastructure should be able to handle the peaks of operation. However, these peaks usually occur rarely, thus the system rarely operates at full capacity. However, the idle hardware produces significant maintenance costs and requires a larger initial investment. To counter this, Cloud Platform offer freely scalable services to the users, which can be scaled up or down seamlessly based on the current needs and a "pay-for-what-you-use" pricing model, in order to ensure that a significant reduction in costs occurs.

As it was explained by (Fernando et al., 2013), Cloud Technologies have enabled the transition from MC (Mobile Computing) to MCC (Mobile Cloud Computing); MCC Technologies, when combined with other novel technologies, such as Data Analytics for example, have brought about several novel systems, such as the following examples proposed by (Wang et al., 2015):

- Arterial traffic monitoring through statistic learning [Herring et L.,2009)]
- Multicasting with feedback in social networks (Wang et al, 2013)
- Mobile healthcare systems (Wu et al., 2013)
- Precision agriculture (Rupnik et al, 2019)

In addition to the applications that were already specified, Cloud-based technologies have also been proposed to be used for monitoring critical infrastructure. Some examples introduced by (Younis et al., 2013) in this category include power plants and water treatment facilities – however, his paper focuses more on the requirements that both the Cloud Services and the types of software deployed to the cloud must fulfil in order to ensure the correct functionality of the systems.

A different approach is presented by (Chen et al., 2016) who advocates for the transition to CPS (Cloud-physical systems) for already existing systems – smart transportation, smart cars, smart medical systems, smart electrical power grids or smart manufacturing systems, often with the help of novel fields of research, such as Big Data. He also presents a general framework and possible implementation of such a system in his paper.

However, developing complex system with many components has proven a difficult task – for this reason, a specialized system component, whose purpose is to collect information from all the other system components and analyse it, in order to properly manage the functionality of the entire system is required in order to enable complex systems to function. Initially proposed by (Demirkan et al., 2013), the so-called Decision Support System (DSS) has now become a staple in many cloud based complex applications. Some examples are: Smart Agriculture (Lindblom et al, 2014), Disease Prevention in Smart Agriculture (Foughali et al., 2018), Solar Map Generation (Boulmier et al., 2016) or even Cancer Diagnosis (Aruna et al., 2016).

Other applications have successfully added novel components to already established systems in order to improve performance:

- for example (Stehr et al., 2015) and (Trippichio et al., 2015) have proposed to use drones in **Smart Farming and Sustainable Agriculture**.
- Drones and other novel elements (both cloud based and not cloud-based) have been proposed for several other applications, such as: **Intelligent Railway Infrastructure Monitoring,** proposed by both (Flammini et al., 2016) and Banic et al., 2019).
- The MOMIT Project takes the concept a step further, by trying to find **deformation areas in railways using drones** and images acquired from a high altitude.

A1.4.2 Diagnostic systems

Each railway vehicle consists of a number of subsystems, assemblies, subassemblies, and single elements. The work and behaviour of each of them are directly related to the overall operational capacity of the system. Reduction or complete loss of functionality can happen due to various factors that affect the parameters of the system and cause damage such as aging, wear, deformation, fractures, corrosion, etc. In general, there are two possible states of any technical system: the state of the system in regular operation mode and the state in failure mode. These states recur cyclically over the lifespan of the system. When we say that the state of the system is in regular operation mode, its condition is optimal and can perform the specified task in the prescribed manner and at the prescribed time. When the system is in a state of failure, it is considered defective and cannot perform the defined task at all or in a prescribed manner. The main features that define failure are the cause of the failure, manifestation of the failure, location of the failure, and the way of removing the failure.

From the perspective of maintenance and monitoring of the health of components in the system, it was always challenging to design a reliable diagnostic method for identifying critical vehicle conditions and foreseeing its overall behaviour. Diagnostic tools check the defectiveness, working capacity, functionality, and localization of faults. Such analysis aims to detect a failure or an anomaly and isolate it by locating its position within a single component, according to the occurred symptoms. Every diagnostic process can be followed through three steps: identification of undesirable conditions (by comparing nominal and observed behaviours), observing noticed symptoms and determining possible faults, and initiation of reaction measures.

