Timo Malm*, Taru Hakanen, Josepha Berger and Sami Karadeniz

Uncertain information related to situational awareness of mixed fleet and AMR - Safety perspective

Abstract: Situational awareness is a key to enable safe mixed fleet operations. Mixed fleets in internal logistics consist of Autonomous Mobile Robots (AMRs), Automated Guided Vehicles (AGVs), and manually operated mobile machines such as forklift trucks, and overhead cranes. In mixed fleet material handling operations uncertain information is the puzzling factor, which affects safety of the system. Uncertain information may be used sometimes, when reliable information is not available, for example due to limited Performance Level (PL), disturbances, environment, or poor visibility. The question here is, how uncertain information can be applied for safety purposes. Safety must not be jeopardized. Case specific risk assessment is needed to ensure safety. Safety measures based on uncertain information may be acceptable if they are limited to specific conditions, such as a defined time frame, reduced speed, controlled distance, adequate visibility, or a particular mode of operation.

Keywords: uncertainty, autonomous mobile machine, AGV, AMR, mixed fleet

***Corresponding Author: Timo Malm:** VTT, Finland,
E-mail: timo.malm@vtt.fi
Taru Hakanen: VTT, Finland,
E-mail: taru.hakanen@vtt.fi
Josepha Berger: VTT, Germany,
E-mail: josepha.berger@vtt.fi

1 Background

This study focuses on industrial mixed fleets, which operate in material handling tasks indoors in factories and warehouses. Mixed fleets consist of various mobile machines, such as AGVs, AMRs, manually driven forklift trucks, and overhead cranes. Thus, it is a combination of autonomous and manually controlled mobile machines. In addition, humans operate in the same space.

In order to ensure the safety of such mixed fleet systems, situational awareness is a central prerequisite for safe operations. By definition, Situational Awareness (SA) consists of the following elements or phases: "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in near future" [1], [2]. In MixedFleet project, we complement the original definition by applying it on mixed fleets including both autonomous and manual systems as well as both M2H (Machine-to-Human) and M2M (Machine-to-Machine) perspectives [3].

We propose that situational awareness is one central component in ensuring the safety of mixed fleets. Autonomous systems use complex sensing, software, and communication solutions for perception, navigation and obstacle avoidance. In our study, we emphasize shared situational awareness (SA) so that SA is created both by humans (e.g. forklift truck drivers or factory employees) of machines and between machines in order to operate safely (Figure 1).

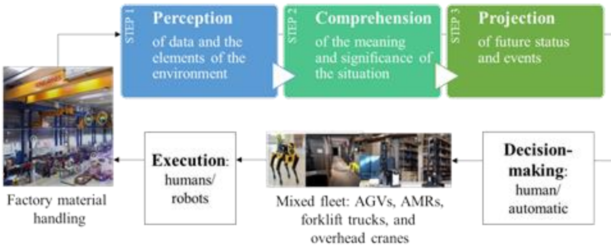

Figure 1 Mixed fleet situational awareness framework (Hakanen et al., 2024 [3]: based on Endsley, 1995 [1] and Bavle et al., 2023 [4]).

Our study pinpoints that uncertainty involved in all phases of mixed fleet situational awareness (perception, comprehension, and projection) as mixed fleet SA heavily relies on data and information. Inherently, the concept of information is closely connected with the concept of uncertainty. For instance, problem-solving always involves some information deficiency [5]. Zhu et al. address challenges in autonomous systems from the "unknowns" – the unexpected disturbances from component faults, environmental interference, and malicious attacks, as well as the inherent uncertainties in system inputs, model inaccuracies, and machine learning techniques [6]. However, this study does not aim to address all potential uncertainties related to mixed fleet operations. Instead, it focuses specifically on the uncertain information associated with situational awareness that is crucial for ensuring the safety of mixed fleets. Thus, mixed fleet SA framework provides the first framework guiding this study. Another framework used in this study is derived from computational modelling and simulation domain defining and classifying the concept of uncertainty [8].

Situational awareness refers typically to on-board systems to the vicinity of the mobile machine and in peripheral protection systems to situational awareness of fleet control. Situational awareness can be also dynamic so that it depends on, for example, the phase of the process or the traffic density. Situational awareness can be related also to persons (M2H), which means that a person receives information and forms his own situational awareness notion. All these different situational awarenesses are related to safety.

