COLLISION PREVENTION SYSTEMS

Zone Functionality and Sensor Fusion Report

(I.E., WORK PACKAGE 9)

INDUSTRY ALIGNMENT ON TMM REGULATIONS; SPECIAL PROJECT OF THE MINERALS COUNCIL SOUTH AFRICA

REV 3

Sensor Fusion and Zone Functionality Report Acceptance			
Name	**Signature**	**Organisation**	**Date**
Kobus Blomerus	[signature]	**SECDI**	**30 May 2022**
Stanford Malatji	[signature]	**Minerals Council**	23 June 2022

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1. Purpose of this document

This document reports on the zone functionality requirements and the need for sensor fusion to meet the requirements.

It is not the purpose of this document to detail the technical specification of each sensor or the way the sensors interact with one another to accurately detect and track objects. This document details the most common sensor technologies available today, logs high-level methodologies on sensor fusion and makes recommendations thereon.

The main purpose of this document is therefore to create an understanding of the importance of sensor fusion and dynamic zoning in achieving effective detection and tracking of TMMs and pedestrians in collision prevention systems.

2. Definitions and abbreviations

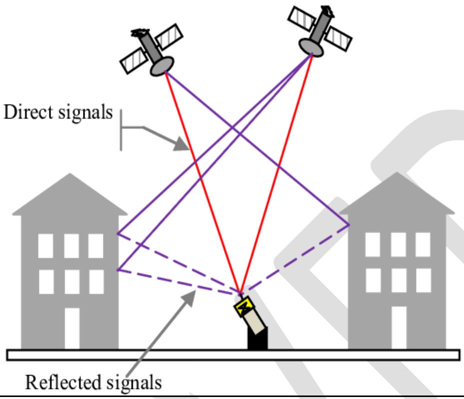
The following definitions and abbreviations will be used to create a common approach for all deliverables: (Note: The rationale for some of the terms and definitions is set out in the CMS Technical Specification Guideline Review Report).

3rd Party	An entity appointed to execute work (testing, witnessing of testing and verifying portfolios of evidence) on behalf of SAMI. Note: The purpose of 3rd party execution is to establish independence and to eliminate duplication.
Accelerated Development	Development of CPS products in a coordinated and integrated way that will require less time (for the entire SAMI need), than the previous individual mine and supplier / OEM driven CPS product development approach.
Accuracy	The degree to which the result of a measurement, calculation, or estimate conforms to the correct value, i.e. the preciseness of the measurement.
C102-F9R	C102-F9R application board Easy evaluation of ZED-F9R with sensor fusion. Application board for ZED-F9R
CMS	Collision Management System: The overall combination of preventative controls, mitigation, recovery and supporting controls, implemented by a mine site to prevent TMM collisions.
Controlled area	Area that is dedicated to testing with no interference from vehicular or pedestrian traffic. Example: Gerotek Test Facilities, section on mine isolated from any mining activity, or demarcated area at a TMM OEM assembly plant.
CPS	Collision Prevention System: A Product System that comprises the functionality and characteristics that comply with the RSA TMM collision prevention regulations. (TMM Regulations 8.10.1 and 8.10.2 and user requirements.)

CWAS/(CxD)	Collision Warning and Avoidance System device (CxD): Device with sensors providing collision warning and avoidance functions, to detect objects in the vicinity of the machine, assess the collision risk level, effectively warn the operator of the presence of object(s) and/or provide signals to the machine control system, to initiate the appropriate interventional collision avoidance action on the machine, to prevent the collision. Note to entry: Proximity Detection System (PDS) is a colloquial industry term for a physical device, providing a warning or collision avoidance functionality.
CxD	Collision warning/detection/management Device.
CxDC	CxD Controller: A sub-system of the CxD, that is typically the computer that contains the decision-making logic.
CxDI	CxD interface: A integration function between the CxD and the Machine Controller.
CxDLK	CxD Log Keeping: The function that receives, and stores CxD data.
D&T	Detect and Track: A functional group of a CxD enabling detection and tracking of TMMs and pedestrians inside the detection area of a surface TMM and an underground TMM respectively.
DAQ	Real time computer with data acquisition and control capabilities. Has ISO21815 interface. Example: DSpace MABX II.
Data scientist	Experienced person in the field of data processing and statistics. This person will analyse data collected during TRL9 pilot site roll-out testing.
Detection	Detection is sensing that an object has entered the detection area.
DMRE	Department of Mineral Resources and Energy.
Driver or operator reaction time (also known as perception response time)	The time that elapses from the instant that the driver recognises the existence of a hazard in the road, to the instant that the driver takes appropriate action, for instance, applying the brakes. The response time can be broken down into four separate components: detection, identification, decision and response. When a person responds to something s/he hears, sees, or feels, the total reaction time can be broken down into a sequence of components namely: • Mental processing time (sensation, perception / recognition, situational awareness, response selection and programming). • Movement time, and • Driver response time. Driver reaction time is also affected by several issues such as visibility, operator state of mind (fatigue), and direction or position of perceived danger.
EAV	Exposure Action Value
ELV	Exposure Limit Value
EM engineer	Qualified person (BEng, BTech) in the EMC environment, with extensive experience in EMI/EMC testing.
EMC	Electromagnetic Compatibility
EMESRT	Earth Moving Equipment Safety Round Table
EMI	Electromagnetic Interference

Employee	Employee means any person who is employed or working at a mine.
EW (Surface)	Effective Warning: For surface TMMs: The expected outcome of the operator action is that the potential collision is prevented, therefore an effective warning must inform the operators of both TMMs what the appropriate action(s) are, to prevent the potential collision.
EW (Underground)	Effective Warning: For Underground TMMs: The expected outcome of the operator and pedestrian action is that the potential collision is prevented. Therefore, an effective warning must inform the operators of TMMs what the appropriate action(s) are to prevent the potential collision and must alert the pedestrian to potential collisions, or interactions with TMMs in the vicinity.
F	Function: Indicates a function of the CPS or functional group.
F&TPR	Functional and Technical Performance Requirements
FMECA	Failure Mode Effect and Criticality Analysis
FTS	Fail to Safe: The functionality that will bring a TMM to a controlled stop
Functional Specification	Specifications that define the function, duty, or role of the product/system. Functional specifications define the task or desired result, by focusing on what is to be achieved, rather than how it is to be done.
G	General: Indicates a general requirement that is applicable to the entire CPS and all of it elements, modules, and components.
Homologation	Homologation means to sanction or "allow." Homologation refers to the process taken to certify that a TMM fitted with a CPS is manufactured, certified, and tested to meet the standards specified for critical safety related devices fitted to TMMs.
HP GNSS	High Precision Global Navigation Satellite System, capable of measuring position, with an absolute accuracy of 0.1m and velocity to within 0.2km/h with an update rate of 100Hz. Example Racelogic VBOX 3i.
ICASA	*Independent Communications Authority of South Africa*
ICMM	International Council on Mining and Metals.
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ID	Identifier.
Independent	Separate from the CPS product developer. Note: Independent does not imply an accredited 3rd party, although where required by local or international standards, it includes accredited 3rd parties.
Independent person	A person, typically a test-, software- or EM engineer, who is not affiliated with the CPS provider or TMM OEM, that can provide an unbiased assessment.
Integrated Testing Regime	A holistic method of testing, optimising existing testing facilities that are currently available irrespective of who owns them. This method ensures specific CPS tests are only done once (CxD and TMM CPS Product combinations) and verification is done as early as possible in the development process.

