Accepted version of the manuscript published in 'Symposium on Fluid Power and Motion Control FPMC 2021'. For the final published version, please use the following DOI: https://doi.org/10.1115/FPMC2021-70251

Proceedings of the ASME/BATH 2021
Symposium on Fluid Power and Motion Control
FPMC2021
October 19-21, 2021, Virtual, Online

FPMC2021- 70251

TOWARDS A STANDARD TAXONOMY FOR LEVELS OF AUTOMATION IN HEAVY-DUTY MOBILE MACHINERY

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ABSTRACT

Automated and autonomous systems change the nature of human interactions and their respective role within the systems. To characterize such changes, several domain specific levels of automation (LOA) taxonomies have been proposed over the years. The SAE J3016 levels for driving automation have been adopted as the de-facto standard in the automotive industry and the broader society. However, the heavy-duty mobile machinery (HDMM) industry does not have a commonly accepted LOA taxonomy, thereby relying on organizational specific LOA taxonomies adapted from SAE J3016. Moreover, HDMM handle and transport external materials in addition to driving tasks. Thus, SAE J3016 inadequately captures the manipulation operations of HDMM. This paper proposes a new LOA taxonomy for HDMM, to accommodate both, the manipulation and driving operations of HDMM. Building on the SAE J3016 taxonomy, the LOA in this paper is proposed as a two-dimensional 6 x 6 matrix, with machine manipulation operations on one dimension, and driving operations on the other. Thus, the LOA matrix could be generalized for HDMM in different application areas. The proposed LOA matrix could also serve as a guide and starting point for future standardized and collaborative discourse in HDMM research, development, and subsequent deployments.

Keywords: Automation, autonomy, driving, heavy-duty mobile machinery, levels of automation, LOA matrix, manipulation, SAE J3016, taxonomy.

NOMENCLATURE

D	Driving.
M	Manipulation.

ABBREVIATIONS

HDMM	Heavy-Duty Mobile Machinery.
HMI	Human-Machine Interaction.
LOA	Levels of Automation.
LHD	Load-Haul-Dump.
ODD	Operational Design Domain.
OEM	Original Equipment Manufacturer.
SAE	Society of Automotive Engineers.
SLAM	Simultaneous Localization and Mapping.
UAV	Unmanned Aerial Vehicle.

1. INTRODUCTION

The past few years have been characterized by an increased focus on transforming products and services from manual systems towards automated and autonomous systems. However, automation and autonomy are different concepts which are often used interchangeably [1-4]. Thus, a distinction needs to be made for a better understanding of levels of automation (LOA). We define automation as the machine execution of a function previously performed by a human [5], wherein a machine agent executes predefined actions automatically, within well-defined situations, and without any decision autonomy [1,6]. Automation can also be viewed as the optimization of an existing function to increase its efficiency or productivity [2]. Autonomy on the other hand is defined as an extreme case of high automation where a machine agent can understand and perceive its environment, self-govern the system, and make its own decisions independent of humans [1,3,6,7,8]. In simple words, autonomy is automation with decision autonomy or "free-will". Therefore, to understand the transformations from manual systems to automated systems, and the implications of such transformations on the interactions between humans and machines, multiple domain specific definitions and taxonomies have been developed for LOA.

In [1], a comprehensive literature study mapped out and compared the evolution of LOA taxonomies from the 1950s until 2015. These taxonomies were defined for different applications such as undersea teleoperation, space exploration, unmanned aerial vehicles, etc. The LOA taxonomies mapped out in [1] vary from 3 automation levels to 12 automation levels, depending on the application and purpose of the taxonomy. Such LOA taxonomies support decision making during the development and deployment of automated and/or autonomous systems, by providing standardized definitions for technical and social discourse. More importantly, the taxonomies are used to characterize the human-machine interaction (HMI) in automated systems since automation does not simply replace the human, but rather changes the way in which the human controls and interacts with the system [3,7]. Thus, domain/application specific LOA taxonomies are very useful in understanding and visualizing the changes of the human's role in automated systems, which could explain the presence of several extant LOA taxonomies in research literature [1,8].

Considering the automotive industry, research into autonomous mobility or self-driving road vehicles has gained prominence in different parts of the world. Consequently, the Society of Automotive Engineers (SAE) released the "*SAE J3016: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*" [9], also referred to as SAE J3016. SAE J3016 was initially released in 2014 and has been revised thrice with the latest revision in 2021, and is a key example of an LOA taxonomy which has become the de-facto standard for the automotive industry, despite the presence of other LOA taxonomies for automobiles [8,10]. Due to the importance and interdependence of the automotive industry on other industry domains in the society, the SAE J3016 LOA taxonomy has also been adopted by the broader society (policy makers, industry, academia) and has contributed to standardized discourse on topics related to automated and autonomous driving, technological capabilities, time frames, regulations, infrastructure development, and so on [12]. Similarly, the heavy-duty mobile machinery (HDMM) industry is actively working on developing automated and autonomous machines. HDMM, also referred to as non-road mobile machinery, are a wide range of machinery used in diverse, predominantly off-road application areas such as construction, demolition, forestry, mining, ports, etc. Front loaders, excavators, bulldozers, forwarders, and mobile cranes are just a few examples of HDMM.