Determining operating conditions and diagnostic state of an integral part of the system can be performed by utilizing appropriate equipment and instruments or by making manual observations by experts from the field. Human inspection means that a qualified technician personally assesses the conditions of train assemblies. Thus, the condition assessment of railway vehicles depends on the subjective conclusions of the technician. Having in mind that technicians and engineers need to diagnose more than 100 different types of faults on a large number of different vehicle models, it can be easily concluded why the human expertise is not optimal and the most reliable solution for diagnostic tasks. Also, the manual inspection does not cover all the vital assemblies (axles, wheels, brake elements, springs, etc.). Such an approach leads to the increased risk of railway accidents with severe consequences for vehicles, passengers, infrastructure, and the environment (Ngigi et al., 2012).

A few decades of railway diagnostic experience showed the substantial influence of diagnostic tools on maintenance costs and railcar reliability. Modern diagnostics is based on the measurement of the selected parameters and comparing the measured values with the previously established norms. Additionally, a quality diagnostic could extend the lifetime of the rolling stocks and the associated infrastructure. Diagnostics cannot be performed under any condition equally, so it is necessary to control the conditions in which the characteristics of the system are determined, in parallel with the measurement of diagnostic parameters. Therefore, adaptable diagnostic methods should be used from case to case to formulate all the specifics of the relationships between the states of the system and appropriate indicators for each diagnostic object. Diagnostic systems can be utilized in parallel with a maintenance process for monitoring a vehicle and its operating conditions, predicting upcoming services, and providing engineers with reliable monitoring data as it is presented in (Ward et al., 2011) and (Brickle et al., 2008). Some of the most common railway features that could be monitored using diagnostic systems are: electric and diesel motors parameters, wheel-rail interactions and forces, axle bearings, accelerations and vehicle running gears, contact pantograph, ride quality and comfort, and the safety (Moynihan et al., 2007) and quality parameters such as the status of doors, ventilation subsystem, air conditioners, etc. Finally, temperature and acoustic emissions of moving parts are additional measurable parameters that could be valuable for a diagnostics and maintenance process.

Electronic subsystems in vehicles are improving every year, becoming more complex and challenging for maintenance, resulting in troubles in identifying all component malfunctions. Remote communication and control, as one of the most exploited modern technologies, shifted in the great sense diagnostic processes of vehicles by enabling a remote vehicle diagnosis during a drive but also opening the systems to external threats and malicious internet attacks. The privacy of diagnostic data could be easily jeopardized as a consequence of modern communication technologies. From the perspective of data quantity, diagnostic systems generate vast amounts of high dimensional data during an operational time and the great challenge is to treat them correctly, to extract useful and meaningful information and remove noises, incomplete data, and outliers (Tang et al., 2001). If the diagnostic data is not treated in a right way, it could be a useless and expensive feature.

Onboard and stationary diagnostic systems

Two main topologies of diagnostics systems are onboard and stationary (wayside). An onboard system is mounted inside a vehicle while a wayside system is a stationary system positioned as the addition to the railway infrastructure. Onboard systems (Zang et al., 2019) are installed in vehicles and used for continuous monitoring of vehicle in service conditions and providing status information on the current operational behaviour of a train and its components. They perform acquisition of diagnostic and environmental data, elaboration of information according to the predefined set of rules, and fault detection in real-time. All measured data is checked and compared to the predefined threshold values (based on specific operating and environmental conditions and built-in specifications) and, if the threshold value is exceeded, on-board diagnostic warns of malfunctions and the need for performing maintenance activities. Other functionalities that a modern onboard diagnostic system can provide, as it is presented in (Sunder et al., 2001) and (Bannasch, 2005), are auto diagnosis, remote system reconfiguration, system management, intelligent diagnosis, decision making, etc.