Situational awareness can be based on

- reliable information gathered from sensors and safety PLCs having adequate (safety) Performance Level (PL) and applied according to device manual, or
- uncertain information based on information from sensors having inadequate PL, inadequate physical capability (e.g. detection range), information is not up to date, or the information may contain errors.

Performance Level (PL) means “discrete level used to specify the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions”. [8]. PL describes the safety ability and probability to operate in control system well, but it does not give any estimate of the performance related to sensor detection capability, calculation capability of a logic, or capability to resist difficult environments. These factors and their uncertainties need to be estimated separately according to the need in the application.

2 Aims and methodology

The aim and research question of this study is: How can uncertain situational awareness information be applied for safety purposes?

The method is here first to get information from interviews, group discussions, standards, and literature. Then the gathered ideas related to uncertainty have been discussed with researchers and experts from companies. Finally, the conclusions are made based on the material gathered.

3 Classification of uncertain information

There are many definitions for uncertainty depending on the domain it is applied [8]. This section presents some examples for classification of uncertain information.

As situational awareness of mixed fleets foremost rely on data and software, we use computer science related theories for studying uncertainty. In the computational modelling and simulation domain, uncertainty is associated to lack of knowledge or incomplete information (Figure 2). Incomplete information can refer to vagueness, which characterizes information that is imprecisely defined, unclear or indistinct. Nonspecificity refers to possible alternatives in given situation. Dissonance refers to the existence of conflicting evidence. [8] Variability is defined as inherent variation associated with physical system or the environment under study. Error is a recognizable deficiency that is not due to lack of knowledge. Furthermore, all of the definitions presented in the model in the Figure 2. can be found also in specific mixed fleet cases.

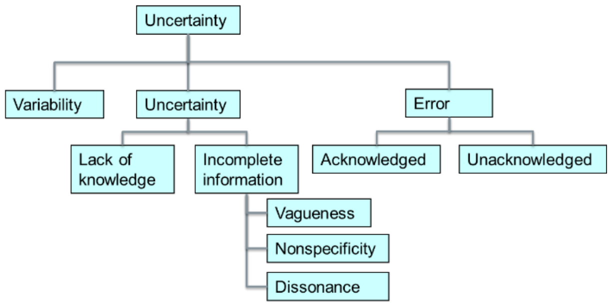

Figure 2. Uncertainty classification used in computational modelling and simulation. [8].

According to Andreas Kreuz, uncertain knowledge can be defined as “Any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system” [9]. Uncertainty can be distinguished from Aleatoric uncertainty, which is related to inherently random processes in nature, like human behaviour. The other type is Epistemic uncertainty, which is related to lack of knowledge [9]. In our case lack of knowledge (epistemic) is more common, because in most cases of the Table 1. safety is tried to be realized with reliable components, which have high reliability and low failure rate. However, in some cases uncertain phenomenon increases randomness (e.g. sunlight and lack of calibration) and aleatoric (random) uncertainty is present.

Uncertainty in situational awareness for a mobile machine refers to the lack of precise or complete information about the environment and the machine’s state within it. Uncertainty can be associated to the steps of situational awareness of mixed fleet as described in Figure 1. Here are the steps and related uncertainties [3], [4], [1]:

1. **Perception**. Inaccuracies or limitations in the sensors used to perceive the environment can lead to incomplete or erroneous data. Using state-of-the-art sensors, suitable sensors for various environments and conditions, regular calibration of sensors, and maintaining the system can help to ensure that the data remains accurate and reliable.

2. **Comprehension** of the significance and meaning of the situation. Machine needs to comprehend when it needs to slow down in a case of an approaching obstacle or human, and when an emergency stop needs take place. At all times, the machine needs to “know” its location in the map and the next control actions to be taken in autonomous navigation. Uncertainty can be related also to the next control action, which means that although the machine knows the situation, it does not know what to do, like how to bypass another machine. Changing environments can make it difficult for the machine to maintain an accurate and up-to-date understanding of its surroundings. Up-to-date digital terrain maps (layouts) are essential tools for fleet and mission control. Combining data from multiple sensors to form a coherent picture of the environment can introduce errors and inconsistencies.
3. **Projection** of future status and events. Delays in the transmission of data between sensors, processors, and actuators can lead to wrong, insufficient or outdated information being used for decision-making.
4. **Decision making and execution**. When machines comprehend that there is e.g. a human close by, it needs to take action that is slowing down or stopping. Safety zones around the machine need to be correctly defined, stopping time needs to be short enough, and all delays so short that the machine does not harm a human. Incorporating redundant systems and fault-tolerant designs can help to mitigate the impact of sensor failures or data inaccuracies. Machine Learning and AI can help in better interpreting sensor data, predicting environmental changes and improving decision-making processes. Human-Centered Design can help to reduce cognitive load and improve the overall situational awareness of operators.