Development and implementation of automated functionalities in HDMM are not entirely new, especially in mines and quarries [2,8,11]. Despite these early developments in HDMM, the extant literature has very few mentions of standard LOA taxonomies for HDMM, with most of the taxonomies being simple adaptations of SAE J3016 [7,8,12]. Furthermore, the literature also mentions that the lack of a standardized way to categorize industrial HDMM leads to a more pragmatic, application-domain specific categorization, thereby proposing the need for standardized LOA taxonomies for HDMM [8]. However, HDMM are very complex and versatile machines with diverse product offerings. For example, the same type of machine (e.g., wheel loader) could have different configurations based on specific application areas. The above-mentioned aspects of HDMM are further confirmed through informal discussions with different original equipment manufacturers (OEMs), their suppliers, and a technical research center working with HDMM developments, who also highlight the lack of a commonly agreed upon LOA taxonomy for HDMM. During these informal discussions, for example in webinars, conferences, meetings, and emails, whenever LOA was mentioned to explain technological developments, a clarification was needed to understand which LOA taxonomy was being referred to, that is, SAE J3016 or an organization specific adaptation of SAE J3016.

Accordingly, the HDMM industry currently relies, either on the SAE J3016 LOA taxonomy in its original form, or an organization specific LOA taxonomy adapted from SAE J3016 [2,7,8]. This is problematic due to two primary reasons: firstly, HDMM operations perform two different tasks, that is, driving or navigation of the machine, and manipulation(s) of an end-effector on the machine to change the shape, size, form, or location of external materials. Moreover, SAE J3016 defines the automation levels in terms of the dynamic driving tasks required for the safe operations of an automobile in on-road conditions. Furthermore, other differences that separate HDMM from automobiles is that HDMM carry no passengers, predominantly move and operate in off-road environments, are operated by skilled professionals, and change the shape and center of gravity of the machines due to several moving components, among some other differences. Thus, the SAE J3016 taxonomy, which deals with on-road driving operations only, does not account for the manipulation operations of HDMM [2]; Secondly, due to organization specific LOA taxonomies such as in [4,12], the discourse on HDMM developments and deployments becomes complicated, especially in collaborative environments outside an organization. This is important because the current industry trends indicate increasing multidisciplinary and cross-industry collaborations in automated and autonomous HDMM developments [2,4]. Therefore, we propose a new LOA taxonomy for HDMM as a two-dimensional matrix, with the manipulation operations on one dimension, and driving operations on the other, using SAE J3016 as a reference.

The paper is organized as follows: section 2 has a brief description of the methodology used; section 3 defines and clarifies the concepts and terminology used in defining the proposed LOA taxonomy, outlines the findings from the literature, describes the definitions of each automation level in the proposed LOA taxonomy, provides guidelines to interpret the proposed LOA taxonomy, and also discusses the implications of the LOA taxonomy with examples; section 4 provides the concluding remarks and recommendations for future research.

2. METHODOLOGY

In this paper, we analyze the existing LOA definitions and taxonomies found in research literature from different industry domains. Furthermore, we analyze organization specific LOA taxonomies or definitions found through online articles, reports, and by requesting company specific documents, some of which are confidential. Since the SAE J3016 LOA taxonomy is part of popular discourse within the HDMM industry as well as the broader society, we build upon the 6 levels defined in SAE J3016 to propose a new taxonomy for LOA in HDMM. We propose the

LOA taxonomy for HDMM as a two-dimensional 6 x 6 matrix shown later in Fig. 1, wherein the manipulation operations (M) of the machine are defined on the horizontal dimension, while the driving (D) operations of the machine are defined on the vertical dimension. The LOA on each dimension is divided into a continuum of 6 automation levels, wherein level 0 corresponds to no automation and level 5 corresponds to full automation.

The delineation of the responsibilities between the human and the machine are decided based on four HMI parameters: system control or control of the system (machine), environment perception or exteroceptive capability, decision making, and worksite communication. These parameters are further defined in section 3.1. Thus, we analyze the existing LOA and related categorization from the literature, then we find/propose a common ground (the four HMI parameters) for deciding the individual automation levels, and finally, we propose and define the individual levels of automation.

Furthermore, this study is part of the MORE[1] project where several leading OEMs, suppliers, and technical universities related to the HDMM industry are working towards developing innovative solutions driven by digitalization and artificial intelligence. Therefore, representatives from Liebherr-Werk Bischofshofen GmbH Austria (OEM) and Bosch Rexroth AG Germany (supplier), who are industry partners in the MORE project, participated in regular discussions and provided valuable documents, feedback, and suggestions regarding the LOA requirements for HDMM, from their perspective. Another industrial partner (OEM) in the MORE project explained their internal LOA standard, which was also adapted from SAE J3016, but maintained confidentiality about the actual definitions.

The primary requirement of LOA taxonomies for the industry partners was to ensure standardized discourse between different departments internally, as well as with external suppliers, while working on automation related topics. The secondary requirements of an LOA taxonomy were to estimate new product development and deployment timelines. Moreover, other researchers in the MORE project, who are working on different topics such as automated driving and navigation for HDMM, automated motion control of HDMM implements, and energy efficient powertrain architectures for HDMM, also provided valuable feedback, criticism, and suggestions on the initial concepts of the LOA matrix and definitions, from their own research perspective. Thus, the LOA matrix and the subsequent proposed levels were refined by combining the diverse inputs from the different partners in the MORE network.

