Autonomy levels in mobile machine applications

Summary

Mobile machine applications are increasingly aimed to perform tasks autonomously. Companies encounter a multitude of challenges when striving for autonomous operations. Industrial production sites have often evolved over time, leading to a mix of modern and legacy equipment. That often results in issues such as:

- missing interfaces,
- incompatible communication standards,
- software systems from different providers.

A 4-dimensional Levels of Autonomy framework is introduced to guide the development of autonomous machines and systems. The framework covers four dimensions:

- machine driving
- machine manipulation
- system operation
- system mission

It integrates both individual machine capabilities and system-wide autonomy aspects.

The ultimate vision is to contribute to a future where autonomous systems across all domains operate seamlessly and efficiently without human intervention. The framework provides a common language that enables stakeholders — such as equipment manufacturers, suppliers, experts, and system integrators — to develop and implement autonomous systems.

Authors

Josepha Berger

Johannes Hyrynen

Risto Tiusanen

Introduction

Mobile machines are changing rapidly, becoming greener, smarter, and more independent. The machines are being designed to complete tasks on their own, utilizing sensors to understand their surroundings and AI to make decisions. The shift requires significant investments from both industry and research. The key drivers of the transition are electrification, automation, and communication. The development path is not straightforward. Many challenges must be overcome before machines can operate autonomously on worksites. Cross-industrial collaboration is highly beneficial for the transition, as the machines share synergies in terms of features and tasks.

A framework for Levels of Autonomy is introduced to guide the development of autonomous machines and systems. The concept looks at autonomy in different dimensions: from individual machine functions and tasks to entire work processes and system missions, each with its own elements of autonomy. The framework is a comprehensive tool that can be applied for several purposes:

1. Understanding and advancing autonomy in machines and systems.
2. Providing a structured approach to assess the real potential of autonomy in various processes.
3. Helping to understand the requirements for machines, either operating individually or as part of a fleet or wider system or executing from simple to complex tasks.
4. Enabling the development of safe, efficient, and cost-effective autonomous technologies by supporting cross-industrial collaboration through a common concept.
5. Offer methodology to evaluate the business value of investments in fully or partially autonomous systems.

Why a level of autonomy framework

Companies encounter various challenges when implementing autonomous operations. *Many industrial production sites have evolved over time, leading to a mix of modern and legacy equipment. This results in issues like missing interfaces, incompatible communication standards, and multiple software systems.* Limited IT and AI expertise among site operators hinders their ability to identify, implement, and trust new technologies, exacerbated by a shortage of skilled professionals. There are no turnkey solutions available to upgrade existing plants to specific autonomy levels. Technology providers' expertise must complement the site operator's needs and understanding. A comprehensive framework for autonomy levels is essential to address the challenges. A structured approach provides a means for integrating and managing diverse systems and technologies while also bridging the expertise gap. [1]

Companies can identify and prioritize areas that require attention to achieve their desired level of autonomy.

By utilizing a Levels of Autonomy framework, companies can systematically identify and prioritize areas needing attention to reach their desired level of autonomy. The common framework helps to determine technology requirements for individual machines to operate effectively within a system. It's important to consider the specific needs and constraints of each situation. The framework can point out that aiming for the highest level of autonomy is not always the best approach.

Insights into both current and future opportunities associated with various levels of autonomy are provided, facilitating a thorough evaluation of investments in autonomous systems. Companies can incrementally implement necessary measures, identify suitable partners for support, and streamline their operations.

The framework fosters collaboration with turnkey providers by establishing common terminology across the industry.

Example - mine operator´s transition to a highly autonomous mining system. To achieve a leap in the transition, the operator must engage various mining machine manufacturers in detailed discussions of the current and desired conditions at the mine site.

It is crucial for the mine management and designers to understand the possibilities and limitations of the autonomous mining technology they plan to use, along with the new safety risks and requirements that come with higher autonomy levels.

The physical mine design needs to be suitable for the integration of autonomous equipment, as well as potential combinations of autonomous, semi-autonomous, and manual equipment.

