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INFORMATION MODEL FOR A-UGV PERFORMANCE MEASUREMENT STANDARD

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ABSTRACT

Automatic through autonomous - Unmanned Ground Vehicles (A-UGVs) have the potential to be applied over a wide range of manufacturing systems under industry 4.0 paradigm. In order to use A-UGVs efficiently in a manufacturing system, it is necessary to select the A-UGV suitable for each factory or workplace. A framework for evaluating the A-UGV performance under a specific manufacturing environment is needed. ASTM International Committee F45 has been developing standards[2] providing a basis for A-UGV manufacturers and users to compare tasks to the A-UGV capabilities. This paper proposes information models for A-UGV performance measurement along the standards development. The standard needs are analyzed to show how the standard and information model can be used for the introduction of A-UGVs into factories. The information model in this paper provides a structured way to describe the factory elements affecting the A-UGV performance, and the measured A-UGV performances against the factory elements. To validate the proposed information model, an A-UGV performance testbed was built and the information model instance is developed to describe the testbed elements. An A-UGV is tested against the testbed elements and the measured performance is described by the other instance. This paper contributes to mutual understanding, between A-UGV makers and users, to deliver A-UGV performance information efficiently and to provide basis for A-UGVs to be tested under the same conditions.

Keywords: autonomous mobile robots, performance standard, navigation, obstacle avoidance, information model

1. BACKGROUND

With the development of information technology (IT), driverless vehicles are being developed and applied in many ways. In the manufacturing domain, the development and application of various types of unmanned vehicles, including the well-known Automatic Guided Vehicle (AGV), have been continuously conducted [1,2]. In the meantime, the emergence of Automatic through Autonomous – Unmanned Ground Vehicles (A-UGVs) is the starting point for the manufacturing system to more dynamically respond to changes. A-UGV is defined as “automatic, automated or autonomous vehicle that operates while in contact with the ground without a human operator” [3]. In terms of logistics support, A-UGVs enable active logistics flow control by real-time scheduling and execution. Beyond logistics support, an A-UGV combined with a robot arm, called a mobile manipulator, can autonomously perform manufacturing processes like assembly. A-UGVs have the potential to implement digital manufacturing, smart factories, and industry 4.0 in various ways [4]. Autonomy is one of the keys to implement Industry 4.0, and A-UGVs can serve in advanced logistic and manufacturing applications. For example, the modular factory [5] aims at a plug-and-produce manufacturing system, which makes it easy to add or change the production line modules as needed. A-UGVs can be used to transport the modules making the manufacturing system more flexible and autonomous. Delivering manufacturing components is one of the areas that have been actively researched [6].

Every A-UGV application assumes that the A-UGV can move freely in the factory. In terms of the A-UGV movement, laboratories, aiming to develop and test new technologies, and factories, aiming to manufacture products, have completely different A-UGV operational focus. In the laboratory, A-UGVs are developed and tested where the experiments may not test the required vehicle performance needed in the factory—for example, low or bright lighting, floor surface defects, stationary or moving obstacles, etc. On the other hand, factories are focused

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[2] Commercial products are identified in this paper to foster understanding. This does not imply recommendation or endorsement by NIST, nor that the products identified are necessarily the best available for the purpose.

on the manufacturing process and the products they make, and A-UGVs are one of the tools they use to be more efficient and effective.

In order to introduce A-UGVs into a factory, it is necessary to understand the elements that consist of the factory and the expected A-UGV performance. However, the very different situations for the A-UGV maker and the user make it difficult to grasp. It is impossible for the A-UGV maker to test in advance in the laboratory, and for the A-UGV user (i.e., factory) to know, what affects the A-UGV performance in the actual manufacturing environment. At a minimum, it is necessary for makers and users to share A-UGV performance for conditions (environment and obstacles) that are commonly present in the factory.