3. RESULTS AND DISCUSSION

This section is divided into 4 subsections: definitions and terminology, literature review, description of the elements in the LOA taxonomy for HDMM, and implications of the LOA matrix approach.

3.1 Definitions and terminology

In this section, we clarify the terminologies and definitions that will be used in the subsequent sections of this paper.

The definitions for *automation* and *autonomy* are already clarified in section 1 of this paper.

Systems are defined using the systems engineering approach outlined in [2], wherein a system is a set of interacting and interconnected elements that accomplish one or more specific objectives. *Machine* refers to HDMM and is also considered as the HDMM system in the context of this paper. The human operator of the machine is also considered as an element of the machine, as long as the human interacts with at least one element of the machine (for example, directly controlling/operating the different implements using joysticks, levers, etc., or indirectly controlling the different implements through active supervision, decision making, and/or emergency override of automated functions).

S*ystem control* or control of the system refers to the process of controlling the movements of the different elements of the machine. For example, when a human operator uses a joystick to move an end-effector or presses a pedal to displace the machine from its position, the system control is with the human. On the other hand, if the machine controls the end-effector motion or moves the machine without any active human input, the system control is with the machine.

Decision making refers to the ability of the machine or its elements (e.g., the human) in making decisions to achieve certain objectives. Decision making could also be defined as intelligence, either human intelligence or artificial intelligence.

Environment perception or *exteroceptive capability* is defined as the ability of a system or its elements to perceive and/or interpret the environment of the machine. Everything surrounding the machine is considered as the environment.

Worksite communication is defined as the communication between different systems present on a particular worksite. Here, the overall operations at the worksite are in focus and not just an individual machine. For example, a human manager on the worksite who allocates tasks or goals for different machines is predominantly responsible for worksite communication.

LOA matrix is the proposed LOA taxonomy for HDMM. The LOA matrix is two-dimensional, wherein the horizontal dimension of the LOA matrix is manipulation (M), while the vertical dimension is driving (D).

Manipulation (M) is defined as the movement or manipulations of the implements and/or end-effectors of a HDMM to change either the shape, size, form, location (or a combination of the four) of an external physical material.

Driving (D) is defined as the physical displacement of the machine from one location to another location, to achieve a particular objective.

[1] MORE is an innovative European Industrial Doctorate (EID) research and training programme under Marie Skłodowska-Curie Actions. See https://www.more-itn.eu/ for more information.

3.2 Literature review

As mentioned earlier, very few LOA taxonomies for HDMM were found in the literature. Among the ones that used LOA taxonomies for HDMM [2,7,8], most were simply minor modifications of the existing SAE J3016 taxonomy. These LOA taxonomies were used to describe the state of the art and to suggest future developments in their respective HDMM application areas such as earth moving and forestry. A few LOA taxonomies for HDMM that were unique are outlined further, without describing the specific levels. Firstly, an LOA taxonomy for earth moving machinery is described using 7 automation levels: no automation; remote control; guidance; coordinated; partial automation; autonomous; and autonomous swarm [12], albeit, without any reference to the origin of the taxonomy. Secondly, an LOA taxonomy for off-highway vehicles is described using 4 automation levels: no automation; operator assistance; semi-autonomy; and full autonomy [4]. This LOA taxonomy is an example of an organization specific taxonomy. Lastly, an LOA taxonomy for autonomous machines in mines is described using 6 levels: manual operation; remote control; teleoperation; blind autonomy; semi-autonomy; and full autonomy [8].

Several two-dimensional approaches to LOA have been introduced in different contexts. The earliest one dates back to 1989, wherein the LOA of a human-machine system are described on one dimension, while the levels of intelligence of the system are described on the other dimension, with each combination referring to a unique state of automation [1]. Here, the vertical dimension has 12 levels of automation divided into two parts with each level subsuming the previous level, wherein the first 6 levels define the roles and abilities of the machine in information processing and overriding the display of the operator, while the remaining 6 levels define the roles and abilities of the machine in executing specific actions. The horizontal dimension has 7 levels of intelligence indicating how the machine responds or processes the data available from the machine. This LOA taxonomy was not designed for any specific application [1].

Similarly, a two-dimensional 7 x 7 matrix for LOA in manufacturing assembly operations was proposed in [13], wherein physical LOA (automation for physical tasks) are described on one dimension and cognitive LOA (automation for cognitive tasks) are described on another dimension. The horizontal dimension of the matrix has 7 levels of automations which define the cognitive assistance for the human such as providing decisions, teaching the operator, intervening, etc. The vertical dimension of the matrix has 7 levels of automation which define physical automation such as using the hands, using static tools like a screwdriver, using automated tools like a drill, etc. Thus, the matrix provides 49 possibilities and is divided into 3 sections with different HMI where, the human is assembling and monitoring simultaneously, or the human is assembling and the machine is monitoring the technique separately, or the machine is assembling and monitoring simultaneously [13]. Inspired by these matrix approaches to LOA, we propose a new LOA taxonomy for HDMM as a two-dimensional 6 x 6 matrix.