Connectivity issues may arise if part of the mobile machine equipment remains manually operated.

Additionally, defining the necessary skillsets for operating and maintaining the systems is important.

Mine operators and vendor partners will equally benefit from a uniform framework allowing them to make informed decisions and overcome confusion and inefficiencies that arise from using their own definitions. A common Level of Autonomy framework provides guidance in aligning autonomy solutions to specific operational needs. [3]

Levels of autonomy across different sectors and industries

In defining the levels of autonomy, it is vital to make a distinction between autonomy and automation. Differences of the terms ‘automation’ and ‘autonomous’ have been defined e.g., [3] in mining industry.

- **Automatic:** A process or part of a process when a machine follows well-defined rules.
- **Automation:** The technique, method, or system of operating and controlling a process or machine by automatic means with minimal human intervention.
- **Autonomous:** A process or machine that is intended to accomplish task(s) within a set of defined operations without human intervention or direct control.
- **Autonomous system:** A system that can perform desired tasks in unstructured environments without continuous human guidance.

Definitions for levels of autonomy vary widely across different sectors and industries. SAE J3016 [2] focusing on autonomy in driver control and vehicle operation has influenced the development of Level of Autonomy in domains, including mining [3], construction [4], trains and metros [5], [6] and the maritime sector [7], [8], [9]. Even companies adopt unique approaches to classifying autonomy levels. For example, Roland Berger Manufacturing developed its own matrix for autonomy levels in manufacturing [1]. Similarly, researchers at ABB [10] have outlined their own framework for autonomy within the industrial sector.

The definitions so far have mainly concerned single machinery, vehicle or vessel specific autonomy functions. However, as industrial activities increasingly focus on whole missions or processes to be carried out autonomously, it would be advantageous to extend the approach to the machinery system and work process dimensions.

Dimensions of the Framework

Traditional levels of autonomy have primarily focused on single-machine capabilities, evaluating them in a narrow, task-oriented manner. The SAE J3016 levels for driving automation, for example range from Level 0 (no automation) to Level 5 (full automation). As the push for system-wide autonomy grows, a broader perspective is needed to adequately assess and implement autonomy across entire systems.

Evaluating autonomy solely based on single-machine functions is insufficient for understanding system-wide capabilities. Assessing autonomy becomes more complex when evaluating how multiple machines work together as a unified system. *Understanding their interactions, coordination, and the overall system behaviour are required instead of considering the autonomy of individual machines.* The number of criteria needed to characterize autonomy levels grows as we move from evaluating individual machine capabilities to evaluating autonomous interactions of multiple machines. This is illustrated in Figure 1.

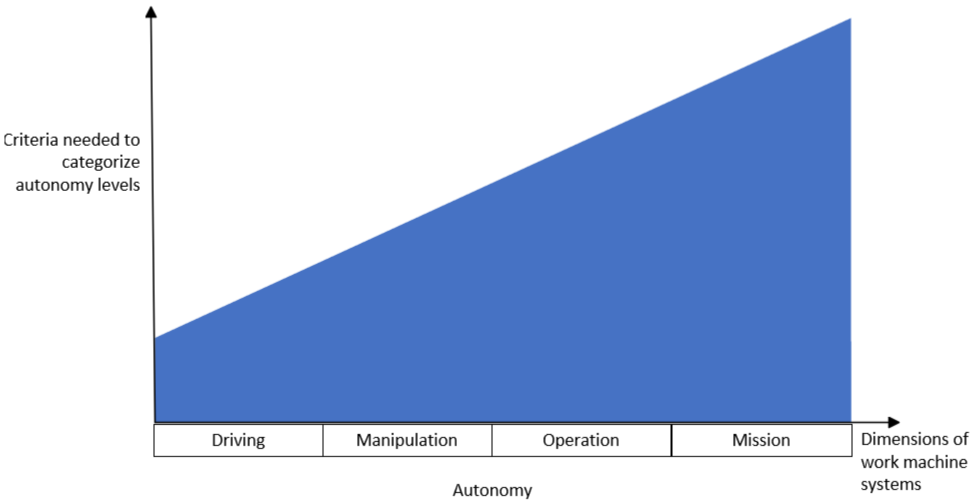

Figure 1. Criteria for categorizing autonomy levels increases as the autonomy of work machine and their systems increase.

