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# Technical review of emerging risks and mitigation strategies for mobile autonomous machines in outdoor construction

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The progressive introduction of autonomous and semi-autonomous machines in outdoor construction environments is reshaping traditional risk scenarios, requiring an update of existing safety frameworks and design methodologies. This contribution presents a comprehensive state-of-the-art review conducted within the research project MACHINE5.0, funded by the Italian National Institute for Insurance against Accidents at Work (INAIL) under the 2024 "Bando di Ricerca in Collaborazione (BRiC)" program. The aim is to support the development of new approaches to risk assessment and management for autonomous mobile machinery operating in unstructured, dynamic outdoor contexts.

The review is structured in two complementary sections. The first provides an overview of the emerging risks associated with the deployment of autonomous systems in the construction sector, analysing their interaction with workers, the environment, and other equipment.
The second part surveys current commercial and prototypal autonomous construction machines, classifying them according to their degree of autonomy, sensing technologies, and operational safety strategies. A comparative analysis is provided to evaluate how manufacturers and research prototypes address identified hazards, such as collision avoidance, stability under variable terrain conditions, and fail-safe mechanisms in case of perception or communication failure.

*Keywords*: Autonomous machines, Construction sector, Perception systems

## 1. Introduction

The adoption of autonomous and semi-autonomous mobile machines for carrying out complex operations is rapidly increasing, particularly in outdoor industrial sectors (Malm et al. 2022). Among them, construction sites represent some of the most unstructured, dynamic, and safety-critical environments, characterized by uneven terrain, poor visibility, variable weather conditions, frequent changes in working conditions, and the coexistence of human workers and heavy machinery. Consequently, machines such as autonomous excavators, trucks, compactors, and mobile robots are increasingly deployed to improve productivity, reduce operational costs, and mitigate workers' exposure to hazardous conditions (Czarnowski et al. 2018).

With reference to mobile machines used for outdoor construction activities, three main aspects must be considered (Shalal et al. 2013). First, the operating modality of the machine, which may range from manual to automatic and fully autonomous operation. Second, the perception systems adopted among the available sensing technologies, together with their respective advantages and limitations. Third, the control techniques implemented to manage machine behavior. These aspects significantly influence the risk assessment process and the corresponding risk reduction measures to be adopted. A key enabler of autonomy is the machine's ability to perceive its surroundings, localize itself, and understand ongoing activities in real time. The adopted perception system or systems provide the fundamental data upon which decision-making, motion planning, and control algorithms rely. The performance and limitations of these sensors directly affect the machine's capability to detect obstacles, recognize human workers, interpret terrain conditions, and ultimately respond to hazardous situations. Shortcomings in perception can propagate through the autonomy stack and lead to unsafe conditions and behaviors, especially in outdoor environments where dust, mud, rain, and occlusions are common. As a result, autonomous machines operating in construction sites introduce additional challenges that are not fully addressed by existing studies (Chen et al. 2025).

This paper presents a technical review aimed at supporting risk assessment for autonomous mobile machines operating in outdoor construction environments. The contribution is structured into two main parts. In the first part, the paper reviews and discusses the state of the art in perception systems, providing an overview of existing sensing technologies along with their capabilities, limitations, and sensitivities. In the second part, the paper presents current commercial and prototypical autonomous mobile construction machines, analyzing their perception architectures and safety-related design choices.

## 2. Technical review

The first aspect of interest concerns the operational functionality of the mobile machine. In general, three main operative modes can be identified:

- Manual: the operator must operate, regulate, and monitor the machine throughout the entire process.
- Automatic: the machine carries out the working operations independently following a defined program, but it cannot take decisions such as getting around an obstacle.
- Autonomous: the machine carries out working operations independently, similarly

to an automatic machine, while also being able to take decisions in an autonomous manner, such as avoiding identified obstacles.

The focus of this work is on the last category, namely autonomous machines. For this reason, it is necessary to clearly define what is meant by an autonomous machine, particularly from a system safety perspective. In this context, an international standard specifically addressing earth-moving machinery and mining equipment is available (ISO 17757:2019). It provides a set of definitions that are fundamental for the consistent classification of machine functionality and for risk assessment activities.