Interface	A boundary across which two independent systems meet and act on, or communicate with each other. Four highly relevant examples: 1. CxD-machine interface – The interface between a Collision Warning and Avoidance System Device (CxD) and the machine. This interface is described in ISO/DTS21815-2. 2. The user interface – Also sometimes referred to as the Graphic User Interface (GUI) when an information display is used. This is the interface between the user (TMM operator or pedestrian) and the CxD or pedestrian warning system. 3. V2X interface – the interface between different CxD devices. V2X is a catch-all term for vehicle-to-everything. It may refer to vehicle-to-vehicle (V-V), vehicle-to-pedestrian (V-P), or vehicle-to-infrastructure (V-E). 4. CxD-peripheral interface – This is an interface between the CxD and other peripheral systems that may be present on the TMM. Examples include a fleet management system, machine condition monitoring system, or fatigue management system. Note: An interface implies that two separate parties (independent systems), are interacting with each other, which may present interoperability and/or EMI and EMC challenges.
LO	Local Object: Denotes the TMM that is detecting other TMMs (S) or pedestrians (P)
Localization	Localization is measuring the position of the object within the detection area; it provides the local object with a map of the remote objects within the environment.
Loss of control	The uncontrolled movement of a TMM due to operator, machine, or environmental reasons. Note: Section 8.10.3 of MHS Act. Loss of control may result in several scenarios: • Machine failure – park brake, or service brake, or tyre blowout. • Operator disabled – fatigue, medical condition, inattention, distraction, or non-compliance with TMP rules (e.g., over speeding on decline, or overloading)
MBS	Machine Braking System: The physical components that makes an unintelligent TMM intelligent and enables the CPS auto slow-down and stop functionality.
MC	Machine Controller.
MCI	Machine Control Interface: The interface between the Machine Controller and the CXD interface.
MHS Act	Mine Health and Safety Act No. 29 of 1996 and Regulations.
MHSC	Mine Health and Safety Council.
Minerals Council	Minerals Council South Africa.
MLK	Machine Log Keeping: The function that receives, and stores TMM CPS data.
MOSH	Mining Industry Occupational Safety and Health.
MRAC	Mining Regulations Advisory Committee.

MRL	Manufacturing Readiness Level. A manufacturing maturity level within a manufacturing readiness framework.
MS	Machine Sensing: Sensing functionality on a TMM that enable a fully functional CPS.
Multipath	Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths, typically some direct signals, but also some reflected signals. 
OWS	Operator Warning System: The system that provides the effective warning and other warnings to the operator of a TMM.
PDS	Proximity Detection System – see CxD.
Pedestrian	A person lying, sitting, or walking rather than travelling in a vehicle.
Project	Industry Alignment on TMM Collision Management Systems Project: CAS READINESS PHASE.
PWS	Pedestrian warning System: The system that provides the effective warning to pedestrians.
Quality Assurance	Verifying a process, product, or service; usually conducted by an experienced person in the specific field.
Reasonably practicable measure	Reasonably practicable means practicable with regards to: (a) The severity and scope of the hazard, or risk concerned. (b) The state of knowledge reasonably available, concerning the hazard or risk, and of any means of removing or mitigating the hazard or risk. © The availability and suitability of means to remove or mitigate that hazard or risk, and (d) The costs and the benefits of removing or mitigating that hazard or risk.
Reliability (sensor)	Sensor reliability refers to the consistency of a measure. Achieving the same result by using the same methods under the same circumstances, is considered a reliable measurement.
RO	Remote Object: Denotes TMM(s) (S) or pedestrian(s) (U) being detected by the LO.
Robustness (sensor)	Sensor robustness is the ability of the sensing device (sensor), to remain functional in the presence of normal operating conditions of TMMs on a mine, such as electromagnetic interference, mechanical vibration, dust, adverse weather conditions, etc.
S	Surface: Indicating that a specific aspect is applicable to surface TMMs/operations.

Safe Park	A way that a TMM is parked, namely: Machine static, engine switched of and park brake applied.
Safe speed	The speed that will ensure the controlled stopping of a TMM without any immediate negative impact on the operator or machine. Note: This is a conditional variable value, depending on multiple input variables.
SAMI	South African Mining Industry.
Sensor fusion	Sensor fusion is the process of combining sensory data, or data derived from disparate sources, such that the resulting information has less uncertainty than when the sources were to be used individually.
Significant risk (of collision)	The reasonable possibility of a TMM collision, given all the controls that a mine has put in place to prevent a TMM collision.
Slow down	ISO/TS 21815-2: 2021 defines slow down as: "The SLOW-DOWN action is sent by the CxD to reduce the speed of the machine in a controlled / conventional manner, as defined by the machine control system. The intent of this command is to slow down the machine when the CxD logic determines that a collision / interaction can be avoided by reducing speed".
Software engineer	Qualified person in the communications/computer environment, with extensive experience in ISO 21815 – 2:2021 programming and testing.
SP GNSS with self-recorder	Standard Precision Global Navigation Satellite System: A system that is capable of measuring position with an accuracy of 1.5m, with an update rate of 10Hz. Can also store its own data. Example: UBlox C102-F9R.
Stage gate	A step in the testing regime / process where the CPS product system is tested against acceptance criteria, the failure of which would limit the CPS product system from moving to the next step in the regime / process.
Stop	ISO/TS 21815-2: 2021 provides for two definitions, an emergency stop, and a controlled stop, both of which are a 'Stop'. The definitions are: 1. "The EMERGENCY-STOP action is sent by CxD to instruct the machine to implement the emergency stop sequence defined by the machine control system. The intent of this command is to stop the machine motion as rapidly as possible, to reduce the consequence level, if the CxD logic determines that a collision is imminent. The equivalent of an emergency stop is the operator slamming on the brakes in an emergency." 2. "The CONTROLLED-STOP action is sent by CxD to instruct the machine to implement the controlled stop sequence, defined by the machine control system." The intent of this command is to stop the machine motion in a controlled / conventional manner, when the CxD logic determines that a collision / interaction can be avoided by slowing down and stopping. The equivalent of a controlled stop is slowing down and stopping when approaching a red traffic light.

System	A combination of interacting elements organized to achieve one or more stated purposes (ISO/IEC/IEEE 2015).
T	Technical: Indicates a technical requirement of the CPS or functional group.
Technical specification	Specifications that define the technical and physical characteristics and/or measurements of a product, such as physical aspects (e.g. dimensions, colour, and surface finish), design details, material properties, energy requirements, processes, maintenance requirements and operational requirements.
Technician	Competent person with testing experience in the mining / vehicle environment, e.g. testing technician, TMM OEM technician, CxD technician, auto electrician, etc.
Test engineer	Experienced person in the engineering/mining environment with extensive experience in CPS testing.
This document	CPS Zone Functionality and Sensor Fusion Report.
TMLP	Traffic Management Leading Practice: The MOSH Traffic Management Leading Practice for Open Cast/Cut mines in South Africa.
TMM	Trackless Mobile Machine. (Machine, vehicle, etc.)
TMM CPS	The functional group comprising all TMM CPS related functions.
TMM CPS Product	The product that will make a non-intelligent TMM intelligent and CxD ready.
TMM OEM	Original Equipment Manufacturer of TMMs. Original Equipment Manufacturer of a TMM may be the organisation which originally supplied, or last rebuilt, or modified the TMM, or the supplier per section 21 of the Mine Health and Safety Act, 1996 (Act No. 29 of 1996).
TMP	Traffic Management Plan: A document that defines the traffic management system that a mine employs to ensure the safe movement of TMMs and pedestrians on the mine.
Tracking	Tracking is the monitoring of the progress of the objects in the detection area over time.
TRL	Technology Readiness Level: A technology maturity framework for measuring and monitoring technology maturity in 9 increasing levels from TRL 1 to TRL 9.
U	Underground: Indicating that a specific aspect is applicable to underground TMMs/operations.
UTC	Coordinated Universal Time.
V2X	Vehicle to anything.
Vicinity (Surface TMMs)	The distance/time of two TMMs from the point of a potential collision, such that, if the operators of both machines are instructed to take action to prevent a potential collision, and one or both does not act, then the CPS will be able to prevent the potential collision. Note: Vicinity is a conditional, variable value, depending on multiple input variables. It is smaller than any value that is within the range of normal operation.

Vicinity (Underground TMM and pedestrians)	The distance/time of a TMM from a pedestrian, such that, if the operator of the TMM and the pedestrian do not take action to prevent a potential collision, an emergency slow down and stopping of the TMM can be successfully executed, to prevent a potential collision between the TMM and the pedestrian. Note: Vicinity is a conditional, variable value, depending on multiple input variables. It is smaller than any value that is within the range of normal operation.
V-E	Vehicle to environment.
V-P	Vehicle to pedestrian.
V-V	Vehicle to vehicle.
Walking speed	In the absence of significant external factors, the average human's walking speed is 1.4meters per second. This is included to help define the crawl speed of vehicles.
WP 9	Work Package 9: Testing protocols (including legacy equipment). One of the work packages of the Industry Alignment on TMM Collision Management Systems Project: CAS READINESS PHASE.