To address the complexity, the framework should include criteria for both individual machines and the coordination of fleets and subsystems. Adding new dimensions to the framework allows for a more comprehensive assessment of autonomy, covering everything from individual machine functions to their integration into larger systems. For example [11], proposes adding a “Manipulation” dimension. While this is a valuable addition, it does not fully capture the broader complexities of managing system-wide autonomy.

The multi-dimensional Level of Autonomy framework presented in Figure 2 aims to provide a more detailed analysis. Existing models focus solely on system-level autonomy [3] or individual machine autonomy [2]. The new presented framework incorporates dimensions for:

Machine driving
Machine manipulation
System operation
System mission

The approach ensures a thorough categorization of autonomy covering individual machines and their integration into larger, coordinated systems.

<table>
<tr><th></th><th>D – Driving
(Machine)
Navigating and/or moving from place to another</th><th>M – Manipulation
(Machine)
Interacting with and modifying objects</th><th>O – Operation
(Connected machines)
Performing tasks to single work processes as a machine group (fleet)</th><th>S – Mission
(System mission)
Several connected machine fleets perform tasks in different work processes to achieve an overall system goal</th></tr>
<tr><td>**0**
No automation</td><td>**D0**
Full manual control. Lateral and longitudinal motion controller manually e.g. steering, braking, acceleration</td><td>**M0**
Joint space control. Individual joints controlled e.g. boom, bucket</td><td>**O0**
Human based task management. Machines are operating as individuals. Task management by humans, H2H communication</td><td>**S0**
Human based mission management. Human operators are the only source of situational awareness</td></tr>
<tr><td>**1**
Operator assistance</td><td>**D1**
Unidirectional control. Either lateral or longituinal motion, but not both, is controlled. Huvan provides inputs e.g. traction control</td><td>**M1**
Cartesian space control. End effector is contolled e.g. bucket, harvester head</td><td>**O1**
Assisted task management. Model based worksite. Machine control system gives task related guidelines for the operator of the individual machine.</td><td>**S1**
Assisted mission management and situational awareness. Providing real-time alerts for potential hazards, requiring operator attention</td></tr>
<tr><td>**2**
Partial automation</td><td>**D2**
Bidirectional control. Both longitudinal and lateral motion control possible. Limites exteroceptive capabilities e.g. 'blind autonomy' in mines</td><td>**M2**
Configuration control. Pre-configured motion trajectories, no exteroceptive sensors e.g. swing control in harvester</td><td>**O2**
Automated task management. Model based worksite. Machine control system gives task related parametres for the individual machine.</td><td>**S2**
Enhanced situational awareness. Integrating more advanced sensors and data to support automated functions and human supervision.</td></tr>
<tr><td>**3**
Conditional automation</td><td>**D3**
External perception. Machine has exteroceptive capabilities and can navigate in structured environments e.g. Y or V cycle in loaders</td><td>**M3**
External perception. Extension of level M2 with exteroceptive perception e.g. obstacle detection during trajectory</td><td>**O3**
External perception. Every machine selects its next task depending on the state of the mission. E.g in mining, dedicated machine continue the preparation of a tunnel after the previous machine has completed its task, In a harbor an individual machine enters a charging station, when it is optimal considering the entire fleet. M2M communication</td><td>**S3**
Automated Decision-Making.
Algorithms to handle safety-critical decisions in real-time, with human override capabilities.</td></tr>
<tr><td>**4**
High automation</td><td>**D4**
Navigation autonomy. Simultaneous localization and mapping capabilities. Machines can navigate in semi-structured environments with low level real time decision making capability e.g. autonomous haulage systems</td><td>**M4**
Task autonomy. Interaction with homogenous materials in semi-structured environment e.g. perception based pile characterization</td><td>**O4**
Operation autonomy. The individual machines can give instructions and train other machines (exchange information) based on the state and goal of the mission.</td><td>**S4**
Comprehensive System Coordination . Dynamic risk awareness. Different autonomous systems can work together safely. Mechanisms for safe automatic recovery after system stops or failures.</td></tr>
<tr><td rowspan="2">**5**
Full automation, autonomy</td><td>**D5**
Machine autonomy. Active localization, mapping and collision avoidance systems</td><td>**M5**
Machine autonomy. Interaction with heterogenous materials.</td><td rowspan="2">**O5**
Fleet autonomy. The mission itself is not well defined (e.g. the consecutive missions are different) and the fleet of the machines can redefine the mission for achieving improved performance (aka autopoesis).</td><td rowspan="2">**S5**
Mission autonomy. Dynamic risk assessment. System is capable of making safety-critical decisions without human intervention. Incorporating machine learning and AI to improve safety measures and adapt to new challenges.</td></tr>
<tr><td colspan="2">**Intelligent, self-governing, independent machine.** Machine can operate in any environment with minimal human supervision and intervention. Human in a role of supervisor.</td></tr>
</table>