According to ISO 17757:2019, an autonomous or semi-autonomous machine system (ASAMS) is defined as the *"machine and supportive systems and infrastructure that enable the machine to operate in autonomous mode"*. Such systems are equipped with an ASAM supervisor system, which provides the primary user interface as well as the command-and-control center for operation in autonomous mode. More specifically, the autonomous mode is defined as the *"mode of operation in which a mobile machine performs all machine safety-critical and earth moving or mining function related to its defined operation without operator interaction"*. Consequently, if a machine is intended to operate in autonomous mode during its normal operating cycle, it is classified as an autonomous machine. In contrast, the manual operation mode refers to a mode of operation in which the machine is controlled by an operator who is fully accountable for monitoring the surroundings and for the safe operation of all machine controls.

## 2.1. *Perception systems*

Perception systems represent a fundamental component of autonomous machines, as they provide the information required to perceive the environment, detect hazards, localize obstacles and human workers, and support safe decision-making. In outdoor construction environments, perception is particularly challenging due to unstructured layouts, variable terrain morphology, dynamic obstacles, adverse weather conditions, and the presence of dust, mud, and debris (Chen et al. 2025). Consequently, perception architectures typically rely on the combination of multiple heterogeneous sensors, each characterized by specific operating principles, strengths, and limitations. Following established classifications in the autonomous vehicle literature, perception systems can be composed of ultrasonic sensors, radar, LiDAR, and cameras (Rosique et al. 2019).

### 2.1.1. *Ultrasonic sensors*

Ultrasonic sensors operate by emitting acoustic waves, typically in the range of 20–40 kHz, and measuring the Time of Flight (ToF) of the reflected signal to estimate the distance to nearby objects. These sensors are mainly suited for short-range perception tasks and are widely used in industrial applications due to their low cost and simplicity.

In outdoor construction environments, ultrasonic sensors can be effective for detecting obstacles at close proximity, particularly at low speeds and during precise maneuvering operations. They exhibit limited sensitivity to surface color and lighting conditions and can perform adequately in dusty or humid environments. However, their short operating range, low angular resolution, and susceptibility to false detections caused by signal reflections significantly limit their applicability for high-speed or large-scale autonomous operations. Moreover, the presence of blind zones near the sensor and the inability to classify detected objects restrict their contribution to comprehensive risk mitigation strategies

### 2.1.2. *Radar sensors*

Radar systems operate in the radio-frequency domain, typically in the millimeter-wave range (e.g., 24, 77, or 79 GHz), and estimate object distance (by measuring ToF) and relative velocity by analyzing reflected electromagnetic waves. Radar sensors are widely recognized for their robustness under adverse environmental conditions, including rain, fog, dust, and poor visibility.

For autonomous construction machinery, radar sensors are particularly valuable for detecting large obstacles, moving equipment, and vehicles over medium to long ranges. Their ability to directly measure relative velocity enhances safety-related functions such as collision avoidance and emergency braking. Nevertheless, radar sensors generally provide limited spatial resolution and object shape information compared to optical sensors. This limitation may lead to difficulties in distinguishing between different types of obstacles, such as human workers versus static infrastructure elements, which is a critical aspect in construction site risk assessment.

### 2.1.3. *LiDAR sensors*

LiDAR (Light Detection and Ranging) systems measure distances by emitting laser pulses, typically in the near-infrared spectrum (e.g., 905 nm or 1550 nm), and analyzing the ToF of the reflected light. By repeatedly scanning the environment, LiDAR sensors generate geometric representations of the surroundings in the form of point clouds, providing accurate spatial information that is essential for environment perception, mapping, and obstacle detection.