3. Executive Summary

Collision Prevention Systems are safety critical systems that must prevent TMM collisions in mining operations. As have been reported previously, a CPS is an extremely complex system of which some of its sub-systems are still in development.

If SAMI stakeholders and executives have a perception that the development of a CPS is comparable to the parking sensors fitted to cars, then:

- a detailed study of this report will reveal the extent of complexity required to develop functional and reliable CPS products, as well as
- the extent to which the SAMI is challenged to introduce such technology as a regulatory requirement.

The MHSC MRAC TMM Task Team reported that zone functionality and the related requirement of sensor fusion is one aspect of CPS technology that has not matured sufficiently, that the suspended TMM regulations can be uplifted soon. Hopefully all CxD providers would have specifically done research and development on sensors and zone functionality since then.

Zone functionality has to do with the ability of a CPS to detect other TMMs and pedestrians for surface and underground TMMs respectively. In its simplest form zone functionality for CPS must:

- accurately detect another TMM(s) or pedestrian(s) for surface and underground respectively,
- not identify an already detected TMM or a pedestrian as second or even third TMM or pedestrian, but be able to continuously detect a specific TMM or pedestrian, respectively,
- not lose sight of the TMM or pedestrian at any time while in the detection zone.

The functionality must be able to detect multiple TMMs and pedestrians, and still function correctly. In congested mining processes multiple TMMs and pedestrians are present as part of normal operations.

Zone functionality must also accurately determine the direction in which another TMM(s) or pedestrian(s) is moving, and how fast each is moving.

Considering that a typical mining environment where TMMs are subjected to harsh environments, ranging from

- poor road conditions,
- dust,
- non-direct visibility due to blind rises, sharp curves, vegetation and other infrastructure (to mention a few examples),
- temperatures ranging from -20 to + 40 degrees Celsius,

one starts to develop a picture of the challenges that detection devices (sensors) must be able to deal with these conditions for extended periods of time while ensuring safe operation. Comparing that with cars' operating conditions, it becomes apparent that any consideration of a plug and play CPS solution using standard automobile solutions is far removed from realty.

Zone functionality further relates to determining how fast TMMs and pedestrians are moving to determine the likelihood of a potential collision. The challenge of an effective CPS is not to auto slowdown and stop TMMs, but to allow normal operation to continue unhindered and only have slowdown and stop interventions when a potential collision is imminent. It is with good reason why international TMM OEMs have set themselves an ambitious goal of having their latest (and future) models of TMMs fitted with technology similar to CPS only from 2025.

The zone functionality must also provide for different distances that TMMs are apart after a slowdown and stop intervention has been executed (stop gap). A fixed distance will imply that the CPS must provide for the worst-case scenario on the mine and that will mean that TMMs being loaded on a surface mine will not be able to come close enough to be loaded or the CPS will have to be switched off. Providing a switch off functionality is defeating the very objective of a CPS in the first place. This requires further intelligence that the CxD must provide.

Zone functionality must not only provide for different stop gaps based on specific mining processes; it must also provide for dynamic vicinity zones. The vicinity zone is the distance around a TMM where an effective warning must be given to the TMM Operators or the operator and pedestrian, respectively, to take action to prevent a potential collision. Since the CPS must be able to prevent a potential collision if the operators or the pedestrian and the operator respectively do not take the correct action, it follows that the vicinity zone depends on many variables such as speed of TMMs (surface), loaded or unloaded state, deceleration rates of the TMM and others.

The description above is a reasonable, practical description of zone functionality for a CPS product. The complexity is obvious, as is the reality that there isn't one single type of detection device that can be used to meet all the zone functionality requirements. The use of multiple sensors of a specific type as well as multiple sensor types is therefore a necessary reality. The report goes into much detail to define how different sensor types work, what their advantages and disadvantages are, their typical specifications as well as some detail of their application. This detail is not only key in creating the correct understanding of the challenge, but also serves as reference information that can be made available to CxD developers, since it is a concise discussion of the essential sensing technologies that CxD developers must choose for use in their products.

With the functional requirements that zones have to comply with, clearly an absolute necessity for functional CPS products, the direct consequence is the integration and correct processing of the data available from the different sensors and different sensing technologies. The process known as sensor fusion is discussed at length and in fact shares valuable knowledge on the algorithm development although it is not strictly within the scope of work. This goes a long way to assist CxD developers to expedite their CxD development.

The report shares the importance of sensor robustness and specific sensor testing criteria to be able to demonstrate CPS functionality in the mining environment.

The report also highlights the importance of EMC and the need for V2X communication. It provides further justification for V2X standardisation, frequency spectrum management and EMC testing.

It can be concluded that:

- The required functionality for effective CPS products is complex.
- Zone accuracy, reliability and robustness are key requirements for effective CxD products.
- Environmental factors, such as line-of-sight, will influence different sensors differently. Using different sensors collaboratively will provide for a robust detection and tracking functionality.
- Appropriate sensor type selection is a key success factor for effective CxD products.
- The sensor fusion layer is more important to test than each individual sensor.
- Sensors must be able to withstand typical environmental challenges, such as high temperature, solar radiation, sand and dust, vibration and shock.
- Dynamic Vicinity Zones is a prerequisite for effective CPS as is the correct sensor fusion strategy and algorithms.
- EMC testing and frequency spectrum management must be expedited.
- V2X communication standardisation for CPS must be addressed
- Aspects that must be considered are amongst others; Intrinsic safety, moisture content, humidity, altitude, atmospheric pressure etc.

Supported by the findings in this report, CPS zone functionality requirements have been incorporated into the CPS F&TPR specification. It is however recommended that:

- This report be thoroughly reviewed by mining employees that are assigned legal (legislation compliance) responsibility for the safe functioning of TMMs, as well as those assigned the responsibility to make CPS product selection decisions.
- Whilst sensor specification is important purchasers should refrain from using phrases such as 'MIL-STD-810G' compliant, as this will unnecessarily increase both cost and complexity of CPS offerings since MIL-STD-810G is a very comprehensive standard of which only selected aspects is relevant. The relevant aspects are specified in the CPS F&TPR specification.

4. Context of this document

This report is a deliverable for Work package 9: Testing Protocols, of the Industry Alignment on TMM Collision Management Systems Special Project of The Minerals Council South Africa: CAS TECHNOLOGY READINESS PHASE work.

5. Background

TMM regulations for the SAMI have been promulgated in 2015. Some of the clauses related to diesel powered TMMs were suspended as a result of non-availability of technology to provide the functionality that is required to auto slowdown and stop these TMMs.

A CPS is a Product System that is complex, comprising of multiple elements (sub systems). Some of the elements comprise of components that are still in a technology development phase.

Some of the relevant challenges that the SAMI faces with regards the TMM regulations are:

- The Regulations dictate specific and implied functional requirements of a CPS product.
- As a safety system that ultimately takes away the control of a TMM from an operator, specific functional and system requirements are required that must be agreed upon between stakeholders and must be ensured to minimise the potential disruption of the introduction of such technology to an entire industry.

CPS products that are not effective in their functioning will not only pose safety risk to operators and pedestrians but also business risk to mines if false slow down and stop interventions disrupt production to a point where the systems must be switched of. Zone functionality challenges and the need for sensor fusion was highlighted by the MHSC MRAC TMM task team report. This report is the result of the Minerals Council initiating a special project to align Industry on TMM Regulations that amongst other seek to address that challenge.

6. Zone Functionality

In terms of zones and the functionality that is required in order to ensure a fully functional CPS product there are three zones:

1. The **first zone** is the detection area; this is the zone around each TMM wherein the Detection System must identify another TMM (surface) or pedestrian (underground) and track the movement of every TMM or pedestrian, in order to determine the risk/likelihood of a potential collision. This functionality is very important as it enables the CxD to, not detect and warn unnecessarily, and also not to wait too long before warning. The detection area is typically a static area around the TMM and is mainly influenced by the sensors' range. The size and shape of the detection range may change if line-of-sight is lost (due to factors such as the presence of underground mining pillars, buildings, berms, vegetation, etc.) or if adverse weather conditions are present (fog, rain, etc.).
2. The **second zone** is the effective warning zone, also defined as the vicinity in the TMM regulations. The vicinity is the boundary around a TMM that is big enough to allow the CxD to give the operators (surface) and the operator and pedestrian(s) (underground) an effective warning to slow down the TMM(s) and stop, before the potential collision occurs. The vicinity boundary will be dynamic – in other words, it will change for each interaction scenario. Factors such as TMM speed, direction of travel, priority and brake performance will influence the vicinity boundary. Different vicinity zones will be present for different objects within the detection area.
3. The **third zone** is the auto slowdown and stop zone. This zone is a time delay of 2,5 seconds from the time the effective warning has been given (based on the URS). If, after 2,5 seconds from the time the effective warning has been given, the

operators (surface) or operator or pedestrian (underground) have not taken the appropriate corrective action, then the CxD Controller instruct the TMM Machine Controller to execute one of a number of potential intervention strategies. (Note: Auto slowdown is only needed if a TMM is moving at a speed that is above the safe speed for that TMM type and model.)

