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Technological assessment for the development of a novel autonomous mobile operating machine with supervision to enhance safety in construction sites

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Within construction activities for buildings, roads, and civil infrastructures, machine operators play crucial roles in driving and managing machines and other equipment used for earthmoving, site preparation, erection or modification of structures, and finishing operations. During these tasks, operators are directly exposed to multiple severe occupational risks, closely related to the specific activity and machinery employed. Recent advancements in automation technologies - capable of providing increasing levels of autonomy and intelligence - offer promising applications in the civil construction sector to make working tasks safer and healthier.
In this context, the paper presents a preparatory study for a novel concept of an autonomous mobile operating machine designed for civil construction sites, capable of performing operations without the presence of an onboard operator, thereby reducing human exposure to hazardous conditions. The design and implementation of the new system will be carried out in compliance with the requirements of the upcoming EU Machinery Regulation 2023/1230 (MR) and aligns with the principles of economic, environmental, social, and safety sustainability.
Limiting the presence of the operator means designing multifunctional and fully autonomous machines with the integration of the supervisory function. This article aims to examine the most suitable technologies and solutions for the development of an autonomous mobile machine that is technologically sustainable in the context of civil construction sites where it is necessary to carry out safe work. The results of this analysis are the first step in a research activity which aims at the development of the completely autonomous mobile operating machine, for two or more functions and supported by a robust control and supervision system compliant with the MR. The preparatory study was carried out 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.

Keywords: autonomous mobile machine, supervisory function, construction sites, safety assessment, technological survey.

1. Introduction

Construction sites for buildings, roads, and civil infrastructures are among the most hazardous working environments, due to the simultaneous presence of multiple companies, workers, mobile machinery, unstructured terrains, and dynamically changing operational conditions (Xu et al. 2025; Eurostat 2023). Machine operators are routinely exposed to a wide range of occupational risks, including mechanical hazards related to moving parts, collisions and overturning, exposure to noise and vibrations, inhalation of dust and exhaust gases, ergonomic overload, as well as low-frequency but potentially high-severity fire and explosion hazards associated with the accidental rupture of underground utilities (Lingard and Rowlinson 2005).

Statistical analyses of occupational accidents in the construction sector show that a significant share of severe and fatal events is directly related to the interaction between workers and mobile machines, such as unintended machine movements, contact with moving components, and run-over incidents (Teizer et al. 2010). Reducing direct human exposure to these hazards therefore represents a primary objective for improving occupational safety in construction activities (Eurostat 2023).

Recent advances in automation, sensing, and control technologies enable machines to operate with increasing levels of autonomy and intelligence (Xie et al. 2024). In other industrial domains, such as manufacturing and agriculture, autonomous or semi-autonomous machines have already highlighted their potential to reduce operator exposure to hazardous conditions while maintaining/increasing productivity levels (Chen et al. 2026). However, the transfer of these technologies to civil construction sites remains limited, mainly due to the intrinsic complexity and variability of outdoor, unstructured, and interference-rich environments (Hamledari et al. 2018).

In this context, the development of autonomous mobile machines for construction requires not only technological innovation, but also a systematic assessment of safety, reliability, regulatory compliance, and sustainability aspects (ISO 12100:2010). In fact, simply creating an autonomous system that reduces human presence by transforming the machine operator into a supervisor working from a safe remote location is not, itself, sufficient to improve safety. The autonomous system must also implement specific safety measures, protective devices, and structured risk mitigation strategies designed to ensure the safety of any other workers who may be in the area. In the present study, safety is treated as the overarching objective, whereas reliability and regulatory compliance are considered enabling dimensions: reliability supports the consistent performance of safety-related functions, and compliance provides the mandatory framework within which risk reduction measures are defined and verified. The recently adopted EU Machinery Regulation 2023/1230 (MR) explicitly acknowledges the presence of machines capable of autonomous behavior and adaptive decision-making, emphasizing the manufacturer's responsibility to perform comprehensive risk assessments and to ensure adequate supervision and control measures (European Union 2023).

The research project MACHINE5.0 is addressing these challenges by studying a possible novel concept of an autonomous mobile operating machine supported by a robust supervision system. Within this framework, the present paper focuses on a preliminary technological assessment aimed at identifying enabling technologies, system architectures, and safety solutions which help achieve reliable autonomous operation of machines in construction sites while significantly reducing operator exposure to risks and evaluating their advantages and disadvantages.

2. Methodological framework of the technological assessment

The technological assessment was conducted as a preparatory activity for the development of a prototype autonomous mobile machine.

