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Towards industrial autonomy: a four-dimensional Level of Autonomy (LoA) Framework

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Industrial systems are transitioning towards greener, digital, and autonomous solutions, resulting in significant changes to their design and operation. This path to full autonomy faces several challenges, especially in integrating modern and legacy equipment at industrial sites, causing incompatible communication standards and diverse software systems. Each site presents unique requirements, necessitating close cooperation between technology providers and site operators.

Site operators need a thorough understanding of the opportunities, limitations, and safety risks associated with increased autonomy. Additionally, the physical design of sites must be suitable for the integration of autonomous machines, alongside potential combinations of autonomous, semi-autonomous, and manual equipment. Communication challenges can arise when certain machines rely on manual operation, complicating overall system's functionality. Beyond technical hurdles, increased autonomy requires adjustments in business-wide operations, including safety management, logistics, product and document management, fleet management, and the refinement of operator skillsets.

To address these complexities, we propose a four-dimensional Level of Autonomy (LoA) framework that helps in identifying and prioritizing key areas for enhancing autonomy. Unlike existing models that focus solely on system-wide or individual machine autonomy, our LoA framework integrates dimensions for machine driving, machine manipulation, system operation, and system mission. The operational dimension considers the orchestration of autonomous driving and manipulation of both individual machines and entire fleets, while the mission dimension emphasizes the management of multiple connected mixed fleets working towards a unified system goal.

Dimensions of autonomy are crucial because they highlight areas where human involvement is necessary and provide insights into strategies needed to enhance autonomy or assess the current level of system autonomy. A comprehensive LoA framework benefits stakeholders, including original equipment manufacturers (OEMs), suppliers, and system integrators, by providing a unified approach for implementing autonomous systems.

Keywords: Level of Autonomy, automation, framework, manual operation, autonomous operation, mixed fleets, industrial autonomy.

1. Introduction

Mobile machines are undergoing a significant transition towards green, digital, and autonomous solutions that will revolutionize their design and operation. These vehicles and machines are increasingly aimed to perform specific tasks without human intervention, relying on sensors to interpret the operational environment and artificial intelligence (AI) to make decisions based on the sensor data. This transition demands substantial resources and investments from both industry and research sectors. The key enablers of this industrial transformation are electrification, automation, and communication. Technologies are continuously evolving to further enable autonomous vehicles and machines. However, the development path is not straightforward, and many challenges must be addressed before autonomous machines can operate effectively on worksites. Cross-industrial collaboration is essential for this transition, as these machines share many synergies in terms of features and tasks.

There are several reasons why automation has not advanced as quickly as some might expect. Technical reasons are significant research requirements and the difficulty of integrating new systems with older infrastructure. Additionally, costs can be substantial, especially when automation technology is new, and requires extensive infrastructure upgrades. Human factors also play a significant role in resistance to automation, particularly concerns about job security. People often fear that automation will replace their jobs. Ethical considerations further complicate the issue, involving questions about AI standards, prioritizing automated operations, and adhering to ethical guidelines. Not all businesses are ready to embrace automation, as they may lack the necessary skills, knowledge, or infrastructure to implement and maintain automated systems. Despite these challenges, automation continues to advance steadily, and system designers are finding innovative ways to integrate highly automated systems into their operations.

In this paper, we present a framework for levels and elements of autonomy that are needed to efficiently develop and deploy autonomous solutions in various applications and environments. The Levels of Autonomy (LoA) framework can be considered for different dimensions (individual functions and tasks of machines, or entire work processes and production systems), each encompassing different elements of autonomy. This uniform LoA framework can provide a structured approach to assess the potential of autonomy in various processes, and support cross-industrial collaboration through a common language. It can help understand requirements for machines, whether operating individually or as part of a fleet or wider system, or executing simple to complex tasks. Our LoA framework can support the development of safe, efficient, and cost-effective autonomous technologies, ultimately offering a methodology to evaluate the business value of investments in fully or partially autonomous systems.

2. Why do we need a comprehensive LoA framework?

Different industrial domains use different LoA frameworks. Foremost, SAE J3016 (SAE International 2021) focusing on autonomy in driver control and vehicle operation laid the foundation and influenced efforts defining other industry specific LoAs. For example, mining sector (Harris 2019), construction sector (Richter et al. 2023), trains and metros (Observatory of Automated Metros 2018, IEC 2014), as well as the maritime sector (One Sea 2022, Poornikoo and Øvergård 2022, American Bureau of Shipping 2019) have their own LoA frameworks. Even companies adopt unique approaches to classifying autonomy levels. For example, Roland Berger Manufacturing (Langefeld et al. 2019) developed its own matrix for autonomy levels in manufacturing. Similarly, researchers at ABB (Gamer et al. 2019) have outlined their own framework for autonomy within the industrial sector. These frameworks have in common, that they are concerned with single-machine capabilities on a task or function level. For example, the SAE J3016 levels for driving automation range from Level 0 (no driving automation) to Level 5 (full driving automation).