3.3 Description of the elements in the LOA matrix for HDMM

Since automation is context dependent and does not simply replace the human, but rather changes the way in which the human controls and interacts with the system [3,7,13], the human is compared to the machine using the four HMI parameters: system control, decision making, environment perception, and worksite communication; to delineate the roles and responsibilities of the human in the machine. The whole machine can be considered as a distributed control system dependent on the above-mentioned four HMI parameters, wherein part of the control/responsibility is with the human and partly on the machine. As we decrease the control/responsibility of the human while simultaneously increasing that of the machine on at least one of the four HMI parameters, we progress to a higher level of automation. The complexity of the four HMI parameters determine the feasibility of achieving a higher LOA in the proposed LOA matrix shown in Fig. 1.

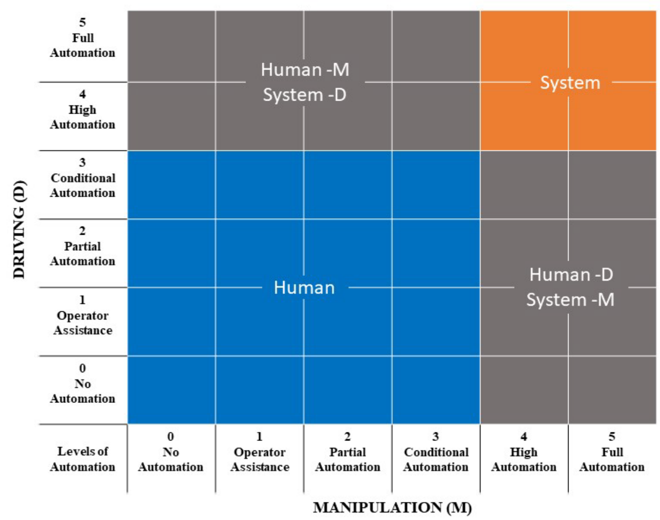

FIGURE 1: LOA MATRIX (6 X 6) INDICATING THE DIFFERENT AUTOMATION LEVELS AND THE COMBINATIONS WHERE THE HUMAN IS REQUIRED TO ACTIVELY MONITOR THE MACHINE. SUFFIXES -M AND -D IN THE GRAY AREAS DENOTE MANIPULATION AND DRIVING OPERATIONS RESPECTIVELY.

Certain combinations in Fig. 1 are shaded for the convenience of the reader, to indicate the necessity of the human to actively monitor the machine during machine operations. For example, the blue areas indicate the areas where the human is always necessary, having either direct control of the machine or a supervisory role, so that the human can actively intervene and/or override the automation functions depending on the circumstances. The orange areas in Fig. 1 indicate the combinations where the human is necessary only for specific event-based scenarios, for example, when the machine is unable to make a decision and prompts the human to intervene or requests a new course of action.

The grey areas indicate combinations where the human may be necessary to actively monitor or intervene for either one of the machine operations, that is, driving or manipulation. Here, it is important to note that the SAE J3016 is one dimensional and has no provision for human take over at the highest LOA, that is, at SAE level 5 [9]. However, since the proposed LOA matrix is two-dimensional, the machine may be at level 5 on one dimension but at a lower LOA on another dimension. Thus, the human retains the capacity to take over the manipulation or driving functions in certain circumstances, even at level 5 in Fig. 1, wherein the functions which the human can take over are denoted by the suffixes -M and -D, indicating manipulation and driving respectively.

If all the four HMI parameters are complex, the appropriate combination of LOA in Fig. 1 would be a combination where the human must actively monitor the machine and actively intervene during automation failures, that is, the blue areas. This is because humans are better suited and more capable in performing cognitively complex tasks when compared to automated systems [13]. On the other hand, if the complexity of the four HMI parameters is low, the feasibility of achieving a higher LOA combination in the LOA matrix would be higher, where the human would not be needed to actively monitor the machine but rather, intervene only when the machine requests human intervention or a new course of action, that is, in the orange and grey areas in Fig. 1.

When reading the LOA matrix, it is important to note that some HDMM, for example, motor graders and bulldozers may need to perform manipulation and driving simultaneously, while HDMM like excavators and haulers may perform only a single operation at a time, for example, manipulation independent of driving and vice versa. Thus, we suggest that the automation levels should be referred to in the following format for all HDMM applications: *level (XM, YD)*, for example, level (3M, 4D). Here, it is important to note the importance of the operational design domain (ODD), as outlined in SAE J3016 [13], wherein an automated function is designed to operate perfectly within the constraints set by the ODD. Thus, a machine can be configured and capable of delivering a higher LOA for a specific function/task in a specific ODD but can only deliver lower LOA for the same function outside the ODD. For example, an excavator at level (3M, 0D) may be configured to perform/deliver automation functions at level 3M only on a mining worksite (the ODD for level 3M), but the same excavator would operate at level (1M, 0D) on a construction worksite (which is outside the ODD for level 3M in this case). This relation of the ODD and LOA applies to single machines with multiple working implements and/or end-effector attachments too, wherein the LOA at any instance is determined by the feature(s) that are currently engaged [13], even though the machine is capable of higher LOA for specific end-effector attachments or manipulation functions.

Furthermore, each automation level in the LOA matrix is described and defined in Table 1, with the delineation of the roles between the human and the machine shown in Table 2. Based on Fig. 1, Table 1, and Table 2, it can be noted that the individual automation levels in the proposed LOA matrix are defined as a continuum of automation levels. Furthermore, the roles and tasks of the human change as the automation level increases on either of the dimensions in the LOA matrix. Thus, let's consider each LOA described in Table 1 individually, while referring to Table 2 for examples.