Figure 2. Level of Autonomy framework with 4 dimensions for mobile machine systems.

The dimensions in a Level of Autonomy framework are essential because even advanced systems have elements at lower autonomy levels. Additionally, companies in the early stages of transitioning to system autonomy can receive guidance on what to consider when upgrading specific parts of their fleet and communication systems. A common concept addressing both individual machines and entire machinery systems helps various stakeholders—such as OEMs, suppliers, subject matter experts, and system integrators—determine the best approaches for implementing increasingly autonomous systems. The autonomy evaluation criteria are categorized into four dimensions, each with its own scope, to provide guidance on autonomy considerations. Table 1 elaborates on the specific scope of each dimension.

Table 1. Scopes of the dimensions

Dimension	Description
Driving	Single-machine functional dimension Encompasses considerations enabling individual machines driving autonomy
Manipulation	Single-machine functional dimension Encompasses considerations enabling individual machines to achieve manipulation autonomy (functions other than driving e.g. drilling, material handling, lifting, task planning, and scheduling)
Operation	Connected machines or a fleet composing of same type of machines but at different autonomy levels executing a single work process Encompasses considerations for machines of the same model or design, with varying degrees of autonomy, collaborating to execute a single type of work process
Mission	Several connected machines and fleets of different types that work together on separate tasks The focus is on integrating diverse types of machines and systems, each with different functionalities and autonomy levels, to complete complex, multi-step tasks or missions

The mission dimension emphasizes system-wide management considerations, for operational and business functions as well as for system safety measures. In the context of the mission layer and safety, increasing the level of autonomy necessitates adjustments in safety considerations. As a system evolves towards handling a broader range of scenarios autonomously, maintaining high safety standards becomes crucial. To address that, advanced capabilities such as 'dynamic risk awareness' and 'dynamic risk assessment' at higher levels of system autonomy are introduced, as illustrated in Figure 2.

Several other aspects of safety are vital for ensuring comprehensive system mission management:

- Connections and interlocking of safety functions of machines with different LoA and varying operating modes
- Terrain map needs to be maintained and updated on moveable and fixed objects (traffic light, boom and gate control for optimizing and prioritizing movements of vehicles)
- Area access control
- Changes of operating modes or autonomy levels of machines or sub-systems
- Gathering and usage of Situational Awareness (SA) information from different systems for safety critical decision making
- Safe start-up, shut-down, operational change or recovery after an (un-) intentional stop or based on real-time SA information
- Systems capability of making safety-critical decisions without human intervention
- Determining situations when human operator must confirm and approve safety-critical actions or changes in planned safety operations
- Assigning responsible persons when machines' operating mode and LoA changes
- Layers of protection (primary, contingency and preventive) to manage any potential failure scenarios
- Plans for human override capabilities and transitions
- Operators must be trained continuously to understand and effectively use varying automation features