Wayside diagnostic systems (Zang et al., 2019)can be used for periodical or constant monitoring of railway vehicles, testing their defectiveness and assemblies' inspection. The stationary diagnostic systems are usually installed in a workshop or along the railway (EN14363, 2005). If diagnostic systems are installed in the workshop, the conditions of assemblies, devices, and units are determined when the vehicle is excluded from traffic, usually during the technical inspection. Two common types of wayside systems are reactive and predictive systems. Reactive only detect present faults on the vehicle, while the predictive systems measure and record vehicle performances and responses of individual components. The collected information is then used to analyze equipment conditions and to predict possible faults in the future. Also, wayside diagnostic systems can be oriented to non-contact measurement technologies, as acoustic detection and video supervision of vehicles.

Diagnostic systems based on artificial intelligence

Traditional diagnostic systems rely on failure mode analysis and looking up for adequate response options within already built-in fault response trees. They can easily result in an unknown-fault message during the diagnostic process, leaving the operator to manually examine the problem, identify causes, and select the required action. On the other side, modern vehicles are upgraded with different sensors, control logics, and actuators with purpose to improve safety and quality of ride. All these novelties nowadays require a more precise diagnostic approaches, with more effective fault diagnostic and better output descriptions of occurred malfunctions. In the recent years, artificial intelligent approaches demonstrated great potential for solving these demanding tasks. With the purpose of developing fully automated diagnostic systems, various intelligent techniques were utilized: neural networks, fuzzy logic, model-based reasoning, computer vision, knowledge-based systems, etc. By applying these approaches, modern diagnostic systems became more reliable, effective, and have notable cost reductions compared to conventional diagnostics. One such example of an intelligent diagnostic technology is presented in (chromasens, online), where a new stationary 3D system is developed for damage detection and visual inspection of the undercarriage of trains.

Artificial neural networks, as the most popular and exploited technique of machine learning, can be utilized for prognostic purposes and emulation of human experience in detecting faults and anomalies. In general, artificial networks are developed to discover and learn patterns within complex data. These patterns can then be easily associated with certain states of dynamical systems, which have significant exploitability inside modern vehicles and their diagnostic systems. For example, an interesting method for diagnosing sensor faults is proposed in (Zhang et al., 2016), based on the application of wavelet packet neural network for identifying fault signal features. In (Yurii et al., 2017), it is shown that a deep learning methodology could be useful in the domain of diagnostic even in cases when otherwise insufficient amounts of data are available. Also, a self-diagnostic system could be also developed by exploiting artificial neural networks, as demonstrated in (Liu et al., 2017), where parallel processing and fast response of diagnostic information from different assembly units and systems were achieved. Deep networks could be also useful for calculation of events probabilities in situations when a system component has a specific curve of failure probability, in which case a neural network reasoning can provide quality guidance on future failure occurrence. One type of probabilistic model is proposed in the form of a genetic algorithms-optimized neural network in (Chen et al., 2017), and used for decision-making in the diagnostic process with an emphasize on the monitoring subsystem for collision avoidance.

Another popular artificial intelligence method for implementing inside diagnostic systems is the fuzzy logic, that enables the application of imprecise terms, much closer to the human reasoning, to the technical systems. Instead of traditional on/off operating regimes, fuzzy logic provides degrees of degradation of a component or a process, and better flexibility in evaluating dynamical systems. Common feature for all expert systems based on fuzzy logic is utilizing experience of human experts. That experience is represented in the form of the diagnostic rules, while the input data are the symptoms of potential faults in the system. The rules are proposed in accordance with multiple examples of the specific problem and can be characterized in the "if-then" form. One example of successful application of fuzzy logic for vehicle diagnostic purposes is presented in (Gonzales et al., 2009). Improved diagnosis and a fault detection are provided by combining auto associative neural networks and adaptive neuro-fuzzy inference systems. The proposal in (Gonzales et al., 2009) also showed notable performances in tackling the problem of false alarms. Additionally, in (Murphey et al., 1998), the fuzzy architecture was designed based on multiple local diagnostic agents, each responsible for diagnosing one specific faulty behaviour. Beside local agents, this system possess the central agent with the complete knowledge of the system as a whole and the behaviour of individual local diagnostic agents.