The assessment follows a structured, multi-dimensional approach, combining technological feasibility, safety and reliability considerations, regulatory requirements, and sustainability principles. The assessment methodology is articulated into the following four main steps:

(i) Definition of the operational context: identification of typical construction-site scenarios, working tasks, environmental conditions, and interference situations relevant to mobile machinery
(ii) Functional decomposition of the system: analysis of the machine as a system-of-systems, including the mobile platform, tools, autonomous guidance module, onboard sensing, communication infrastructure, and supervision system
(iii) Technology screening and comparison: evaluation of candidate technologies for perception, localization, obstacle detection, human–machine separation, environmental monitoring, and remote supervision, based on performance, robustness, maturity, and integration complexity.
(iv) Safety-oriented assessment: analysis of how each technological solution contributes to risk reduction, fault detection, safe states, and compliance with the essential health and safety requirements (EHSR) of the Machinery Regulation.

This methodological framework ensures that technological choices are not driven solely by performance considerations but are primarily geared toward improving worker safety and coherently aligned with safety, reliability, and regulatory constraints typical of high-risk working environments.

The proposed four-step structure follows a systems-engineering and safety-by-design logic. The operational context defines the boundary conditions and use scenarios; functional decomposition identifies the relevant subsystems, interfaces, and safety-critical interactions; technology screening compares candidate solutions at subsystem level; and the final safety-oriented assessment verifies how the shortlisted solutions contribute to risk reduction, safe states, and regulatory compliance. This sequence provides traceability from the worksite scenario to the resulting technological architecture.

3. Technological assessment of the autonomous mobile machine concept

In order to make the technological assessment explicit and reproducible, the comparison of candidate solutions was structured through a set of qualitative comparison tables.

These tables summarize the main technologies considered for each subsystem, highlighting their advantages, limitations, and relevance with respect to system safety, while considering reliability and regulatory compliance as enabling evaluation criteria in construction-site environments.

It is important to stress that the assessment outcomes reported in the various tables represent the result of a technological suitability evaluation with respect to the operational scenario and safety objectives considered. The comparison does not indicate a final design choice but rather identifies certain aspects to be taken into account when developing the system architecture of the future project. To ensure traceability with the methodological framework, the comparison reported in this section is grounded on the outcomes of steps (i) and (ii). The reference operational context consists of outdoor civil construction tasks such as site preparation, excavation support, and related earthmoving activities, characterized by uneven terrain, dust, weather exposure, dynamic obstacles, and interference with workers and other machines. The technological assessment presented below focuses on step (iii), while explicitly building on these preliminary analyses.

3.1. *Mobile platform and operating modes*

The reference platform for the exploratory assessment discussed in this article is a generic, compact, commercially available mobile machine typically used in construction sites assumed to operate in a fully autonomous mode during working tasks. Before proceeding to the technical evaluation of an autonomous solution, various machine control modes were analysed to assess their pros and cons, including the possibility of combining different control modes within the same machine.

3.2. *Autonomous guidance and control*

Table 1 compares operational control modes and associated guidance approaches considered for mobile construction machinery. In particular, it distinguishes between operating modes of the machine: manual on board control, manual wireless remote control, preloaded trajectories, and autonomous guidance. The assessment focused on comparison guidance solutions relying on preloaded trajectories and fully autonomous guidance systems, combined with local perception systems to cope with positioning uncertainties and dynamic obstacles.

3.3. *Perception and obstacle detection*

Obstacle detection and human–machine separation are critical for risk reduction in construction sites. Table 2 compares the main perception technologies evaluated during the assessment.

A core element of the technological assessment concerns the perception system required to support safe travelling and obstacle detection for autonomous mobile machinery, in line with the essential health and safety requirements of Annex III, point 3.3.3 of Regulation (EU) 2023/1230. Within this regulatory framework, the system shall be capable of detecting relevant obstacles and hazardous situations in proximity to the machine, including workers and other exposed subjects. Motroni et al. (2024) is therefore considered only as a technical reference for RFID-based identification solutions, and not as the source of the underlying system-level requirements.

LiDAR systems have been evaluated for their high spatial resolution and accurate geometric representation of the surrounding environment. However, when used as a standalone solution, LiDAR-based perception may suffer from line-of-sight limitations and limited semantic understanding, potentially leading to false positives or ambiguous obstacle classification.

Radio-frequency technologies, such as UHF-RFID and UWB, have instead been evaluated for their ability to detect and identify workers equipped with tags integrated into personal protective equipment.

UWB-based systems, which can be considered a form of RFID technology, have been evaluated for both localization and identification capabilities, as well as for the possibility of being implemented without fixed infrastructure. Their localization accuracy may nevertheless be affected in non-line-of-sight conditions, depending on the nature of the obstacles between tags and antennas. Similarly, UHF-RFID systems can operate in non-line-of-sight conditions, but their performance is influenced by the electromagnetic properties of intervening obstacles and by the overall tag–antenna configuration. These aspects must therefore be taken into account in the assessment when evaluating the robustness of radio-frequency-based human detection solutions.