In mixed fleet systems uncertainty can be categorized also according to input, logic and output.

- **uncertainty in input** information is related to object detection, localization, environment observations, situational awareness, status information, commands, and intentional and unintentional cyberattack/misuse,
- **uncertainty in logic** is related to models, calculation, missions, commands, and decision making,
- **uncertainty in output** is related to performing actions, like stopping performance, implementing specific speed and direction, intentional or unintentional wrong human actions.

4 Cases of uncertain information in mixed fleets

Uncertain information is applied sometimes in the industry in safety-related applications. Uncertainty is more common in outdoor environments, where rain, fog or snow may reduce visibility remarkably. The focus is here on indoor applications, but some examples are related to outdoors use.

Situational awareness is associated here to mixed fleets, including AGVs, AMRs, and manually operated machines, which all are capable to model their environment to avoid collisions. This is related to detection of objects, adequate separation distance, and concluding results with adequate safety logic.

Common reason for uncertain information is inadequate Performance Level (PL). PL means discrete level used to specify the ability of the safety-related parts of the control system to perform a safety function under foreseeable conditions. PL can be associated with the probability of failed safety function [10][8]. Typically, designers and integrators of the system try to choose equipment that fulfill the PL requirements.

The origin of uncertain information related to indoor applications can be caused by poor sensor perception due to e.g. high speed, object surface properties, too long distance, misalignment of sensor (temporary or permanent), disturbance caused by other objects, object dimensions in specific height (e.g. forklift truck), lying person below detection field, inclined ground surface, a hole in the floor, or an object approaching behind a corner. Other origins for uncertain information coming outside of the machine are for example disturbed communication, obsolete terrain map and incorrect position information. Uncertain information can also be related to the situational awareness of a person. The person does not have correct information and makes a hazardous decision due to misinterpretation of the situation.

Usually, the designer tries to keep the system safe by avoiding use of uncertain safety-related information. One can apply, for example, type examined, safety classified devices, which guarantee the performance on defined conditions. However, in many cases additional uncertain information can be used as complementing solution to improve safety.

Table 1. describes cases of uncertainties related to situational awareness and hazardous performance of mixed fleet. Table 1. is gathered from expert group discussions in VTT and with companies. In total, 10 persons participated the study.

Table 1. Uncertainties related to mixed fleet situational awareness and hazardous performance.

Uncertainty	Description
Uncertainty related to the load	The load height, length, mass, or center of gravity may be uncertain. The load may also be unstable, poorly tied or attached to another object. In addition, the pallet carrying the load can be broken.
Objects (other than load) with unusual dimensions or height can be difficult to detect.	Unusual dimensions of objects (narrow or specific height) can cause collisions, when applying only the usual sensors, like laser scanners.
The speeds and masses of the machines are different and this may cause uncertainty, when the machines are approaching each other	When different machines (AMR, forklift truck, and crane) are approaching each other, it is common that only the stopping performance of the machine itself is considered, but the situation should be considered in system level by taking into account the stopping performance of all related machines.
Too long distance for reliable detection	Long range sensors (low PL) can support detection of an object and reduce the speed of an AMR before actual safety sensors initiate stopping within adequate stopping distance.
Blind spots of sensors and difficult object detection due to unusual location, like above in the air or behind a corner	Objects are detected with sensors (low PL), which have 3D capabilities or detection field is directed to unusual direction. These sensors can detect objects, which are in unusual direction, height, or they have too narrow legs to be detected. Also, UWB sensor detects distance to another UWB sensor and limit the speed to avoid collision, e.g. in far distance or behind a corner.
Moving blind spot in the detection field.	Laser scanners are relatively large to be mounted on a mobile machine, especially beside hoisting equipment. Mounting can be difficult for specific models, and this may cause blind spots, which move along with the machine.
Lack of calibration and testing of sensors cause uncertainty in sensor outputs.	E.g. odometers need to be reset in specific locations to minimize errors related to slipping. Also, other sensors and systems need to be tested and calibrated regularly.
Errors and insufficient updates of terrain maps (of fleet controls) cause uncertainty of special locations. Terrain maps may have low PL.	Changes of machines' surroundings, like moved large objects or constructions, areas under construction, ramps, fire doors, narrow places, and crossings need to be put and updated as changes take place on the terrain map. Each area can have specific rules, like, reserved, require slow speed, avoid stopping or follow area access control commands.
Free routes during emergency situation (e.g. fire) may be blocked	Autonomous machines should not stop in front of fire doors or crossings. The fleet control is supervising the situations. However, objects, failures, or fleet management errors may cause stopping at a forbidden place.
Security issues cause uncertainty to the automated performance	Security issues can be related to poor passwords (no password, easy or written to easy place), cyberattack or mechanical sabotage.
Software compatibility problems	Issue is realized at update but detected only during use. For example, limit values may have changed.
Changing environment can make sensor detection uncertain	Since the focus is on indoor applications exposure to water (splashes, puddles, steam/fog) and extreme temperatures are quite rare. However, sunlight coming from window can disturb optical sensors as well as similar sensors from other vehicles and cause changes in lighting. Also, large reflective objects can disturb optical and radio sensors. High currents related to specific process phases can disturb nearby devices and systems. Broken floor (hole) can cause many kinds of problems related to sensors' field of view and driving performance.