At level 0M, the human operator physically controls the machine elements in the joint space. For example, in a boom-stick type machine, the operator will move the boom and stick by controlling their respective actuators individually, to achieve the appropriate manipulation of the end-effector. Thus, the operator needs to have complete situational awareness, while also controlling the machine implements, and has no assistance in achieving the manipulation objective.

At level 1M, the operator only controls the movement of the end-effector in the cartesian space, for example, using inverse kinematics usually assisted by some form of electronic control. Moving on to level 2M, the human operator can now customize certain manipulation motions with predefined trajectories for the end-effector of the machine. The machine relies on internal sensors such as inertial sensors or encoders, and thus, lacks exteroceptive capabilities. The human uses own discretion to activate the automation functionality. However, since the machine has no exteroceptive capability, the motions of the end-effector will continue their predefined trajectory even in the presence of an obstacle. Thus, the human must still have complete situational awareness as outlined in Table 2.

Consequently, level 3M is an extension of level 2M and brings in exteroceptive capabilities or surround sensing to the machine and thus, reduces the cognitive load on the human in terms of the situational awareness, when compared to level 2M. At level 3M, some predefined conditions such as structured environments and bounded human-free zones, need to be fulfilled before the automated functionalities can be activated. At the same time, the machine does not make decisions and thus, the human is still responsible for the control (authorization of automation) of the machine, albeit, in a supervisory role and as a "fail-safe" for the machine. From level 0M to level 3M, the human operator is required to actively take over the machine immediately as indicated by the blue areas in Fig. 1.

Moving on to level 4M, the machine has high exteroceptive capabilities and is expected to have some decision-making mechanisms. The machine can make world models of the worksite or its immediate environment, and consequently, plans, decides, and acts based on these world models. However, these world models and decision-making capabilities ultimately depend on the coding algorithms and availability of data, which cannot account for all possibilities and contingencies. Thus, the machine can make decisions autonomously, as long as the machine operates within certain boundary conditions (ODD) specified by the algorithms. The human must intervene if the machine breaches the limits of the boundary conditions. The machine at level 4M is capable of identifying such a breach of boundary conditions and requests human intervention or a request for action. This is described as event-based human monitoring and intervention.

TABLE 1: DESCRIPTIONS OF INDIVIDUAL LOA IN THE LOA MATRIX. M=MANIPULATION AND D=DRIVING

Automation Levels	**M D**	**Description**
Level 0 No Automation	M	Human has full responsibility for machine manipulation and situational awareness. Human controls the machine in the joint space (e.g., controlling individual actuators).
	D	Human has full responsibility for driving and situational awareness.
Level 1 Operator Assistance	M	Human responsibility is the same as Level 0M but the human controls the machine in the cartesian space (e.g., using inverse kinematics to move the end-effector).
	D	Human responsibility is the same as level 0D, but the machine has assistance functions which can control only one driving function at a time in limited scenarios (e.g., steering OR braking).
Level 2 Partial Automation	M	Human controls the end-effectors and is responsible for situational awareness. Machine can be configured with predefined and/or pre-set trajectories for the end-effector but lacks exteroceptive capability. One-time activation required to initiate automated functions.
	D	Human has full responsibility for driving, situational awareness, and can assign driving tasks to the machine. Machine has assistance functions which can control at least two driving functions simultaneously (e.g., steering AND braking). Machine has limited exteroceptive ability in limited environments. Machine needs new human input if an action is interrupted.
Level 3 Conditional Automation	M	Extension of level 2M but human can assign tasks to the machine which also has exteroceptive capabilities. Machine can perform certain tasks on its own if all conditions for the task are met. Machine needs human authorization to execute actions and can resume an interrupted action.
	D	Human specifies tasks to the machine which has exteroceptive capabilities. Machine is capable of driving on its own using predefined or preconfigured trajectories provided certain conditions are met. Machine has emergency stopping and collision avoidance systems. Machine can resume action with human authorization.
Level 4 High Automation		Human input for work assignment. Human not required for situational awareness inside the machine but only acts as a supervisor with event-based human monitoring and intervention. Machine has high exteroceptive and decision-making capabilities in structured environments along with remote communication capabilities over a network. Machine makes world model (mapping, localization, etc.) and plans and acts based on the world model. Human intervention is needed for new work assignment, unforeseen circumstances like bad weather, and troubleshooting.
	M	Machine can perceive and interact with external homogenous material, map the immediate surroundings, and plan obstacle free motion accordingly. Machine can work alone and request event-based human intervention or a new course of action.
	D	Machine can engage in simultaneous localization and mapping (SLAM) and path planning, navigate in semi-structured and structured environments. Machine can make low-level real-time decisions such as resuming path after an emergency stop or going around an obstacle.
Level 5 Full Automation		Autonomous, self-governing, intelligent, and independent machine. Machine can operate under any conditions and in unstructured environments. Machine creates, updates, and shares world models with other machines. Human is not required onsite but may supervise the machine from a command-and-control center. Human intervention during operations is rare and work assignment is decided by the machine.
	M	Machine can actively communicate and cooperate with other machines (e.g., excavator could order a hauler to arrive), perceive and interact with non-homogenous external materials, and can work autonomously in unstructured environments.
	D	Machine has active localization and mapping, can plan its own path, communicate with other machines, make active high-level decisions such as avoiding and going around obstacles. Machine is suitable for navigation around other machines in unstructured environments and adverse weather conditions.