LiDAR sensors can be broadly classified into two-dimensional (2D) and three-dimensional (3D) systems, depending on the nature of the spatial information they provide. 2D LiDAR systems scan the environment along a single plane, typically producing a horizontal slice of distance measurements. These sensors are commonly used for detecting obstacles at a fixed height and are characterized by relatively low cost, high scanning frequency, and reduced computational requirements. In outdoor construction environments, 2D LiDAR can be effective for basic obstacle detection and boundary monitoring during low-speed operations. However, their inability to capture vertical information limits their capability to perceive complex three-dimensional structures, uneven terrain, or overhanging obstacles, which are common in construction sites. 3D LiDAR systems extend perception capabilities by providing full three-dimensional representations of the environment. They achieve this either through mechanical rotation of multiple laser channels or through solid-state scanning architectures. 3D LiDAR sensors can generate dense point clouds with high spatial resolution, enabling accurate detection, localization, and classification of objects, as well as detailed terrain mapping. In autonomous construction machinery, 3D LiDAR plays a central role in navigation, workspace monitoring, collision avoidance, and path planning, especially in unstructured and dynamically changing environments.

In outdoor construction scenarios, LiDAR sensors play a central role in environment mapping, obstacle detection, and terrain characterization. Their high spatial resolution enables precise localization of objects and supports advanced functions such as path planning and workspace monitoring. However, LiDAR performance can degrade significantly under adverse environmental conditions, such as heavy rain, fog, snow, or airborne dust, which cause light scattering and attenuation. Furthermore, LiDAR measurements are influenced by object reflectivity, potentially reducing detection reliability for certain materials commonly found on construction sites.

### 2.1.4. *Cameras*

Cameras are passive or active optical sensors operating in different regions of the electromagnetic spectrum and represent a key component of perception systems for autonomous machines. They provide rich semantic information that is essential for scene understanding, object classification, and human detection. Depending on the operating principle and wavelength range, cameras used in autonomous systems can be broadly classified into Visible-light (VIS) cameras, infrared (IR) cameras, and special depth-sensing cameras such as ToF cameras.

VIS cameras operate in the wavelength range approximately between 400 nm and 780 nm, corresponding to the human visual spectrum. They are widely adopted due to their low cost, high spatial resolution, and ability to capture color information. In outdoor construction environments, VIS cameras are particularly effective for recognizing human workers, tools, machinery, safety signs, and workspace boundaries. However, their performance is strongly affected by illumination conditions, shadows, glare, dust, rain, fog, and occlusions. As a result, reliance on visible cameras alone may lead to perception degradation and increased risk under adverse environmental conditions.

IR cameras extend perception capabilities beyond the visible spectrum and are typically classified into near-infrared (NIR) and mid-infrared (thermal) cameras. NIR cameras are often used to complement visible cameras, especially in situations with challenging lighting conditions such as low light or high contrast scenes. Thermal cameras, operating in the mid-infrared range, detect emitted thermal radiation and are particularly effective for identifying human workers and animals based on temperature differences. In construction environments, thermal cameras can enhance safety by enabling reliable human detection even in darkness, fog, or visually cluttered scenes. Nevertheless, thermal cameras generally provide lower spatial resolution and limited scene detail compared to visible cameras, which may restrict their ability to support precise object localization or classification.

ToF cameras represent a special class of active optical sensors that directly measure depth information. They operate by emitting modulated near-infrared light, typically around 850 nm, and computing the distance to objects based on the phase shift or time delay between the emitted and reflected signals. As a result, ToF cameras provide dense depth maps of the observed scene, enabling three-dimensional perception with relatively compact hardware.

In the context of autonomous construction machinery, ToF cameras can support short- to medium-range obstacle detection, workspace monitoring, and human–machine interaction tasks. Their ability to directly measure depth simplifies scene interpretation and can improve safety-related functions such as collision avoidance during low-speed operations. However, ToF cameras generally exhibit limited operating range and lower spatial resolution compared to LiDAR systems. Moreover, their performance can be affected by strong ambient light, reflective surfaces, and airborne particles such as dust, which are common in outdoor construction environments.

From a risk assessment perspective, camera-based perception systems provide essential semantic information but are inherently sensitive to environmental conditions and contamination. Consequently, cameras are typically integrated with active sensing technologies such as radar and LiDAR to improve robustness and fault tolerance. Understanding the specific failure modes and limitations of each camera type is therefore crucial when evaluating hazards and defining appropriate risk reduction measures for autonomous construction machines.

### 2.1.5. *Implication for risk assessment*

No single perception technology can meet all the safety and reliability requirements of autonomous machines operating in outdoor construction environments. Each sensing modality is characterized by specific limitations, failure modes, and sensitivities to environmental conditions, which must be carefully considered within the risk assessment process. Table 1, taken from Liu et al. (2021), provides a comparative overview of sensing technologies and human perception capabilities.