Diagnostics of monitoring systems in vehicles

The monitoring systems to be developed under the SMART2 project, are currently either nonexistent or in the initial research phases in the worldwide railway sector. Having in mind that the idea behind the SMART2 project is to use various video monitoring systems for detection of obstacles in rail transport, all types of cameras that will be used should also be part of diagnostic systems. The main faults that should be diagnosed are: the camera is not operating, communication with the camera is lost, or poor quality of a received picture. The main reason for camera malfunctioning is that they are installed in an open environment, causing their volatility to environmental conditions (rain, snow, storms, dirt, extreme circumstances). Quality of received image is generally monitored by constant checking of signal-to-noise-ratio (SNR). Industry standards require SNR thresholds of 10:1 for acceptable image quality and 40:1 for excellent quality. Everything below 10:1 could be diagnosed as poor image quality, and maintenance of problematic cameras should be performed. Finally, if the camera is not fixed and can rotate around one or more axes, the status of related motors should also be monitored.

As a role model for designing adequate diagnostic systems in trains, we can use automotive industry where similar systems have become an indispensable piece of equipment. In the last two decades, manufacturers of modern cars based their production on introducing cameras and sensor equipment to improve steering quality and safety performances on the road. Diagnostic systems for automobile video surveillance can be configured to receive information from various sensors and control subsystems that monitor road conditions, surrounding objects, identify safety threats, and propose measures to deal with unpredictable situations.

Modern automobiles are equipped with electrical instrumentation panels that contain various indicators providing valuable diagnostic information generated at the electronic control unit. Indicator lights provide information of something is being turned on/off, or to notify a driver about occurred malfunction of the system. The most of nowadays automotive manufacturers integrate standard on-line diagnostic packages into their new models that include performance and functional check-ups of rear-view cameras, forward collision components (cameras or sensors), a lane keep assist and lane departure warning systems, adaptive cruise control (automatic maintenance of a safe following distance) and road departure mitigation features. If a component is in a full working capacity (without detected faults), the diagnostic system will not provide any information for a driver within a vehicle's dashboard. If a temporary problem occurs (dirty camera surface, unusual vibrations which cause blurry images, heavy rain and all other occasions which result in the impossibility of proper surveillance), it will be diagnosed, and the information sent to the driver in the form of a yellow gauge or text information. Finally, if the occurred fault requires a physical servicing (the camera not working, critical electric or mechanic malfunction), a red gauge/text information will be sent to the driver. In the cases when a detected fault doesn't represent any danger for reliable manual control of a vehicle, the diagnostic system would allow a driver to continue his ride without any restriction, but with non-stop visual/audio warning messages until the problems are solved. On the other hand, if a critical message occurs, the diagnostic system will initiate slowing down and stopping the vehicle at a safe position on the road and prevent the car from further driving until the malfunction is completely resolved.

Besides the standard equipment, a few other camera features are proposed and successfully used by various manufacturers. For example, Honda developed a new “LaneWatch” blind spot system that alerts drivers to the presence of vehicles to rear in adjacent lanes. Today, Kia and a few other manufacturers provided rear cross-traffic alert and lane change assist systems to their vehicles. Kia models also possess surround-view cameras that can be used mostly for parking purposes. New Volkswagen Passat includes pedestrian detection and parallel park systems. Pedestrian detection uses cameras and intelligent recognition techniques to detect pedestrians and issue a visual or audible warning or, if necessary, trigger automatic emergency braking. Subaru Legacy includes a 180-degree front vision camera for all-around monitoring environment. As additional features, Toyota Corolla Hybrid consists of a cyclist detection mechanism, traffic sign recognition, and road edge detection systems. Each of these surveillance systems is associated with a proper diagnostic system whose purpose is to provide on-board information to a driver.