The presented considerations only describe safety-related autonomy issues. A complete Level of Autonomy framework shall not neglect other business-related and system-wide autonomy capabilities, concerning for example logistics, disposition, procurement, product and document management. The framework should further be developed in the following areas:

- Situational Awareness
- Task management, scheduling, optimization, supervision
- Decision making, roles and responsibilities, operators / automation
- Communication and monitoring: technology, protocols, prioritization, reliability
- Refueling or charging of machines
- Maintenance and troubleshooting

The paper has illustrated how the Level of Autonomy framework can be structured, using safety considerations in the mission dimension as an example. It would be highly beneficial to initiate further research to identify additional business- and system-wide aspects that the mission dimension should contain.

The ultimate vision

This white paper proposes a Level of Autonomy framework, that includes system mission autonomy and single machine autonomy capabilities. The advantages of having a uniform Level of Autonomy framework that can be applied across various industries are highlighted. Such a framework enables providers of comprehensive, turn-key solutions to support companies regardless of their current autonomy level or operational domain.

The ultimate vision is to create a future where autonomous systems operate seamlessly and efficiently without human intervention.

By advancing machine and system autonomy and integrating cutting-edge technologies like AI, machine learning, and robotics, we can enhance productivity, safety, and reliability in sectors such as transportation, manufacturing, marine, and agriculture. The framework contributes significantly to this vision, offering a common language and concept that aligns all stakeholders in achieving the goal.

References

[1] B. Langefeld, M. Moehrle, and J. Zinn, "Rise of the machines – How robots and artificial intelligence are shaping the future of autonomous production," Focus Roland Berger. 2019.

[2] SAE International, SAE J3016 Surface Vehicle Recommended Practice - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. 2021.

[3] "Guideline for the Implementation of Autonomous Systems in Mining," 2018. [Online]. Available: http://www.gmggroup.org

[4] J. Fottner and K. Nübel, Lecture Notes in Civil Engineering. 2023. doi: 10.1007/978-3-031-44021-2.

[5] UTIP, "World Report on Metro Automation. UITP Statistic Brief.," 2018.

[6] IEC, IEC 62290-1:2014 Railway applications - Urban guided transport management and command/control systems - Part 1: System principles and fundamental concepts. 2014.

[7] E. Lehtovaara, "Autonomous Ships - Terms of Reference for Rule Development."

[8] M. Poornikoo and K. I. Øvergård, "Levels of automation in maritime autonomous surface ships (MASS): a fuzzy logic approach," Maritime Economics and Logistics, vol. 24, no. 2, pp. 278–301, Jun. 2022, doi: 10.1057/s41278-022-00215-z.

[9] American Bureau of Shipping, "Advisory on Autonomous Functionality," 2019.

[10] T. Gamer, B. Kloepper, and M. Hoernicke, "The way toward autonomy in industry – taxonomy, process framework, enablers, and implications," in Proceedings, IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society : Convention Center, Lisbon, Portugal, 14-17 October, 2019, 2019.

[11] T. Machado, A. Ahonen, and R. Ghabcheloo, "Towards a standard taxonomy for levels of automation in heavyduty mobile machinery," in Proceedings of ASME/BATH 2021 Symposium on Fluid Power and Motion Control, FPMC 2021, American Society of Mechanical Engineers (ASME), 2021. doi: 10.1115/FPMC2021-70251.

For more information please contact

Josepha Berger
josepha.berger@vtt.fi

About VTT

VTT is one of the leading research and technology organisations in Europe. Our research and innovation services give our partners, both private and public, all over the world a competitive edge. We pave the way for the future by developing new smart technologies, profitable solutions and innovation services.

We create technology for business – for the benefit of society.

VTT beyond the obvious

www.vttresearch.com