Table 1. Comparison of Camera, Radar, LiDAR, and Ultrasonic Sensor

| Metrics | Human | Camera | Radar | LiDAR | Ultrasonic |
|---|---|---|---|---|---|
| Technique | - | Lights | Electromagnetic | Laser Reflection | Ultrasound |
| Sensing range | 0-200 m | 0-100 m | 1 cm-200 m | 0.7-200 m | 0-20 m |
| Cost | - | \$500 | \$3000 | \$500 - \$3000 | \$100 |
| Data per second | - | 20-40 MB | 10-100 KB | 10-70 MB | 10-100 KB |
| Bad weather functionality | Fair | Poor | Good | Fair | Good |
| Low lighting functionality | Poor | Fair | Good | Good | Good |
| Application scenarios | Object detection<br>Object classification<br>Edge detection<br>Lane tracking | Object classification<br>Edge detection<br>Lane tracking | Object detection<br>Distance estimation | Object detection<br>Distance estimation<br>Edge detection | Object detection<br>Distance estimation |

As can be observed, no single perception solution can be considered universally optimal. The suitability of a given sensing system strongly depends on the specific application and operating conditions. For example, human perception exhibits significant strengths in terms of sensing range and adaptability, enabling effective performance across a wide variety of tasks compared to individual sensing technologies. However, human perceptual capabilities are substantially degraded under adverse weather conditions and in low-light environments. Consequently, modern autonomous construction machines typically employ multi-sensor perception architectures, in which complementary sensing technologies are integrated to compensate for individual weaknesses and to enhance overall system robustness and fault tolerance.

### 2.2. *Commercial and prototypical autonomous construction machines*

This subsection presents representative examples of commercial and prototypical autonomous machines operating in outdoor environments, with particular emphasis on the construction and agricultural sectors. For each machine, the main safety-related features associated with the autonomous system are outlined and discussed.

#### 2.2.1. *Exosystem by Built Robotics*

The Exosystem developed by Built Robotics consists of a hardware and software system to be installed on the tails of any excavator to enable fully autonomous trenching while preserving manual operation when needed (Figure 1). The safety system adopted to guarantee safe operations is based on Artificial Intelligence (AI)-powered smart cameras, GPS-Designated Geofence, wireless emergency stop, and continuous remote monitoring. From one hand, the autonomous mode makes it possible to take operators out of harm's way and on the other hand increases equipment utilization and quality of the work.

Figure 1. Excavator with Exosystem installed on the tails, by Built Robotics website.

#### 2.2.2. *Cat Off-Highway Truck 777*

The Cat Off-Highway Truck 777 is a heavy-duty mechanical haul truck designed for the transportation of bulk material in mining and large-scale earthmoving operations (Figure 2). In its autonomous or semi-autonomous configurations, the vehicle is equipped with a perception system that integrates multiple sensing technologies, primarily cameras and radar sensors, to support safe operation in complex and unstructured outdoor environments. The combined use of radar and vision enables reliable obstacle detection and situational awareness even under adverse operating conditions, such as high dust concentrations, poor visibility, and highly variable terrain characteristics, which are typical of mining and construction sites.

From a safety perspective, the perception system supports critical functions including collision avoidance, object detection, and monitoring of the vehicle's surroundings during loading, hauling, and dumping operations. Radar sensors provide robustness against environmental disturbances, while cameras contribute complementary information for scene interpretation and monitoring tasks. In addition, the truck is equipped with a wireless monitoring system that allows remote access to key operational data, enabling operators and supervisors to oversee vehicle status, performance, and safety-relevant parameters in real time.

Furthermore, the truck features a fleet-level wireless communication system that interconnects multiple vehicles operating within the same site. This system supports coordinated fleet management by enabling the exchange of operational information, thereby improving vehicle availability, reducing unplanned downtime, and enhancing overall operational efficiency.

Figure 2. Cat Off-Highway Truck 777, by Caterpillar website.