One more valuable diagnostic feature of some novel car models is the existence of remote telematics systems, as are General Motors OnStar, Hyundai Bluelink, BMW Assist, Kia UVO, Mercedes-Benz’s mBrace, Toyota Safety Connect, etc. These systems provide online monitoring of the vehicle parameters and send only critical and urgent diagnosed information to a dispatch center. The center follows the location of the vehicle and can provide emergency aid on request. For example, if airbags deploy, or some main components of the system stop working, the diagnosed signal is sent to the dispatch center, which summons emergency service if a driver is not responding to a call. Another design possibility is the realization of a mobile application for diagnostic systems (Kim et al., 2015). Such an application can provide an administrator to confirm diagnostic information in real-time. Also, this info is shared with drivers who can always check the operational statuses using smartphones and can respond promptly to any occurred malfunction.

Finally, as a new hot thing in the automotive industry, autonomous cars are specific because they cannot be dependent on offline diagnostics. They must quickly identify the root causes of anomalous situations and determine if the anomaly represents an emergent but safe situation for a further drive, or represents a failure that requires immediate termination of further driving activities. With the purpose of developing reliable autonomous vehicles, self-diagnosis systems are proposed (Jeong et al., 2018), where the diagnostic is provided by deep learning techniques for computation processes and the Internet of Things technology for collecting all the sensor data. The collected data is transferred and transformed into messages and in the formats suitable for destination protocols. In parallel, a training set is created using the data collected from vehicle sensors, and possible risks of the defective component on overall performances of the system are determined and explained to a human operator. Optimization of automated driving is significantly achieved with Tesla Model 3 that includes eight cameras providing 360-degree visibility within a radius of 250 meters and 12 ultrasonic sensors for completing the vision system. This setup provides the detection of soft and hard objects with accuracy two times larger than in earlier models. Tesla also included a radar system that improves the processing capabilities of recorded pictures, in the situations of fog, heavy rain, dust, etc. Further, for detecting obstacles within a radius of fewer than 10 meters around the car, sonars and ultrasound technology is used.

Diagnostics of unmanned flying devices

The primary goal of the SMART2 project is to innovate the OD&TID system utilizing three sub-systems: on-board, trackside, and airborne. During project realization, specific attention has to be paid to the design and development of diagnostic methods for each of them. The previous applications and experiences in usage of unmanned flying devices highlighted the problems concerning their both mechanical and electrical components. Drones are highly non-linear systems for which multiple kinds of faults can have undesirable, and sometimes fatal consequences. One of the most commonly diagnosed problems includes the functional state of propellers that represent the propulsion source of drones. Any propeller defect could cause falling of the flying object and its destruction. The defect of spur gears is one of the examples of diagnosed propeller problems. Further, imperfections and imbalance of propeller blades can also cause operational errors of a system. All these and many other mechanical faults result in a variety of undesirable vibrations.

Further attention should be paid to the diagnosis of sensor faults, inertial measurement unit, and a global positioning system (GPS). A drone's control surface should be evaluated using gyroscope and accelerometer measurements, diagnosing the loss of effectiveness. In general, all sensors can be monitored from the perspective of working/non-working conditions. In the case of a nonresponsive sensor, a high-alert fault should be diagnosed. If the sensor is in the operational state, its generated data should be evaluated against optimal data. If a discrepancy between two data sets exists and if that difference is not acceptable, high-alert faults should be diagnosed. If the operational data is not optimal, but still within an acceptable level, maintenance alert should be activated, and the system should be checked during regular maintenance. Finally, drones are autonomous flying objects supplied with energy from built-in batteries. The requirements for charging these batteries should continuously be monitored, and if the charging info is missing or is unreliable, the appropriate fault should be raised. Also, the status and reliability of power supply can be a major deficiency that should always be diagnosed.