However, implementing autonomous operations is a complex challenge as it eventually expands beyond single machine functionalities. For example, many industrial production sites have expanded over time, resulting in a mix of modern and legacy equipment, leading to missing interfaces, incompatible communication standards, and multiple software systems. A lack of IT and AI expertise limit site operators' ability to identify and implement potential use cases and trust new technologies. Building up these competencies is challenging due to a shortage of experts. Lastly, there are no ready solutions that can be bought for upgrading existing plants to a certain autonomy level. The expertise of the technology providers must complement and be compatible with the site management's understanding and requirements. (Langefeld et al. 2019)

As industrial activities increasingly require the autonomous execution of entire processes and missions, we see it beneficial to extend the LoA approach. This extension should go beyond individual machine functionalities and include fleet operations as well as the overall mission of the industrial system.

3. How a comprehensive LoA framework could look like

Existing LoA frameworks focus either on individual machine autonomy (SAE International

2021) or system autonomy (Harris 2019). There is no comprehensive LoA framework, that considers both. Using single-machine functional dimensions, such as driving and manipulation, to evaluate systems' autonomy levels is inadequate. When autonomy extends from individual machines to entire systems, new aspects and perspectives must be considered. System-specific criteria are needed to properly assess autonomy at the system level. Fig. 1 illustrates that evaluating system-wide autonomy requires additional criteria and considerations than when evaluating autonomy of single machines. Therefore, we propose, that the comprehensive LoA framework should encompass both evaluation criteria for individual machines and for the coordination of fleets and subsystems working together on a mission towards a unified system goal. This can be achieved by adding dimensions. Machado et al. (2021) propose a LoA with "Driving", and "Manipulation" dimensions. While this proposal is a step in the right direction, it neglects that machines with different autonomy levels can cooperate as a fleet to conduct parts of the operation, or even the whole mission.

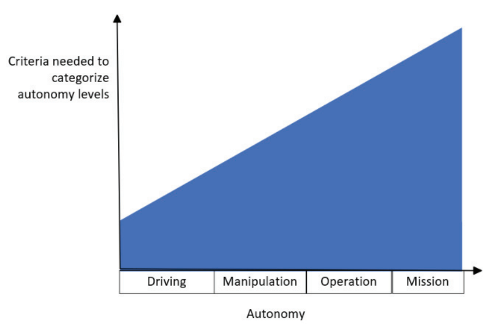

Fig. 1. Considerations to estimate level of autonomy increases when moving from single machine autonomy to mission autonomy.

Our efforts strive for a four-dimensional LoA framework (Appendix A), that allows a detailed and nuanced analysis of autonomy. We propose a framework that encompasses dimensions for machine driving, machine manipulation, system operation and system mission.

We propose the scope of each of the four dimensions to include:

- Driving (Single-machine functional dimension): Encompasses considerations enabling individual machines driving autonomy.
- Manipulation (Single-machine functional dimension): Encompasses factors that enable 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 machines with individual autonomy levels executing single work processes (e.g. mining process, container handling, storage and transportation work process, logistic processes, construction / earth moving processes)): Encompasses considerations necessary for orchestrating autonomous driving and manipulation of individual machines or an entire fleet. For example: Manufacturing Execution System (MES) or Site-Execution-System (SES) with task-management, real-time monitoring, and automatic documentation for sites, control system in automated work processes like mines or container handling
- Mission (Several connected mixed fleets perform tasks in different work processes to achieve an overall system goal autonomously): Encompasses system-wide management considerations for managing responsibility, safety, logistics, disposition, procurement, product and document management, fleet management as well as asset tracking.

The practical implementation process could begin at estimating the current level of autonomy in machine driving, then manipulation, followed by system operation and finally system mission.

4. Benefits of using a four-dimensional LoA

Consider the following example where mine management aims to transition towards an autonomous mining system. Each mining site has unique requirements, needing different levels of preparation for infrastructure and software solutions. To address this, mine management must work closely with mining machine manufacturers to clearly communicate the current conditions and desired outcomes for the site. Additionally, mine managers and system designers must understand the capabilities and limitations of the autonomous mining technology they plan to use, as well as the new safety risks and requirements that come with advanced autonomy. 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, the new necessary skillsets for operating and maintaining these systems must be defined and personnel trained. Harris (2019) A comprehensive LoA framework helps companies systematically understand and plan how to enhance autonomy in their operations. It also enables vendors and solution providers to deliver tailored and effective solutions that meet specific customer needs.

4.1.*Identify priorities*

The LoA framework could enable companies to systematically identify where investments are needed, whether at the level of individual machines, fleet operations, or entire work processes. By pinpointing specific areas that require attention, companies can prioritize actions and allocate resources effectively to achieve their desired autonomy goals. This targeted approach ensures that efforts are focused on the most impactful areas, helping companies make steady and measurable progress toward higher levels of autonomy.

4.2.*Support decision-making*

The LoA framework can provide a comprehensive understanding of the opportunities, but also required investments necessary to achieve different levels of autonomy. Therefore, decision-makers are more easily aligned in their understanding of autonomy goals and the challenges that must be overcome. This enables companies to assess whether fully or partially autonomous systems are the right choice.