Zone functionality is therefore of critical importance for the correct functioning of a CPS product. There are two overarching requirements for zone functionality:

1. **Reliable detection, localization and tracking** of any other TMM (surface) or pedestrian (underground) with which a TMM has the potential of colliding with. This requirement relates to performance of the sensing devices (sensors) used by the CxD developer. **Detection** is sensing that an object has entered the detection area. **Localization** is measuring the position of the object within the detection area; it provides the local object with a map of the remote objects within the environment. **Tracking** is the monitoring of the progress of the objects in the detection area over time, as long as it is within the detection area. These three steps are extremely important for the proper functioning of a CPS.
2. **Accurately quantifying the risk of a TMM colliding with detected TMMs or pedestrians** (as applicable) by considering several variables and then adjusting the vicinity boundary accordingly. This adjustment of the vicinity boundary based on changing parameters is what is referred to as dynamic zones.

These functions imply the following:

1. Objects the TMM are at risk of colliding with, must be detected (i.e. no missed detections), even if the TMM is operating in different ways (such as bucket raised, articulated, drilling, towing, etc.) and/or if there are challenging environmental conditions (such as rain, fog, dust, obstruction).
2. The accurate measurements of the objects' positions, speeds, headings, and orientations are needed.
3. The vicinity boundary must adapt to the prevailing road conditions (e.g. if on a decline or when the road is slippery, the vicinity boundary must extend to allow for longer stopping distances).
4. The vicinity boundary must be able to adapt to different TMM states (e.g. higher speeds extend the vicinity boundary).

Furthermore, the zone functionality must accommodate different separation/stop/following gaps in different mining processes, such required when loading, where TMMs are required to be working close to each other during normal operation (small gap) as opposed to when ensuring the following distance of two TMMs on a haul road i.e. dovetailing (large gap).

The separation/stop/following gap is the distance that TMMs are from each other after the execution of the auto slowdown and stop intervention (surface) or the distance that the TMM is from a pedestrian after the execution of an auto slow down and stop intervention (underground).

6.1 Sensor performance

The performance requirements of the sensing devices (sensors) used to detect and track objects in the detection area of the TMMs, has to be accurate, reliable and robust.

Accuracy is the degree to which the result of a measurement, calculation or estimate conforms to the correct value, i.e. the preciseness of the measurement.

Reliability refers to the consistency of a measure. Achieving the same result by using the same methods under the same circumstances, is considered a reliable measurement. This is essential for operators and pedestrians to trust the CPS technology and also for the mine management to allow the CPS technology to be used for collision prevention. **Robustness** is the ability of the sensing device (sensor) to remain functional in the presence of normal operating conditions of TMMs on a mine, such as electromagnetic interference, mechanical vibration, dust, adverse weather conditions, etc.

Improved accuracy, reliability and robustness (to some extent) can be achieved through sensor fusion.

6.2 Current Sensor Technologies

The state-of-the-art sensor technologies available in the CPS market were reviewed in January 2020. The revision revealed that six (6) sensing technologies were prevalent throughout the industry. Of the nineteen (19) different CxD suppliers included in the review, fifteen (15) offered Surface Mining Equipment (SME) CPS solutions and fifteen (15) offered Underground Mining (UG) CPS solutions. The review was limited to publicly available information from CxD suppliers' websites. The six sensing technologies, in descending order of prevalence are:

1. Radio Frequency (RF) Time-of-Flight (ToF) detection and ranging
2. Global Navigation Satellite Systems (GNSS)
3. Radar
4. Electromagnetic (EM) field generators
5. Cameras
6. Light Detection and Ranging (LiDAR)

Different sensing technologies will utilise different approaches to detect, localize and track TMMs and pedestrians, with benefits and drawbacks associated with each.

Some sensing technologies, such as GNSS positioning, may find localization and tracking easier, but will require each tracked object to be fitted with a GNSS antenna and a communication module (V2X) to broadcast its position. In such a case, localization and tracking are relatively easy.

Conversely, using LiDAR to perceive the immediate environment and then identifying remote objects, localizing and tracking them, does not require that all objects in the environment be fitted with any sensors or communication modules – representing an *independent* system (a.k.a. an active sensor). However, performing localization and tracking with a LiDAR, is technically more challenging compared to the GNSS sensor.

6.2.1 Radio Frequency (RF) Time-of-Flight (ToF)

RF ToF is the most prevalent technology used in the reviewed CPS products. There are several reasons for this, including the sensor's low power consumption, ability to work underground, and a typical unit's small size. When multiple sensors (or nodes) are connected, they form a Wireless Sensor Network (WSN) – a V2X network. The point-to-point distance between two nodes can then be estimated quite accurately (see Table 1) with several different techniques. [1] (Thorbjornsen, White, Brown, & Reeve, 2010).

RF ToF effectively requires that a wireless communication network (V2X) is established between objects (TMMs and pedestrians respectively) that are to be detected.

This means that each object, whether it is a TMM or pedestrian, must be tagged with its own radio transceiver. Timestamped messages are shared on the wireless network, allowing the distance between objects (TMMs and pedestrians respectively) to be estimated. The word estimated is used, because it is not a direct measurement.

Several assumptions regarding network latencies, transmission speeds, processing times and other unknowns need to be made, hence the distance between objects (TMMs and pedestrians respectively) is estimated rather than measured. Using one radio antenna for each object (TMMs and pedestrians respectively) will not be sufficient to provide positioning information, only ranging information. In order to acquire position information (such as distance and angle, or x-y coordinates) will require an array of antennas at known positions on each object (TMMs and pedestrians respectively).

Even if only RF ToF sensing is used for detection and tracking, the data provided by the different antennas need to be fused to provide useable data. In other words, if an array of four antennas is used (left front, left rear, right front, right rear), each individual sensor's measurement must be combined (fused) with the other three measurements.

Advantages

- Sub-metre accuracy at ranges exceeding 100m
- Multipath errors can be overcome
- Low power consumption
- Small size
- Cheap
- Localization and tracking are easily accomplished
- Surface and underground applications are possible
- Not subject to blind spots around the local object (TMMs)

Limitations

- Susceptible to EM interference
- Requires communication between devices (V2X and synchronisation)
- Each object (TMMs and pedestrians respectively), must be issued with a transceiver that must be maintained
- RF ToF is generally limited to line-of-sight to minimise multipath effects
- Requires multiple antennas on each vehicle

- Enclosures are not robust to limit interference with antenna (IP rating not very high).

Typical Sensor Specifications

TABLE 1: TYPICAL TIME-OF-FLIGHT (TOF) SENSOR SPECIFICATIONS: [2] (EXTRONICS LTD, 2019).

Parameter	Specification)
Range [m]	200 (outdoor) and 60 (indoor)
Horizontal Position Accuracy [m]	≤ 1
Operating Frequency	2.4 GHz (802.11b) and 125kHz
IP Rating	IP65

6.2.2 *Global Navigation Satellite Systems (GNSS)*

Satellite navigation is a method that employs a Global Navigation Satellite System (GNSS) to determine position and time anywhere on the planet.

The accuracy with which position and time can be determined, is directly related to the cost of the system that is chosen for a specific purpose. In early 2020there were three fully operational GNSS constellations, with an additional one that was scheduled for operation in 2020. [3] (Zogg, 2009). They are:

1. The Global Positioning System (GPS) operated by the United States
2. Russia's Global Navigation Satellite System (GLONASS)
3. China's BeiDou Navigations Satellite System (operational since June 2020)
4. European Union's Galileo System (scheduled for operation in 2020, unclear if fully operational yet)

GNSSs all use the same working principle to determine position [3] (Zogg, 2009):

- The satellites have a known position and transmit a regular time signal.
- The transmitted signal's travel time from satellite to receiver can be measured.
- Because the transmitted signals travel at the speed of light, the receiver position can be calculated using trilateration.