Uncertainty	Description
Difference between different location systems in different machines brings uncertainty to location accuracy and safety	Different machines can have different location systems, like, SLAM, UWB, odometers, IMU, magnetic navigation and laser-guided navigation, which cause different accuracies for location information. The accuracy difference can be safety issue, since in some cases the accuracy can be inadequate, although usually there are no problems. The differences need to be considered on system level.
Uncertainty related to human actions, when driving manual machines	When driving trucks, do humans follow the rules related to speed limits and do they choose safe routes. The situational awareness of AMRs could be improved by adding manual machines to the terrain maps.
Malfunction of traffic lights, warning system, or personal supportive system reduce situational awareness of persons	Traffic control and warning systems have typically low PL. Broken traffic lights initiate often blinking of the yellow light and a person can detect the uncertain performance. ISO Technical report Safeguarding supportive system (ISO/TR 22053) shows some means for personal communication with other systems [11]. Personal communication is usually more vulnerable than continuous communication, since it is established when needed.

One general aspect is related to legislation and related changes. New Machine regulation (EU) 2023/1230 [7] describes autonomous mobile machinery and related basic requirements and it will be in force 20.1.2027. According to the new regulation the collision avoidance system is based on either a peripheral protection system or on-board devices intended to detect human or any other obstacle in its vicinity to avoid collisions. The peripheral protection system is typically related to fleet management, which is capable of controlling access into parts of the system to avoid collisions. Fleet management controls the situational awareness of the fleet. An on-board protection system forms a situational awareness area around the mobile machine to maintain safe distance to obstacles and humans.

Figure 3. shows some means to control uncertainty. Uncertain sensor information can be redundant, and the results can be compared. A terrain map can show places which require e.g. reduced speed, or no stopping is allowed or the area can be forbidden. Fleet control gives information related to the terrain map. Uncertainty can be caused by exceeded maintenance or updating intervals, which both should be supervised. Communication uncertainty can be related to disturbances, which cause delays or omission of messages. In some cases, the message can be changed intentionally (cyberattack) or unintentionally. The presented cases are general examples of how to deal with uncertain information.

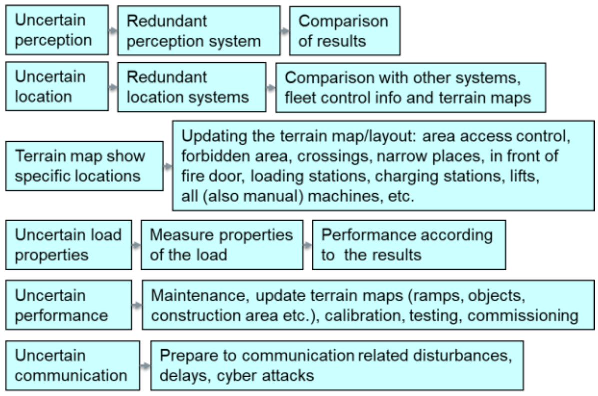

Figure 3. Uncertain information and examples of solutions for managing uncertainty.