At level 5M, the machine can be considered to be autonomous and independent, actively making decisions, and being responsible for all the four HMI parameters, that is, system control, environment perception, decision making, and worksite communication. The machine may rely on advanced learning and decision-making mechanisms using artificial intelligence methods such as deep learning, reinforcement learning, etc.

TABLE 2: DELINEATION OF RESPONSIBILITY BETWEEN THE HUMAN AND THE MACHINE.

LOA Examples	Responsibility
Level 0- No Automation **Manipulation:** Individual boom, stick, and bucket control on an excavator. **Driving:** Regular driving with steering, braking, & acceleration.	**Human:** System control, decision making, worksite communication, environment perception.
Level 1- Operator Assistance **Manipulation:** Boom-tip control in forwarders, grading function in excavators. **Driving:** Traction control OR steering control (path following). Warning signals/beeps for static obstacles.	
Level 2- Partial Automation **Manipulation:** Return to dig in front loaders, swing control in excavators. **Driving:** Traction AND steering control, "blind autonomy" in mines, obstacle detection and emergency stopping.	**Human:** Decision making, worksite communication, environment perception. **Machine:** System control.
Level 3- Conditional Automation **Manipulation:** Machine guidance and machine control in excavators, blade control in bulldozers. **Driving:** Y or V cycle loading in wheel loaders, automated guided vehicles, collision detection and avoidance.	**Human:** Decision making, worksite communication. **Machine:** Environment perception, system control.
Level 4- High Automation **Manipulation:** Perception-based pile characterization in excavators, automated motion control in cranes, perception-based rot characterization and control in forwarders. **Driving:** Autonomous haulers, Load-Haul-Dump (LHD) machines in underground mines.	**Human:** Worksite communication, event-based decision making. **Machine:** System control, decision making, environment perception.
Level 5- Full Automation **Manipulation:** Autonomous excavator, autonomous harbor cranes. **Driving:** Cabinless autonomous hauler. **Manipulation and Driving at level (5M, 5D):** Autonomous bulldozer, autonomous LHD machines, autonomous multi-agent cooperative machines.	**Machine:** System control, decision making, worksite communication, environment perception.

Now, consider level 0D, which is akin to driving the most basic model of a car on the street. Thus, in HDMM, the human operator needs to control the throttle, brakes, and steer the machine, while actively perceiving the environment. Moving on to level 1D, the machine can offer some assistance to the human operator, but the assistance is limited to just one function at a time. Thus, the physical and cognitive load on the human operator changes. For example, on a wheel loader, the human may activate traction control on the machine, which prevents wheel-slip while the machine drives into a pile. At level 1D, the machine could also have static obstacle warning systems such as proximity sensors.

Moving on to level 2D, the machine has at least two automated functions. For example, the machine may have an obstacle detection and avoidance system, wherein it can slow down while providing suggestive actions to the human until the human operator takes over, ultimately bringing itself to an emergency stop. In limited, highly structured environments, the human could activate/authorize two or more automated functionalities. For example, upon authorization by a human operator, a hauler could follow a marked pathway in a mine, while also accelerating and braking depending on different locations. However, if one of these functions is interrupted due to any reason, for example, due to the presence of an obstacle, the machine can request human intervention and in the worst case, apply emergency brakes on its own if the human does not respond in time. Thus, the human is responsible for situational awareness and must also take over control of the machine almost immediately. The nature of driving and manipulation functions are different and thus, a machine may still have limited exteroceptive capabilities at level 2D, especially in a highly structured environment such as marked or paved roadways, even though level 2M does not have exteroceptive capabilities. However, the machine cannot resume its previous action and requires a new input from the human operator.

Moving on to level 3D, the machine has good exteroceptive capabilities and can navigate on its own through highly structured environments, using predefined trajectories or paths. The machine can detect dynamic or moving objects, thereby having active collision detection and avoidance systems such as emergency braking and suggestive actions. However, the machine still lacks decision making capabilities and thus, the human plays a similar role in situational awareness and intervention as in level 3M. The machine at level 3D can still resume an interrupted action, depending on human authorization. For example, the machine which performed an emergency stop could ask for human authorization to continue driving on the previous trajectory.

Moving on to level 4D, the machine has high exteroceptive capability and has the same or similar characteristics such as world modelling, as mentioned for level 4M. The machine is capable of making driving decisions and choosing among different alternatives for path trajectories on the worksite. Additionally, in off-road environments such as forests, the driving path of the machine could be completely unstructured, obscured, or non-existent. Thus, depending on the environment, the machine can also make other complex driving decisions, for example, choosing two-wheel steering over crab steering in machines which have the option. Thus, at level 4D, the machine could drive around autonomously, but only within its ODD, with event-based human intervention.

At level 5D, the same specifications for level 5M apply, the only difference being that the machine can drive and navigate autonomously through unstructured environments and without human intervention. However, at level 5, either for manipulation, driving, or both, if one considers the uncertainty in any physical or cognitive system designed by humans, human intervention is inevitable. Furthermore, the LOA of a system is determined by the automation functions that are engaged during operations. Thus, human intervention at level 5 in the LOA matrix is not ruled out completely.