As the receiver and the satellite(s) clock(s) may not be exactly synchronised, a discrepancy may arise leading to position error. Adding a second (or more) transmitter(s), or satellites, with known positions, the positional accuracy can be improved even though the clocks may not be synchronised. The position of a receiver on earth has to be determined in three dimensions (3D), and because the receiver clock may not be synchronised with the satellites, four (4) satellites must be in view of the receiver to allow it to determine longitude, latitude, altitude and the time error.

The typical accuracy of a standard GNSS receiver is around 5-10m (Zogg, 2009). There are several sources of GNSS error, including: [3] (Zogg, 2009).

- Ephemeris data (i.e. exact satellite position, which may vary by 1m to 5m).
- Satellite clock error (as an example, a time error of 10ns will result in a distance error of approximately 3m).

- Ionosphere effects (retarding the transmission speed of broadcast signals due to ionisation of the atmosphere by the Sun).
- Troposphere effects (retarding the transmission speed of broadcast signals due to varying air density and humidity, i.e. clouds and rain.
- Multipath (reflections of the GNSS signal from buildings, trees, mountains, rock face, high wall, etc.).
- Loss of signal due to solar flares (signal drop-outs).

Fortunately, there are techniques for addressing GNSS errors. The most prevalent in the CPS technology, is differential GNSS. Differential GNSS makes use of one or more base stations. The base stations provide correction data, which needs to be performed in real-time; hence, data communication between the base station(s) and the receiver is required. Differential GNSS can improve the accuracy to approximately 1cm [3] (Zogg, 2009). Real-time kinematics (RTK) is one form of differential correction, that makes use of a base station to reduce GNSS errors.

Although the use of a differential base station will solve the GNSS errors, signal dropouts and loss of communication between the moving GNSS module and stationary base station, can still occur. As a GNSS constellation moves, slight jumps in position (as one satellite drops from the receiver's view or appears on the horizon) may happen. This can be overcome by including an Inertial Measurement Unit (IMU) and integrating its measurements with the GNSS data. An IMU typically consists of gyroscopes and accelerometers, that can be used to smooth GNSS data by fusing it with the IMU data (using a sensor fusion technique such as a Kalman filter). Such an advanced GNSS system then relies on the IMU during temporary (short duration) GNSS data deterioration. [4] (Racelogic, 2018). When an IMU is integrated with a GNSS, it is often referred to as an Inertial Navigation Satellite System (INSS).

Advantages

- Mature technology.
- Cheap sensors.
- Geo-fencing (mapping no-go or restricted areas) can be easily accomplished if differential GNSS is used.
- Not subject to blind spots.
- Localization and tracking techniques are well-established.

Limitations

- Requires infrastructure in the form of differential GNSS base stations
    - Loss of communication can occur with base station and RTK lock
    - Could jump between base stations
    - Base stations require maintenance
- Requires communication between base stations and receivers (V2X).
- Requires communication between different receivers to determine relative position and speed (for all objects to be detected) (V2X).
- Prone to drift if differential GNSS is not used.
- Heading error at low speeds if backwards difference technique is used to determine heading.

- Subject to errors that may be more pronounced in mining environments (multipath).
- Sensitive to errors due to atmospheric conditions (weather, solar flares, etc.).
- Only works on surface mines.
- Accuracy influenced by satellite constellation, which changes throughout the day/week.

Typical Sensor Specifications

Table 2 illustrates typical sensor specifications for both standard (u-blox, 2019) and high precision (or differential) (Racelogic, 2014) GNSS products. The navigation update rate indicates the number of messages the receiver can handle per second. Horizontal position accuracy is quoted in terms of 95% Circular Error Probability (CEP) – the radius of a circle in which 95% of the values occur.

TABLE 2: TYPICAL SENSOR SPECIFICATIONS FOR STANDARD GNSS [5] (U-BLOX, 2019) AND FOR DIFFERENTIAL GNSS [6] (RACELOGIC, 2014).

Parameter	**Specification**	
	Standard GNSS	**Differential GNSS**
Max Navigation Update Rate [Hz]	18	100
Horizontal Position Accuracy	Using GPS: 2.5m 95% CEP Using GLONASS: 4m 95% CEP	2cm 95% CEP
Velocity Accuracy [km/h]	0.2	0.1
Heading Accuracy [°]	0.3	0.1

6.2.3 Radar

Radar is an acronym for radio detection and ranging. Early radars were limited to target detection and range determination. Modern radars are sophisticated, transducer and computer systems that not only detect objects, but also tracks, identifies, images and classifies them while suppressing interference. Radars were originally used in the military industry to track aircraft, but are now used in multiple fields, including collision avoidance. [7] (Richards et al., 2010).

A radar transmits RF EM waves toward a region of interest (detection area) and receives and detects when the EM waves are reflected back from objects (TMMs and pedestrians respectively) in that region. A radar consists of: [7] (Richards et al., 2010).

a. a transmitter;
b. a receiver;
c. an antenna and
d. several amplifiers, signal processors and Analogue to Digital Converters (ADCs).

The range to the remote object (TMMs and pedestrians respectively) can be determined based on the time it takes the EM waves to propagate to the target and back, at the speed of light. The reflected EM waves result in a point cloud of information that needs to be dissected to provide useful information to the CxD.

A radar is different from the RF ToF technology, because radar is an active sensor – it generates and emits its own radio waves and does not require remote objects (TMMs and pedestrians respectively) to be tagged.

The received object (TMMs and pedestrians respectively) signals are detected in the presence of interference. The interference comes in four (4) different forms, according to [7] Richards et al. (2010):

1. Internal and external electronic noise.
2. Reflected EM waves from objects (other infrastructure or trees etc.) not of interest, called clutter.
3. Unintentional EM waves, known as EM interference (EMI).
4. Intentional jamming from electronic countermeasures.

Detection, localization, object classification (TMM and pedestrian identification respectively) and tracking, has to identify and track a target (TMMs and pedestrians respectively) in the presence of noise, clutter, interference, and jamming.

Achieving this reliably in the presence of noise, clutter and EMI is a **major concern** on a typical mining site. The EM waves emitted by a radar is in the range of 3MHz to 300GHz [7] (Richards et al., 2010), but the majority of automotive radars used in the collision avoidance industry, fall within the 75-110GHz band (known as the W-band). [8] (Smartmicro, 2019).

The EM waves transmitted and received by the radar interact with the radar's antenna, then the atmosphere and then the object (TMMs and pedestrians respectively). When the EM waves interact with matter, the interactions are governed by diffraction (antenna), attenuation and refraction (atmosphere), and reflection (object) [7] (Richards et al., 2010). Of main concern to CPS, is the EM waves' interaction with the atmosphere and the object (TMMs and pedestrians respectively).

Attenuation of the EM waves in the atmosphere is influenced by several factors, including: frequency, altitude and humidity (i.e. rain, fog, and clouds). Choosing the correct EM wave frequency lessens the effect of rain, fog and clouds, resulting in the well-known "all weather capability" of radars [7] (Richards et al., 2010). Refraction of the EM waves occurs due to a change in the optical density of the medium within which waves propagate. This happens when the EM waves are transmitted at an angle with the ground plane due to the change in atmospheric density. Refraction is not generally associated with automotive type (medium range) radars [7] (Richards et al., 2010).

Reflection of the EM waves depends on the surface roughness of the target (TMMs and pedestrians respectively). The majority of objects (TMMs and pedestrians respectively) of interest in radar technology, are seen as smooth, i.e. the surface roughness is smaller than the EM wavelength. On the other hand, the reflection from natural surfaces is often rough. This is especially true at higher frequency EM waves, such as those used for automotive radar [7] (Richards et al., 2010).

A final important consideration when discussing radar technology, is the Signal-to-Noise Ratio (SNR). All objects in the universe radiate EM waves at, collectively, all different frequencies. These EM waves are known as thermal noise and are omnipresent at the radar's receiving antenna. When the object (TMMs and pedestrians respectively) signal is present in the radar's receiver antenna, it will be accompanied by the thermal noise. To handle this, a threshold is defined below which no object (TMMs and pedestrians respectively) will be detected. Because the thermal noise is a random variable, it can spike at any given time and exceed the threshold, giving some probability to a false alarm [7] (Richards et al., 2010).