In addition to LiDAR and radio-frequency-based solutions, the assessment also considered radar-based sensors and camera-based systems, including certified 3D and depth cameras designed for outdoor and safety-related applications. In this context, RGB cameras are considered as supportive perception sensors, mainly aimed at providing semantic and contextual information and supporting situational awareness and supervision. Due to their sensitivity to lighting conditions and airborne dust, safety-related stopping actions should be instead entrusted to dedicated safety-rated sensing technologies.

Radar sensors, on the other hand, provide robust presence detection capabilities even in the presence of dust, rain, and poor lighting conditions. Their spatial resolution depends on the specific radar technology and configuration, with advanced automotive radars typically offering finer resolution than more conventional industrial solutions. Depth cameras enable direct distance measurement and improved obstacle discrimination at short and medium ranges, but present limitations when used as standalone solutions. Overall, the technological assessment supports a redundant perception strategy that must ensure high standards of reliability. This approach appears consistent with the safety requirements set out in the new Machinery Regulation, including for autonomous mobile machinery, and with the need to ensure acceptable risk levels in complex and dynamically changing construction environments.

Table 1. Comparison of operational control modes and associated guidance approaches.

Mode/Approach	Operational characteristics	Advantages	Limitations	Safety relevance	Assessment outcome
Manual onboard control	Operator physically onboard during all machine operations	High operator awareness, mature solutions	Requires continuous attention, full exposure of operator to hazards	Low	Baseline reference
Manual wireless remote control	Machine remotely driven by operator positioned in line of sight	Operator positioned in a “semi-safer” area, high flexibility, mature solutions	Requires continuous attention, requires the operator to be in the correct position, limited situational awareness, partial exposure of operator to hazards,	Medium	Suitable in some phases and for some tasks
Predefined trajectory	Machine autonomously follows preloaded trajectories and tasks-under human supervision	Operator positioned in a safer area for loading trajectory and supervision, repeatability of tasks	Medium/higher system complexity, requires greater operator skill to load the trajectories	Medium	Suitable only with additional perception layers and/or segregated work area (unreachable). The definition of reliability requires particular attention. The choice/preference between these two solutions (predefined or autonomous) may depend on the task of the machine
Autonomous guidance	Autonomous execution of working tasks under human supervision	Operator positioned in a safer area (for supervision)	Very high system complexity, very difficult to fully ensure the reliability	High	

Table 2. Comparison of perception and obstacle-detection technologies.

Technology	**Strengths**	**Weaknesses**	**Safety contribution**	**Assessment outcome**
LiDAR	High spatial resolution, accurate geometry	Limited object classification, line-of-sight constraints, limitations in dusty environment	High	Evaluated as perception sensor
Safety radar (outdoor, PL-rated)	Robust to dust, rain, lighting; long detection range	Spatial resolution dependent on radar type and configuration	High	Evaluated as safety sensor
RGB cameras	Rich semantic information	Sensitive to lighting and dust	Medium	Evaluated as perception sensor for contextual understanding
3D / depth cameras (e.g. ToF, stereo, certified)	Direct distance measurement, improved obstacle discrimination	Limited range, sensitivity to environment	High	Evaluated as perception sensor
UHF-RFID	Reliable identification of tagged workers; can operate in non-line-of-sight conditions	Performance depends on obstacle type and tag–antenna configuration	Very high	Evaluated for human detection and pre-tagged obstacles
UWB	Accurate ranging and tag identification; anchors can be mounted directly on the vehicle	Localization performance may degrade in non-line-of-sight conditions	High	Evaluated for detection of pre-tagged humans and obstacles
LiDAR + RFID / UWB sensor fusion	Combines geometry and identity	Increased integration complexity	Very high	Evaluated as geometric representation of the surrounding environment

3.4. *Worksite hazard monitoring*

Worksite hazards such as hazardous gas leaks and fires represent severe risks, particularly in outdoor construction sites where underground utilities and combustible materials may be present. Assessments were therefore conducted on potential technologies that could be used to monitor a “construction site,” considered as a workplace. The technological assessment therefore addressed sensing solutions capable of detecting hazardous conditions that can rapidly evolve into critical events for both workers and machinery.

With respect to gas and fire detection, the assessment considered different sensing technologies commonly adopted in industrial and construction environments (Table 3).

Semiconductor (MOS) sensors and pellistor-based devices, although mature and cost-effective, were found to be inadequate for the scenario considered due to their relatively slow response times and sensitivity to interfering substances. In realistic scenarios and tasks typically carried out on construction sites, such delays may result in operator exposure to dangerous concentrations before the alarm is triggered.