5 Conclusions

As seen, there are many causes for uncertain information. In some cases, uncertain information may exist for a specific time, in a specific operation mode, for individual loads or in specific situations.

Usually the aim is that safety-related safety functions are based on reliable information, which have also adequate safety performance level (PL). However, one can find several cases, which are complex and not all needed reliable information is available.

For example, AMRs have typically laser scanners at about 20 cm height, but if the object is “flying” in the air and therefore it is not detectable at that particular height, because it is not touching the floor. The fork and load of a forklift truck can be at almost any height, and it is possible that the laser scanner would not see the object although it is very reliable. The laser scanners cannot see negative objects, i.e. holes in the floor or stairs downwards either.

Further, one AMR can stop within its detection range, but if two AMRs are moving towards each other at full speed they cannot stop within their sensor detection range, if there were no additional safety margin in the detection range.

Also, the load to be handled can cause uncertainties related to its weight, dimensions, stability, and rigidity. In addition, the load can be loose or attached. All these factors can cause collisions, falling of the load or AMR.

The examples in the previous paragraphs as well as those listed in Table 1 show that there are hazardous situations, which are difficult to detect with usual safety devices. Something additional is needed and it is common that the required detection capability differs from the usual safety devices. It may be difficult to find devices/system with a specific PL, but if the situation is rare, as described in the examples, the PL requirement might be lower. Usually, fleet control prevents collisions by giving the AMRs routes, which do not intersect with other routes, but typically, fleet control does not have any PL. The fleet control can also dynamically adjust speed, direction and separation distance to other objects according to the location information. However, some means to deal with uncertainty increase complexity which furthermore increases probability of errors, and the uncertainty remains. Anyway, an adequate level of safety can be achieved by increasing redundancy and accepting uncertain information in a controlled manner. Risk assessment is a suitable tool to estimate if the uncertain information is acceptable [12][11]. However, it is not feasible to make universal rules for applying uncertain information for safety-related applications, instead the situations need to be solved on case-by-case basis.

This paper is made in MixedFleet project, which is mainly funded by Business Finland.

6 References

[1] Endsley, M. R. 1995. Toward a theory of situation awareness in dynamic systems. Human Factors, vol. 37, no. 1, pp. 32-64.

[2] Mica Endsley. 2000., Theoretical underpinnings of situation awareness. In Situation awareness analysis and measurement. Ed. Endsley M. and Garland D. (Link).

[3] Hakanen T., Berger J., Karadeniz S. Liski T., Bunjaku A. 2024. Industrial mixed fleets: An empirical study on central situational awareness activities. (Link)

[4] Bavle H., Sanchez-Lopez J., Cimarelli C., Tourani A., and Voos H. 2023. From slam to situational awareness: Challenges and survey. Sensors, vol. 23, no. 10, p. 4849.

[5] Klir, G., & Wierman, M. 1999. Uncertainty-based information: elements of generalized information theory (Vol. 15). Springer Science & Business Media.

[6] Zhu, Q., Li, W., Kim, H., Xiang, Y., Wardega, K., Wang, Z., & Choi, H. 2020. Know the unknowns: Addressing disturbances and uncertainties in autonomous systems. In Proceedings of the 39th International Conference on Computer-Aided Design (pp. 1-9).

[7] (EU) Machinery Regulation (EU) 2023/1230 of 14 June 2023. Link

[8] Thunnissen, D. P. 2003. Uncertainty classification for the design and development of complex systems. In Proceedings of the 3rd Annual Predictive Methods Conference, Veros Software, Santa Ana, CA (pp. 1-16).

[9] Kreuz A. 2022. Uncertainty in autonomous systems, part 1. Not just a question of perception. Magazine of Fraunhofer Institute for Cognitive Systems IKS.

[10] ISO 13849-1. 2023. Safety of machinery Safety-related parts of control systems Part 1: General principles for design. ISO. 164 p.

[11] ISO/TR 22053:2021. Safety of machinery — Safeguarding supportive system. ISO Technical Report. 16 p.

[12] Malm T., Montonen J., and Hakanen T. 2022. Safety considerations for multi-purpose robots in industrial environments. VTT White Paper. 8 p. Link