The purpose of analyzing each LOA of the LOA matrix individually was to clarify the descriptions in Table 1. However, since a full machine is the unit of analysis, we stress that the LOA in the LOA matrix should not be viewed or analyzed individually but in its totality, that is, level (XM, YD). In Fig.1, the LOA matrix provides 36 combinations for HDMM systems. However, some of these combinations may be impractical, unlikely, or have low feasibility, as shown in Fig. 2. The reference machines for Fig. 2 are chosen from different application areas such as earthmoving, forestry, material handling, and construction. Thus, Figure 2 is not representative and is only indicative of the current state of the art in HDMM based on the knowledge of the authors, since mapping out all the varieties of HDMM and their respective application areas is outside the scope of this paper.

DRIVING (D)						
5 Full Automation	Unlikely combination	Unlikely combination	Unlikely combination	Concepts	Concept, low feasibility	Not feasible yet
4 High Automation	Specific applications	Prototypes & limited offerings	Research prototypes	Research prototypes	Limited product concepts.	Concept, low feasibility
3 Conditional Automation	Specific applications	Limited offerings	Limited offerings	Prototypes & limited offerings	Research projects	Concepts
2 Partial Automation	Specific applications	State of the art	State of the art with add-on solutions	Limited offerings	Research prototypes	Research projects
1 Operator Assistance	Older machines	State of the art	State of the art with add-on solutions	Add-on solutions	Low feasibility	Low feasibility
0 No Automation	Older machines	State of the art	Add-on solutions	Specific applications	Specific applications	Unlikely combination
Levels of Automation	0 No Automation	1 Operator Assistance	2 Partial Automation	3 Conditional Automation	4 High Automation	5 Full Automation

MANIPULATION (M)

FIGURE 2: LOA MATRIX (6X6) INDICATING THE DIFFERENT AUTOMATION LEVELS AND THE POSSIBLE COMBINATIONS FOR HDMM BASED ON THE CURRENT STATE OF THE ART.

Furthermore, certain machines like bulldozers and motor graders need to perform simultaneous manipulation and driving operations, and thus, it may be optimum to achieve the same LOA for manipulation and driving simultaneously. For example, the LOA for a bulldozer should change from level (2M, 2D) to level (3M, 3D). On the other hand, machines like excavators and forwarders can remain stationary while performing only manipulation operations and thus, their LOA could change as a combination, for example, from level (2M, 1D) to level (3M, 2D). Moreover, the work tasks of a HDMM in a particular application area influence the economic feasibility of a higher LOA, wherein a machine may have a high LOA on one dimension while having a low LOA on another dimension. For example, consider a large excavator which is loading soil into haulers or a large material handler unloading ships. These machines could perform several hours of continuous work with hundreds of work cycles of manipulation. Thus, the machine could be at level (4M, 0D), wherein an operator only needs to climb in and drive the machine to another location, where it can perform automated manipulation operations without active human supervision for many work cycles again. The other combination is possible too. For example, an off-road vehicle at level (0M, 4D) with a loader crane attached on top of it, could navigate autonomously through different environments, that is, at level 4D, but the crane on top of the machine could have no automation, that is, level 0M. Thus, the crane on the off-road vehicle at level (0M, 4D) would be a manually operated when the vehicle is stationary. When the vehicle is needed elsewhere, it could move autonomously to the new location. Thus, HDMM with multiple LOA combinations are possible in different application areas, even though they may have low feasibility based on the current state of the art in different application areas.

3.4 Implications of the LOA matrix approach

The names for the individual LOA such as no automation, operator assistance, partial automation, conditional automation, high automation, and full automation were chosen due to the prominence of SAE J3016 in societal discourse on automated systems. Thus, if the LOA matrix proposed in this paper is adopted by different stakeholders within the HDMM community, the transition to the proposed LOA matrix would be relatively easy and straightforward. Therefore, the proposed LOA matrix is a starting point towards creating a standardized LOA taxonomy for HDMM. Furthermore, since the application areas of HDMM are diverse, machines in some application areas, such as underground mines, could operate in areas that have no humans in the active working area of the HDMM, for example, when humans teleoperate or remotely operate the machines. Thus, the proposed LOA matrix does not consider functional safety in the LOA taxonomy for HDMM, although it is still an important topic when considering the LOA.

In defining the LOA taxonomy with manipulation and driving as two different dimensions, we believe that our proposed LOA matrix could be generalized for HDMM operating in different application areas such as mining, construction, forestry, etc. Moreover, the LOA matrix could be used to identify future research and development initiatives within HDMM. For example, different types of earth moving machines have been analyzed for automated functionalities in military applications in the literature [11]. The HDMM functions for driving and manipulations in [11] are analyzed independently to showcase the state of the art in earth moving machine automation. If the proposed LOA matrix approach were applied in [11], the analysis of the machine functions could have been standardized to some extent, thus creating a proper structure for technical discourse. Furthermore, consider the example of the different autonomous haulers that are currently available as HDMM products on the market. The manipulation functions on these autonomous haulers are very few, chief among them being the tipping operation. Analyzing a traditional hauler using the proposed LOA matrix could have indicated that the manipulation operation is relatively easy to automate but makes little economic sense without automation of the driving function of the hauler. Thus, the analysis of a hauler using the LOA matrix would have suggested that the research efforts be directed towards the automation of the driving functions of the hauler.