The following measurements are typically detected with a radar[7] (Richards et al., 2010):

- Azimuth angle
- Elevation angle
- Range
- Range rate (i.e. relative velocity)
- Polarisation.

The azimuth angle, elevation angle, and range, describe the objects' (TMMs and pedestrians respectively) position relative to the radar. The range rate is determined by the Doppler shift of the return signal and gives the rate at which the range changes (closing speed). The polarisation is related to all the signals received from the object (in real-life, an object will return multiple signals). Due to the scattering of the return signals, the polarisation contains some information of the geometry of the target. Polarisation is often used to discriminate between returns from real objects (TMMs and pedestrians respectively) and unwanted returns (such as from rain drops). [7] (Richards et al., 2010).

Advantages

- Remote objects (TMMs and pedestrians respectively) do not require tags.
- No need for a communication network between objects.
- Mature technology in the automotive sector.
- Surface and some underground application.

Limitations

- Development cost associated with sensor technology is high.
- Localization and tracking requirements are onerous.
- Subject to blind spots around machine.
- False positives may arise due to SNR.
- Subject to multipath in underground applications.
- Influence of dust and weather conditions for high frequency radar is difficult to quantify.
- Limited Field-of-View (FoV).
- Line-of-sight.
- Difficult to develop a physics-based sensor model for simulation-based testing.

Typical Sensor Specifications

Table 3 illustrates typical specifications of a long-range and medium-range automotive radar sensor. The automotive radar is configurable between the two modes, resulting in a narrow-beam configuration (long-range) and a wide-beam (medium-range) configuration (Smartmicro, 2019).

TABLE 3: TYPICAL AUTOMOTIVE RADAR SPECIFICATIONS [8] (SMARTMICRO, 2019).

Parameter		Specification	
		Long-Range Mode	Medium-Range Mode
Operating Frequency [GHz]		76	76
Range	Min/Max [m]	1.0/175	0.5/64
	Discrimination [m]	≤1.8	≤0.66
	Accuracy [m]	<0.5 or 1% (bigger of)	<0.25 or 1% (bigger off)
Velocity	Min/Max [m]	-400/+200	-340/+170
	Discrimination [m/s]	<0.26	<0.26
	Accuracy [km/h]	≤0.4	≤0.4
Angle	FOV Azimuth [°]	[-16, +16]	[-50, +50]
	FOV Elevation [°]	[-7.5, +7.5]	[-7.5, +7.5]
	Discrimination Azimuth [°]	4	15
	Accuracy Azimuth [°]	≤0.25	≤0.5
	Accuracy Elevation [°]	≤0.5	≤0.5

6.2.4 Electromagnetic Field Generators

Electromagnetic Field Generators are often seen in the underground coal mining industry. They operate on a principle similar to that discussed in the RF ToF section, but rather than making use of Time-of-Flight (ToF) approaches, Near-Field Electromagnetic Ranging (NFER) is used. NFER has superior propagation properties as compared to conventional RF-based localisation techniques [9] (Schantz, 2007).

NFER technology relies on the near-field characteristics of the electric and magnetic components of an electric wave. Close to the antenna (within one wavelength), the electric and magnetic waves are 90 degrees out of phase. Further away from the antenna, they converge to become in phase. By separately detecting, measuring and comparing the electric and magnetic phases before they converge, the distance from the transmitter can be determined. Once the distance has been measured by the receiver, it needs to be broadcast back to the transmitter [9] (Schantz, 2007). The NFER principle relies on the antennas being less than one wavelength from each other. This results in low frequency, very long wavelength applications, typically in the range of 750kHz to 1.7MHz and a wavelength of 300m [9] (Schantz, 2007).

Advantages

- Does not require Line-of-Sight.
- High position accuracy in challenging industrial environments.
- Low power requirements.
- Surface and Underground applications.

Limitations

- Requires communication (V2X) between remote and local objects TMMs and pedestrians respectively.
- Does not measure speed.
- Limited range between objects.
- Multiple antennas are required with specific separation gaps between them that must be maintained.

Typical Sensor Specifications

TABLE 4: TYPICAL NFER SENSOR SPECIFICATIONS [10; 9] (Q-TRACK, 2020; SCHANTZ, 2007).

Parameter	Specification
Range	70m
Accuracy	<40cm
Update Rate	>1Hz with up to 36 tags

6.2.5 Cameras

There are several methods of using cameras to do object (TMMs and pedestrians respectively) detection and ranging. All camera methods involve the use of cameras (similar to any other camera) to record images and then process them. There are too many of these methods in the literature to discuss in depth in this report. However, it is important to note that camera-based sensors will provide a series of 2D images that can be combined or processed to provide a perception of the depth of any scene. Processing the camera images is often done in a non-deterministic manner that involves some form of artificial intelligence and machine learning.

Aperture size, focal length, sensitivity and shutter exposure time are all variables that affect the image quality. Sensor sensitivity (known commonly as the ISO) is a measure of amplification used prior to the digital conversion. A higher sensitivity requires less light to achieve the same effect as a lower sensitivity. Shutter exposure time is the time that the photo diode in the light sensor is exposed to light. A higher exposure time gives the photo diode a longer period to build a charge. Low shutter times in dark conditions, will lead to under exposure of the light sensor, compared to high shutter times which lead to overexposure[11] (Botha, 2015).

The lens aperture is the opening through which light travels to hit the light sensor. A larger opening allows more light photons to enter. The aperture opening is specified by the F-number. The F-number is the ratio of lens focal length to effective aperture opening diameter. A lower F-number denotes a larger aperture opening. Increasing the F-number decreases the image exposure but increases the image field depth.

Lens focal length is the optical distance from the plane at which the light rays converge from the lens. This is related to the magnification of the lens. Focal length thus affects the image region [11] (Botha, 2015).

Advantages

- Large detection region (field of view).
- Remote (Secondary or Tertiary) objects (TMMs and pedestrians respectively) don't require tags or infrastructure.
- Surface and Underground applications.

Limitations

- Optimal lens and camera settings will change as lighting conditions change.
- Lens may be dirty, limiting performance (robustness to the environment).
- Detection limited to Line-of-Sight.
- Accuracy dependent on distance to object (quadratic) and camera separation (linear relationship) for the stereo camera case.

- Blind spots around local object.

Typical Sensor Specifications

TABLE 5: TYPICAL CAMERA SENSOR SPECIFICATIONS[12] (DOTNETIX (PTY) LTD, 2019).

Parameter	Specification
Range [m]	5 (wide angle) to 150 (narrow angle)
Accuracy [m]	Not specified (can differentiate between classes of objects, such as pedestrians and vehicles – this largely depends on the implementation)
Field of view [°]	25 to 170 (see above for range at different angles). Note, 360 is also possible given certain cameras (i.e. fisheye lens)

6.2.6 Light Detection and Ranging (LiDAR)

Light Detection and Ranging – also known as LiDAR – is a similar technology to radar in many ways. However, compared to radar, LiDAR relies on an optical technique as opposed to a radio technique. LiDAR systems are used in many industries, often with aviation related applications, such as meteorology, Unmanned Aerial Vehicles (UAV) and space exploration[14] (Chazette, Totems, Hespel, & Bailly, 2016).

LiDAR is an active, optical remote sensing technique because it uses an artificial light source emitted from a laser. Wavelengths are typically in the range of 0.25 to 11µm. The laser beam then encounters the target (TMMs and pedestrians respectively) and is reflected back to the LiDAR. The optical flux is collected by an optical imaging system. Some filtering techniques are then applied to the collected optical flux to remove noise and to reduce the spectral bandwidth to that of the emitted laser beam's wavelength. Conversion of the optical flux into measurable electric voltage is done in a way similar to the optical sensor of a digital camera [14] (Chazette et al., 2016).

Both 2D and 3D LiDARs are available on the market. A 2D LiDAR consist of a single laser beam that rotates. A 3D LiDAR has multiple LiDAR beams that Rotate. The automotive industry almost exclusively makes use of 3D LiDAR for detection, ranging and tracking. Information obtained from a 3D LiDAR is in the form of a point cloud. This cloud of points needs to be dissected in order for useful information to be produced.