4.3.*Improved collaboration*

A common LoA framework creates a shared language not only between companies (site operators) and technology providers but also internally within subject-matter experts. This reduces misunderstandings and inefficiencies, making it easier to collaborate, upgrade systems, and solve technical challenges. Further, it helps companies identify suitable partners to support them as they progress toward higher autonomy. Turnkey providers can also benefit by using the LoA framework to offer tailored upgrading solutions, as it streamlines communication and fosters smoother interactions.

4.4.*Better technology integration*

As systems progress toward higher autonomy, challenges emerge, such as combining manual, semi-autonomous, and fully autonomous equipment within the same operation. For example, communication and coordination issues may arise when part of the equipment remains manually operated while other components become automated. Similarly, ensuring that sites can accommodate advanced technologies, such as autonomous fleets, requires early planning and foresight. A common framework facilitates the identification of technology requirements for individual machines to be able to operate within a fleet. The LoA framework ensures smoother transitions to higher levels of autonomy, helping companies design sites, operations, and workflows that accommodate mixed equipment and minimize disruption during the integration process.

5. Conclusion

This paper advocates for a LoA framework that incorporates autonomy aspects across four key dimensions: driving, manipulation, operation, and mission. These dimensions are critical, as even highly advanced systems may include components at varying levels of autonomy. 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. This uniform LoA framework is applicable across industries and supports the communication between various stakeholders like original equipment manufacturers (OEMs), suppliers, internal and external subject matter experts and system integrators, in determining appropriate approaches.

Our ultimate vision, which this paper aims to support, is the seamless and safe operation of mixed fleet systems across various domains and autonomy levels. We believe the 4-dimensional LoA framework can play a key role in introducing and developing autonomy in industrial work sites by offering a comprehensive set of considerations and facilitating communication and adoption across industries.

However, we emphasize the need for further research to complete and refine the framework. While we hope to have established a foundation, additional input is required to define suitable criteria especially for the operation and mission dimensions.

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Appendix A. Proposal for a 4-dimensional LoA Framework. (modified from (Machado 2021))

	D – Driving *(Machine)* *Navigating and/or moving from place to another*	**M – Manipulation** *(Machine)* *Interacting with and modifying objects*	**O – Operation** *(Connected machines)* *Performing tasks in single work processes as a machine group (fleet)*	**S – Mission** *(System mission)* *Several connected machine fleets pe tasks in different work processes to a an overall system goal*
0 **No automation**	**D0** **Full manual control.** Lateral and longitudinal motion controller manually e.g. steering, braking, acceleration	**M0** **Joint space control.** Individual joints controlled e.g. boom, bucket	**O0** **Human based task management.** Machines are operating as individuals. Task management by humans, H2H communication	**S0** **Human based mission management.** Hu operators are the only source of situatio awareness
1 **Operator assistance**	**D1** **Unidirectional control.** Either lateral or longituinal motion, but not both, is controlled. Huvan provides inputs e.g. traction control	**M1** **Cartesian space control.** End effector is controlled e.g. bucket, harvester head	**O1** **Assisted task management.** Model based worksite. Machine control system gives task related guidelines for the operator of the individual machine.	**S1** **Assisted mission management and situa awareness.** Providing real-time alerts fo potential hazards, requiring operator att
2 **Partial automation**	**D2** **Bidirectional control.** Both longitudinal and lateral motion control possible. Limites exteroceptive capabilities e.g. 'blind autonomy' in mines	**M2** **Configuration control.** Pre-configured motion trajectories, no exteroceptive sensors e.g. swing control in harvester	**O2** **Automated task management.** Model based worksite. Machine control system gives task related parametres for the individual machine.	**S2** **Enhanced situational awareness.** Integr more advanced sensors and data to supp automated functions and human supervi
3 **Conditional automation**	**D3** **External perception.** Machine has exteroceptive capabilities and can navigate in structured environments e.g. Y or V cycle in loaders	**M3** **External perception.** Extension of level M2 with exteroceptive perception e.g. obstacle detection during trajectory	**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	**S3** **Automated Decision-Making.** Algorithms to handle safety-critical decis real-time, with human override capabilit
4 **High automation**	**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	**M4** **Task autonomy.** Interaction with homogenous materials in semi-structured environment e.g. perception-based pile characterization	**O4** **Operation autonomy.** The individual machines can give instructions and train other machines (exchange information) based on the state and goal of the mission.	**S4** **Comprehensive System Coordination.** D risk awareness. Different autonomous sy can work together safely. Mechanisms fo automatic recovery after system stops o failures.
5 **Full automation, autonomy**	**D5** **Machine autonomy.** Active localization, mapping and collision avoidance systems	**M5** **Machine autonomy.** Interaction with heterogenous materials.	**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).	**S5** **Mission autonomy.** Dynamic risk assess System is capable of making safety-critic decisions without human intervention. Incorporating machine learning and AI to improve safety measures and adapt to n challenges.
	Intelligent, self-governing, independent machine. Machine can operate in any environment with minimal human supervision and intervention. Human in a role of supervisor.			

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