Similarly, the proposed LOA taxonomy could also be used to define and understand scenarios where the LOA changes during automated machine operations, when a human must take over the automated machine for a driving operation, without interfering with the manipulation operations, or vice versa. For example, in load-haul-dump (LHD) machines, only the haul and dump processes are currently automated, whereas a human operator is required for the loading process of the LHD work cycle. Such a change in LOA during operations is also referred to as adaptive automation or dynamic function allocation [1,5,14]. Furthermore, the proposed LOA matrix can also be used as a guideline for the design of automated HDMM, wherein the system architecture and system requirements for HDMM can be formulated by analyzing HDMM in the LOA matrix.

The LOA matrix could also be used during the deployment of HDMM in practical applications. For example, increasing the LOA changes the HMI. This has implications for the machine itself, which may require additional sensors for environment perception, communication infrastructure for worksite communication, modular components that can be interfaced with external add-on solutions for system control, etc. Moreover, as the LOA increases, human intelligence needs to be supplanted by artificial intelligence, which is not a trivial task and requires additional resources, infrastructure, time, and monetary capital. Thus, the deployment time and costs of HDMM at higher LOA would be significantly higher than those of traditional machines, wherein the business cases need to turn positive with respect to the total cost of ownership for most of the use cases [4]. Thus, the LOA matrix could be used to analyze product portfolios, build business strategies, and to brainstorm new business models for new HDMM developments. With multidisciplinary and cross-industry collaborations becoming very important [2,4], the LOA matrix could serve as guide for standardized technical and societal discourse in collaborative HDMM research and development initiatives, thereby accelerating the deployment of automated and/or autonomous HDMM by providing a common framework to discuss development time frames, regulations, etc.

Moreover, automation is highly context dependent and application specific in the case of HDMM. The nature of automation or what is considered automation will change over time such that a function that was previously an automation function, becomes a basic function of the machine [2,13]. For example, drive-by-wire can already be considered as a basic function for some machines even though it is an automated function. This has implications on how the human perceives the abilities of the automated HDMM [2,10,14]. For example, a United States Department of Defense report on unmanned aerial vehicles (UAVs) with automated functions, highlighted how human operators of highly automated UAVs misinterpreted the respective LOA descriptions, thereby utilizing the UAVs outside their boundary conditions, and ultimately leading to the need for more resources compared to UAVs with low automation [14]. Similarly, many crashes/accidents in automobiles at SAE level 2 and/or SAE level 3, were attributed to the driver misinterpreting the abilities of the automated functions and thereby failing to act during emergencies [10]. Such incidents prompted the revision of different LOA taxonomies. For example, the latest revision of the SAE J3016 was meant to clarify the roles of the human and the system to promote a better general understanding of the abilities of an automobile having a specific LOA [9]. Thus, our proposed LOA taxonomy for HDMM, builds upon the already established SAE J3016 LOA taxonomy as a guideline to define the specific levels in the LOA matrix. However, this is not to say that the definitions are perfect or representative for all types of HDMM but are rather indicative of how we view the current state of the art in the HDMM industry. At the time of writing this paper, we are aware of an LOA taxonomy called, "*ISO/TC 127/SC 4 N 681, ISO/NP 7334 Earth-moving machinery-Taxonomy and definitions for terms related to automated and autonomous machines*" [15] which is still in the draft stages and is one dimensional, unlike the two-dimensional LOA matrix proposed in this paper. Moreover, while the above-mentioned standard applies to earth-moving machinery and utilizes the term dynamic operating task to define the different LOA, it is still very relevant to HDMM in other application areas too. Thus, the fully developed and published version of ISO/NP 7334 standard, would be useful in developing the LOA matrix further.

4. CONCLUSION

We have proposed a new LOA taxonomy for HDMM as a two-dimensional 6x6 matrix, using SAE J3016 LOA as a guideline. With the proposed LOA taxonomy, the discourse around automated and autonomous HDMM machinery could be simplified and possibly lead to the development of a standard LOA taxonomy for HDMM in the future, thereby enabling better collaboration, understanding, and early decision-making support for the development and deployment of automated and autonomous HDMM. We hope that this opens a discussion on the important topic of LOA for HDMM. For future work, we recommend empirically testing the applicability of the LOA matrix in different application areas of HDMM, and subsequently, working towards the development of a standard LOA taxonomy for HDMM. Inputs from industry and academia in improving and correcting the concept proposed in this paper will be vital, and we hope to receive feedback when the HDMM community uses the proposed LOA taxonomy in practice.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 858101.

We would like to thank Dr. Christine Brach and Mr. Ulrich Lenzgeiger from Bosch Rexroth AG Germany, and Dr.-Ing. Manuel Boes and Mr. Christian Hallinger from Liebherr-Werk Bischofshofen GmbH Austria, for their continual support and active discussions in developing the concept for the levels of automation matrix proposed in this paper. We would also like to thank Dr. Hannu Karvonen from VTT Technical Research Centre of Finland, for providing valuable inputs for this research by facilitating communication between the mobile machinery experts at VTT and us.

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