Infrared-based solutions were therefore analyzed in greater detail. Non-dispersive infrared (NDIR) sensors provide good selectivity but may suffer from performance degradation under intense vibrations and require periodic calibration. Tunable diode laser absorption spectroscopy (TDLAS) sensors emerged as an interesting solution, due to their very fast response time (typically below one second), high selectivity for target gases and low drift over time.

In outdoor worksites, wind and turbulence can quickly displace gas plumes, therefore single-point measurements may miss short-term releases. In addition to methane and fire, excavation can involve oxygen depletion and toxic gases.

Fire detection technologies were also evaluated, considering the presence of ignition sources such as cutting tools, welding operations, and combustible dust. Conventional flame detectors were found to be insufficient on their own, due to their limited coverage. Infrared thermal cameras were found instead effective for the early detection of abnormal thermal patterns over extended areas, even in dusty or low-visibility conditions.

3.5. *Supervision system and human-in-the-loop*

The technological assessment identified human supervision as a key enabler for safe autonomous operation. Table 4 compares alternative supervision approaches.

A central outcome of the technological assessment is the recognition that fully autonomous operation in construction sites requires a robust supervision architecture in order to assure full operational safety.

Considering the essential health and safety requirements concerning the supervisory function for autonomous mobile machinery (Annex III, point 3.2.4 of the MR), various solutions may prove effective (depending on the specific contexts and tasks), including direct visual monitoring, fixed cameras located at a distance, even up to a supervision station that receives real-time information from the machine. In critical conditions, such as those due to degradation in communications or hazardous environmental conditions, supervisors may face limitations that must be taken into account during the design phase.

3.6. *Regulatory and safety implications*

From a regulatory perspective, the technological assessment confirms that autonomous mobile machines cannot rely solely on traditional safety solutions developed for manually operated equipment. The integration of autonomous functions requires explicit consideration of reasonably foreseeable misuse, failure modes, communication losses, and human–machine interaction scenarios.

The assessment therefore emphasizes the need for a safety-by-design approach, supported by systematic risk analysis according to ISO 12100 and aligned with the new requirements introduced by the Machinery Regulation 2023/1230, especially with respect to autonomous behaviour and supervision functions.

4. Discussion and outlook

The technological assessment presented in this paper indicates the feasibility of developing an autonomous mobile operating machine for construction sites that significantly reduces operator exposure to hazardous conditions. At the same time, it highlights the complexity of integrating autonomous functions in unstructured and interference-rich worksites and the need to protect workers who may, even accidentally, find themselves in the autonomous machine's working area.

The results of the preliminary assessment provide a structured basis for subsequent design, implementation, and validation activities within the MACHINE5.0 project, guiding technological choices toward solutions that are not only technically viable, but also safe, reliable, and aligned with regulatory and sustainability requirements.

Future work will focus on developing an autonomous machine capable of operating safely and with the necessary reliability in a construction site environment, on experimental validating the identified solutions and on refining risk assessment methodologies to support future certification pathways.

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Table 3. Comparison of gas and fire hazard monitoring technologies.

Hazard	Technology	Key technical characteristics	Advantages	Limitations	Assessment outcome
Gas detection (CH_4)	MOS sensors	Semiconductor sensing, typical response time >30 s, cross-sensitivity to multiple gases	Low cost, simple integration	Slow response, cross-sensitivity	Discarded
Gas detection (CH_4)	Pellistor	Catalytic combustion principle, response time ~10–15 s, oxygen-dependent	Robust, mature	High power consumption	To be considered
Gas detection (CH_4)	NDIR	Infrared absorption, good gas selectivity, response time <30 s, sensitive to vibrations	Good selectivity	Sensitivity to vibrations	To be considered
Gas detection (CH_4)	TDLAS	Tunable diode laser absorption, response time <1 s, very high selectivity, low drift	Fast response (<1 s), high selectivity	Higher cost	To be considered
Fire detection	Conventional flame sensors	UV/IR flame detection, fast response, limited spatial coverage	Simple implementation	Limited coverage	To be considered
Fire detection	IR thermal cameras	Infrared thermal imaging, wide-area monitoring, early hot-spot detection, robust in dust	Early detection, robust in dust	Cost, data handling	To be considered

Table 4. Comparison of supervision and monitoring solutions.

Supervision solution	Advantages	Limitations	Safety level	Assessment outcome
Direct visual supervision	Immediate feedback	Requires proximity to machine	Low	Discarded
Fixed remote cameras	Continuous monitoring	Occlusions, limited perspective	Medium	To be considered
Supervision station	Centralized safety management	Dependence on communication links	High	To be considered

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