Advantages

- Remote objects don't need tags or infrastructure.
- Wide Field of View (FOV).
- Mature technology in the automotive industry.
- Known shortcomings as discussed by leading suppliers.

Limitations

- Expensive in terms of cost.
- Localization and tracking have high computational requirements.
- Untested (at this stage) in typical mining scenarios (angled approaches, rural roads, multiple interactors in close proximity).
- Line-of-sight.

- Blind spots.

Typical Sensor Specifications

TABLE 6: TYPICAL LIDAR SPECIFICATIONS FOR AN ENTRY-LEVEL LIDAR[?] (VELODYNE LIDAR, 2019B) AND A TOP-END LIDAR [13] (VELODYNE LIDAR, 2019A).

Parameter	Entry-level LiDAR	Top-end LiDAR
Detection Range [m]	100	150
Accuracy [cm]	±2	±3
Horizontal Field of View (FOV) [o]	360	360
Vertical FOV [o]	41.33 (-30.67 to 10.67)	40 (-25 to 15)
Azimuth Resolution [o]	0.08 to 0.33	0.1 to 0.4
Vertical Angle Resolution [o]	1.33	0.11
Update Rate [Hz]	5 to 20	5 to 20
3D LiDAR Data Points [points per second]	1, 390, 000	4, 800, 000

7. Sensor Fusion

It is evident from the literature, that the majority of existing CxD suppliers make use of combinations of the six (6) identified sensing technologies discussed in this report. The combination of multiple sensing technologies is known as sensor fusion. There are, in fact, multiple benefits to the combination of sensors in a multisensory system [15] (Klein, 2004). The following stipulates key issues that may arise without sensor fusion:

- Some objects (or vehicles) may be detected by one sensor but not another, due to the manner in which their signatures are generated.
- The signature of an object may be masked with respect to one sensor but not another.
- One sensor may be blocked from viewing objects because of its position on the local object, but another sensor positioned elsewhere on the local object may have an unimpeded view of the object.

Clearly the selection of an appropriate fusion algorithm has significant advantages. The following section details the advantages and challenges associated with sensor fusion.

Distributed estimation has been an active research area since the late 1970s. Advances in sensing and communication hardware have resulted in a resurged interest in estimation algorithms that use multiple sources of information [16] (Zhang, 2010). In fact, [17] Smith & Singh (2006) discusses several common approaches to combining multiple sensors, with the two main benefits being:

1. Improved accuracy from existing sensors; and
2. Obtaining the same accuracy level from smaller, cheaper sensors.

Sensors may be combined in several ways and this combination is not limited to the sensors on a single platform. A haul truck may have several sensors, such as LiDAR, GNSS and RF ToF on-board or multiple pedestrians on the mine may carry single sensors (such as GNSS chips in a smartphone). Sensor data available to a processing node may come from one of three sources [17] (Smith & Singh, 2006):

1. The platform's own sensors, known as organic data.
2. Network connections to other platforms.
3. A database of data previously received and of local track estimates.

Traditionally, the combination of sensor data has been done by some form of Kalman or Bayesian filter, but other techniques, such as fuzzy logic and Artificial Neural Networks (ANNs) are also on the rise [17] (Smith & Singh, 2006). The most widely used model for fusion consists of four levels, namely [17] (Smith & Singh, 2006):

1. Level 1 – Object refinement
2. Level 2 – Situation assessment
3. Level 3 – Threat assessment
4. Level 4 – Process assessment

Level 1 is usually divided into data registration, data association, position or attribute estimation and identification. This is the fundamental fusion of sensor data and is relevant to detection and tracking of the CxD. **Levels 2 to 4** are concerned with the decision making based on the information obtained in Level 1, and this is thus related to CxD decision making [17] (Smith & Singh, 2006). Provided how critical detection and tracking is toward the CxD maturity, the remainder of this section will focus on the divisions of Level 1, which are defined below:

- **Data Registration:** Aligns the sensor data into a common frame of reference. This is usually to change coordinate systems from local, sensor related frames of reference to, for example, latitude and longitude [17] (Smith & Singh, 2006).
- **Data Association:** Compares measurements and attempts to collect measurements originating from the same real-world object into a single track. The challenge is in distinguishing from which object (if any) each measurement originates. This becomes especially challenging in dense environments with multiple interactors in close proximity of the platform. When multiple sensors track multiple objects, the data association problem can be shown to be NP-Hard – non-deterministic polynomial-time hardness. This complicates matters, because a NP-Hard problem cannot be solved in a computationally efficient manner. As a result, approximation algorithms have been developed to deal with this. ANNs and fuzzy logic algorithms are often used to this end [17] (Smith & Singh, 2006).
- **Position and Attribute Estimation:** Is the process of taking numerous measurements and then estimating the target's state. Several methods are prevalent, notably the Kalman filter and its extensions, particle filters, and Artificial Intelligence (AI) approaches. These various approaches may also be combined to give hybrid algorithms, such as a fuzzy logic-based adaptive Kalman filter [17] (Smith & Singh, 2006).
- **Identification:** Classifies the object from which the measurements originate. Typically, the primary object/platform (i.e. Haul Truck) utilises its own sensors to produce its own best estimate of the target identity, along with an associated confidence value. Once identified locally, it must be fused with remote

estimates (such as that of another haul truck in close proximity) to form a global solution [17] (Smith & Singh, 2006).

There are two main challenges that face multisensory tracking systems [17] (Smith & Singh, 2006):

1. The order in which the data arrives may not be suitable for processing or may be out of sequence.
2. The effect of one sensor on another, or data correlation.

Each measurement arrives at the processor with a discrete timestamp. Propagation times for each sensor vary and it is typical for some data to arrive out of sequence. This increases the computation and memory requirements of processors. The majority of techniques to handle this problem are Kalman filter-based [17] (Smith & Singh, 2006).

Data correlation is a concern when object positions are shared via a network of connected processors (V2X). The main reason this is a challenge, is that the Kalman filter requires measurements to be independent or that the cross-covariance is known. The problem with a distributed network of connected processors is data incest (also known as rumour propagation).

Data incest is the situation in which raw measurements are inadvertently used multiple times as if they were independent information. This situation may occur when the same information reaches the same processor via different paths and is prevalent when all network nodes are communicating with each other (V2X).

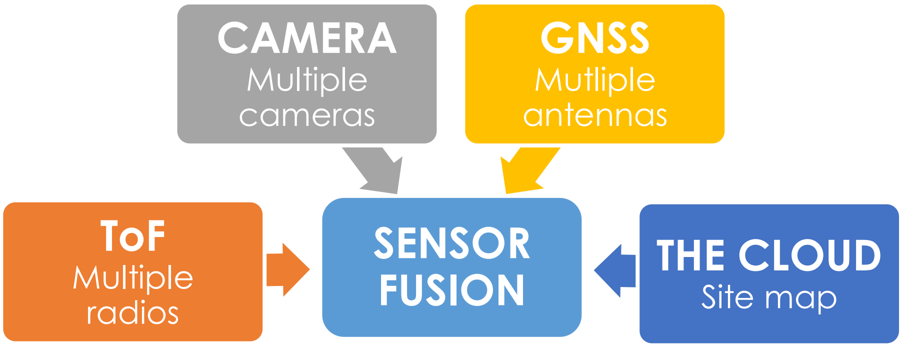


FIGURE 1 - MULTISENSOR SUITE ARCHITECTURE.

Therefore, as the number of sensors and nodes increase, data incest becomes harder and harder to identify and avoid [17] (Smith & Singh, 2006). There are, however, ways of managing this challenge by producing incest free estimates at the output of each node by extracting only the most recent Node Time Pair (NTP) – an event taking place at a particular node at a particular time – before being fused with current local estimates.

below, illustrates the system architecture of a typical Detection and Tracking System implementation with sensor fusion. It is anticipated that the majority of CPS developers will make use of off-the-shelf components for their individual sensors. Detailed specification sheets should thus be readily available for these individual sensors, along with the relevant EMC certifications, IP ratings, etc.

The sensor fusion layer, on the other hand, is more likely to be developed in-house by the CPS developer. Therefore, the sensor fusion layer is more important to test than each individual sensor.