#### 2.2.3. *AUTONA/Earth*

Similarly, Volvo developed the Volvo AUTONA/Earth. It is an autonomous hauling concept developed for earthmoving operations in quarrying and construction environments (Figure 3). The machine is designed to operate without an onboard operator and relies on a multi-sensor perception system that integrates cameras, radar, and positioning sensors to enable safe navigation and obstacle detection in unstructured outdoor environments. The perception architecture supports essential safety functions such as collision avoidance, path following, and interaction with other machines and infrastructure within the worksite.

From an operational and safety perspective, AUTONA/Earth is intended to function as part of a coordinated fleet, where vehicle movements and tasks are centrally supervised. Wireless communication and remote monitoring systems allow real-time supervision of machine status and operational conditions, contributing to enhanced situational awareness and risk management at the site level. The combination of autonomous operation, multi-sensor perception, and fleet-level coordination highlights the system's focus on improving safety and efficiency in hazardous earthmoving applications.

Figure 3. AUTONA/Earth truck, by Volvo website.

**2.2.4.** ***Unmanned machine for forestry operations***

The Swedish University of Agricultural Sciences in Umeå developed one of the earliest autonomous machines specifically designed for forestry operations (La Hera et al. 2024). The system is intended to autonomously recognize the presence and spatial distribution of wood logs on the ground, grasp them using an onboard crane, and load them onto an appropriate trailer. To enable these functions, the machine is equipped with an AI-based smart camera system for visual detection and identification of logs, combined with a dual-antenna GNSS system that provides both positional and orientation information.

Autonomous operation is achieved through waypoint-based navigation, where a human operator defines the target locations using GPS coordinates. The machine then executes the loading tasks without direct human intervention. While this system represents a significant step toward automation in forestry applications, it remains at a prototypical stage of development. Limitations have been reported with respect to data transmission reliability and GNSS positioning accuracy, particularly in densely forested areas where satellite signal degradation affects localization performance. These constraints highlight the challenges associated with deploying autonomous machines in heavily occluded outdoor environments and underscore the importance of robust perception and localization systems for safe and reliable operation.

**2.2.5.** ***John Deere autonomous tractors***

John Deere has developed autonomous tractor solutions, starting from the 8R series and above, targeting agricultural operations in open-field environments. These machines are designed to operate without an onboard driver during field tasks such as tillage and soil preparation. Autonomous functionality is enabled through a perception system that integrates multiple cameras positioned around the tractor to provide 360° situational awareness, complemented by high-precision GNSS with real-time kinematic correction for accurate localization and path following.

From a safety perspective, the camera-based perception system supports obstacle detection and monitoring of the working area, allowing the tractor to identify unexpected objects or human presence and to safely stop or adapt its operation. Autonomous missions are typically planned and supervised remotely, with operators defining field boundaries, task parameters, and waypoints through digital interfaces. Continuous wireless connectivity enables real-time monitoring of machine status and operational performance.

Although these systems represent one of the most advanced commercial implementations of autonomous machines in outdoor environments, their operational reliability still depends on favorable GNSS conditions and relatively structured working scenarios. Consequently, their deployment is currently best suited to open agricultural fields with limited occlusions.

## 3. Conclusions

This paper reviewed key aspects relevant to the risk assessment of autonomous mobile machines operating in outdoor environments, with particular attention to the construction and agricultural sectors. The analysis highlighted how autonomous operations shift safety-critical responsibilities from human operators to perception, decision-making, and control systems.

Perception systems were identified as a central enabler of autonomy and a primary determinant of system safety. Ultrasonic sensors, radar, LiDAR and camera-based systems, each present distinct capabilities, limitations, and environmental sensitivities. No single sensing technology can guarantee reliable perception under all operating conditions typical of outdoor environments. As a result, perception failures may propagate through the autonomy stack and lead to hazardous behaviors if not adequately addressed during the risk assessment process.

The analysis of commercial and prototypical autonomous mobile machines across various sectors confirms the widespread adoption of multi-sensor perception architectures to enhance robustness and fault tolerance. Overall, the findings underline that effective risk assessment for autonomous machines in outdoor environments requires a detailed understanding of perception system performance, intended functionality, operations and failure modes, the surrounding environment and integration strategies, which are essential to support the safe deployment of autonomous technologies in real-world applications.

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