8. Sensor robustness

Environmental stresses on CPS sensors may reduce their performance during their lifespan. MIL-STD-810G contains materiel acquisition program planning and engineering directions, for considering the influence of environmental stresses on materiel throughout all phases of its service life. MIL-STD-810G further defines twenty-eight (28) test methods that can be used to establish these effects in a quantifiable manner. Finally, guidelines pertaining to world climatic guidelines are provided.

Six (6)of the twenty eight (28) test methods are relevant to the sensor technology discussion of this report and are discussed in the subsequent paragraphs. It is important that the purchasers and the vendor consider all twenty eight (28) of the test methods, because some of them that are not discussed here, may be relevant to specific sites (such as salt fog, which may not be generally applicable to the mining industry, but may be relevant to salt mines). It is also advised that purchasers should refrain from using phrases such as ‘MIL-STD-810G’ compliant, as this will unnecessarily increase both cost and complexity of CPS offerings.

High temperature

High temperature refers to instances where the environmental temperature regularly exceeds 30 degrees Celcius. It is separate from solar radiation and high temperatures associated with solar radiation, but if both conditions are present, both test methods should be considered. High temperature effects that may reduce sensor performance include:

- Differential expansion of components.
- Lubricant become less viscous.
- Dimension changes of components.
- Seals, packing, gaskets etc. fail.
- Electrical resistor values change.
- Electromechanical components overheat.
- Weakening of solder joints.
- Blistering, peeling and delamination of paints, composites and surface laminates applied with adhesives.
- Softening of potting compounds.

Low temperature

Low temperatures refer to conditions where materiel will be exposed to temperatures below the standard ambient. It is especially relevant in South African mines that regularly experience frost during winter months. Low temperatures have adverse effects on almost all basic materiel. The following problems are typically associated with exposure to low temperatures:

- Hardening and embrittlement of materials.
- Binding of parts from differential contraction of dissimilar materials.
- Loss of lubrication and lubricant flow.
- Changes in electronic components (resistors, capacitors, etc.).
- Changes in performance of transformers and electromechanical components.
- Condensation and freezing of water in or on the materiel.
- Decrease in dexterity, hearing and vision of personnel wearing protective clothing.

Solar radiation

High levels of solar radiation have two main effects, namely heating and actinitic effects (photodegradation). Heating effects are discussed in the section on high temperature above. Actinitic effects include:

- Fading of colour.
- Deterioration of polymers.

Sand and dust

Dust is defined as particles smaller than 150µm and sand as particles ranging from 150 to 850µm in size. IP ratings are often used to indicate a materiel's ability to withstand the ingress of particles, with an IP rating of IP6X (X indicating any number) indicating that an object is impervious to dust. The effect of sand and dust environments include:

- Abrasion and erosion of surfaces.
- Penetration of seals.

- The degradation of electrical circuits.
- Obstruction and clogging of openings and filters.
- Interference with optical characteristics.
- Overheating and fire hazard due to restricted ventilation or cooling.

Vibration

Vibration tests are performed to ascertain that materiel can withstand the vibration exposures of a life cycle. MIL-STD-810G goes into extensive detail on performing vibration testing and it is recommended that Annex D (of MIL-STD-810G) and tests I and III of Annex D are performed – this section is relevant to materiel installed on ground vehicles with wheels. Vibration during the life cycle may induce the following effects:

- Chafed wiring.
- Loose fasteners and components.
- Intermittent electrical contacts.
- Electrical short circuits.
- Deformed seals.
- Optical and mechanical misalignment.
- Excessive electrical noise.

Shock

Shock tests are performed to provide a degree of confidence that materiel can physically and functionally withstand infrequent, non-repetitive shocks encountered in service environments. Testing can determine the strength of the mounting devices used to fix materiel to platforms that can crash. Shock effects include:

- Failure of components including cracks in fracturing crystals, ceramics, epoxies or glass envelopes.
- Changes in dielectric strength and insulation resistance.
- Variations in magnetic and electrostatic field strength.
- Electrical circuit damage such as circuit card malfunction and connector failure.
- Permanent mechanical deformation.
- Piezoelectric activity of materials.

9. Dynamic vicinity boundary.

The decision-making strategy of the CPS has two main goals, firstly that it avoids all collisions and secondly that no faulty interventions occur (false positives). These two goals are often contradictory.

The vicinity boundary is the point at which a TMM operator has to be warned of a potential collision, after which the automatic slow and stop intervention will be triggered. The vicinity boundary will be different for each interaction, depending on:

- The local object's speed and heading (trajectory).
- The remote objects' trajectories.
- The local object's braking performance – the braking performance is influenced by the TMM's brake system capabilities, TMM state (speed, payload, brake and tyre wear), and site conditions (friction coefficient, road grade).

Once a remote object is detected, it triggers a series of events. The time each event takes, coupled with the speed of the local and remote objects, determine the vicinity boundary. Because the vicinity boundary changes, it is deemed to be dynamic. The sequence of events is:

1. A remote object is detected by the local object (it enters the detection area). The detection area will typically be more or less constant, depending on the sensor accuracy, reliability and robustness. Achieving this was discussed in Section 0.
2. The local and remote objects' states (speed, heading, orientation) are used to predict a potential point of collision.
3. The time the local object will take to reach the potential point of collision is determined and compared against the time the operator must be given to react and the time needed to slow and stop the TMM. If the time to the point of collision is equal to or less than the operator reaction time and stopping time, the remote object is deemed to be within the vicinity.
4. The EWS warns the operator of the potential collision. The operator is given 2.5seconds to react.
5. If the operator fails to react or reacts incorrectly (e.g. speeds up when expected to slow down), the intervention strategy is triggered. The intervention strategy consists of:
    a. Slowing the TMM to a safe speed (if the TMM is travelling above the safe speed).
    b. Once the safe speed is reached (or if already at or below the safe speed), the TMM is brought to a stop.

To determine the vicinity boundary, the following has to happen:

1. The remote object(s) must be detected, and their states measured or estimated.
2. The local object's and remote objects' trajectories are used to predict a potential collision point (if it exists).
3. The time or distance to the potential collision point is estimated and compared against the time needed to warn the operator and the distance needed to slow and stop the local object.
4. If the time and distance to the potential collision point is less than the time and distance needed to warn the operator, slow and stop the machine, with an acceptable gap, the remote object(s) are deemed to be within the vicinity.

The vicinity boundary will thus be different for each interaction scenario, with multiple vicinity boundaries present at any given moment.

The prediction of a potential collision point is a crucial step in the decision-making process of the CxD. The potential collision point is predicted based on the current state estimate of the local object and the estimates of other objects in the detection area. Because of measurement and process noise, the state estimates are uncertain.

Uncertainties stem from:

- Remote object state uncertainty.
- Local object state measurement inaccuracy.
- Operator reaction time (influences the warning period before triggering automatic slow and stop).
- CxD delays (sensing delays, processing delays, communication delays).
- Brake performance.

Remote and local object state measurement was discussed extensively in Section 0 and will not be repeated here.

Operator reaction time will vary, depending on:

- Operator fatigue.
- Cabin ergonomics.
- Other human factors, such as age, gender, etc.

The URS specifies that the effective warning system must give the operator 2.5 seconds to respond to a warning from the CxD. If the operator fails to take corrective action within this period, the automatic slow and stop intervention will be triggered.

CxD delays refer to the time taken by the CxD to:

- Detect a remote object – this may vary due to the fusion of sensors.
- Predict the remote objects' paths – this will depend on the type of prediction algorithm used.
- Communicating with remote objects – transmitting a message (such as a Basic Safety Message, see Interoperability document) or an effective warning, takes time. The time taken depends on the distance between the objects, the communication protocol, the presence of RF hindrances (such as buildings, trees, pillars, etc.).

CxD delays are measurable and are short in comparison to operator reaction times.

The braking performance is the time and distance taken by the TMM to slow and stop once the intervention has been triggered. The braking performance of any TMM is significantly influenced by the prevailing operating conditions and TMM status. Some of the factors that influence the braking performance are:

- Friction coefficient.
- Gradient and side slope.
- TMM payload.
- Tyre wear.
- TMM status (bucket raised, boom extended, etc.)
- Braking system response time (machine delay).
- Machine control method (e.g., apply service brakes, apply retarder, de-throttle).

Dynamic vicinity boundaries are therefore a key functional performance requirement for effective CPS products.

10. References

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