Previous studies defined common environmental conditions and obstacles that should be identified for A-UGV use in the factory [7]. The effects of factory commonalities, including ramps, lighting, forklifts, and pedestrian walkways, and the required function and performance of A-UGV against the commonalities were analyzed. Each factor can have a significant effect on A-UGVs possibly causing accidents and needs to be managed.

Reflecting the conducted studies, ASTM International (formerly: American Society for Testing and Materials) F45 committee is developing driverless automatic guided industrial vehicles standards for environment, navigation, and obstacle detection[3]. ASTM F45 standards include A-UGV performance measurement and documentation methods for exact replication of vehicle tests. Through this, the user can define the A-UGV operating environment prior to implementation, and better express the expected A-UGV performance upon integrating the A-UGV into the factory. In addition, A-UGV manufacturers can build a mock test environment based on factory environment information, test A-UGVs according to measurement methods, and express A-UGV performance.

There has been research to define performance metrics, to develop measurement technologies and test methods. Bostelman et al [8] summarizes the existing studies for measuring the performance of A-UGVs and mobile manipulators. According to the summary, the metrics have been defined for the measurement of time/task duration, distance traveled, repeatability, accuracy, effectiveness, efficiency, autonomy, etc. The summary includes the measurement technologies like wireless indoor position measurement, perception sensing, motion tracking camera, laser tracking, and indoor global position system. It also includes measurement methods like benchmark, simulator, competition, and existing and ongoing international standards.

There have been many studies to enhance the performance, especially of object detection and navigation. Young et al [9] suggest framework to predict performances of A-UGV according to outdoor terrain. Wu et al [10] applied neural networks to single colored camera object detection.

Although there are research needs for describing the factors, and the A-UGV performance against them, in the factory, research to identify and define them have not been conducted yet. Among existing studies, it is difficult to determine how various obstacles or environments may affect the A-UGV's ability to navigate, to recognize obstacles, and to avoid obstacles. This means that the manufacturing environment combined with the user's requirements for the implementation of A-UGVs in factories have not been fully analyzed.

Information models are a good way to describe factory conditions and A-UGV performance information quickly and accurately. Unified Modeling Language (UML) [11] defines various diagrams to describe system components and behaviors. Among them, a class diagram well represents the components, properties, and relationships of the system, and is good for factory environment and vehicle performance information modeling. In addition, an object diagram, which is an instance of the class diagram, can be used to describe the measured A-UGV performance and the actual factory environment.

Accordingly, this paper aims to develop factory environment and vehicle information models for the introduction of A-UGVs into factories. The class diagram and object diagram of UML are used as modeling methods. The scope of this paper considers the environmental and obstacle factors including the elements discovered by previous research [7] and defined in the ASTM F45 standards [3]. In addition, newly discovered elements are added as well.

Before developing an information model, it is important to analyze why the standards and information models are needed based on the difference between the user and the maker. To this end, the requirements analysis comes first prior to information model development. Then, a factory information model for the introduction of A-UGVs, and A-UGV performance information models for evaluation, are developed. As a case study, an instance for a factory-like testbed and an A-UGV is developed.

2. NEEDS FOR A-UGV PERFORMANCE STANDARDS

Manufacturing standards generally serve as a guide for designers, engineers, builders, operators, and decision makers [12]. They also play roles in facilitating communication between stakeholders across manufacturing lifecycles, manufacturing supply chains, and from the factory floor to enterprise domains. In this paper, the focus is on the mutual understanding between A-UGV makers and users. This understanding will allow determination of whether the A-UGV can be operated or not and if so, performance estimation of A-UGVs within their operating environment. As a result, this will help efficient use and market expansion of A-UGVs. This section will first analyze the different views between A-UGV makers and users. Then, the section will suggest how standards can help enable mutual understanding between makers and users, and later, summarize what items should be defined as standards.

The analysis in this section shows one of the ways to use standards. The purpose of standards varies and is not limited to this.

2.1 Different views between makers and users

A-UGVs have various technical specifications. In catalogs, it is easy to find specs such as maximum speed, maximum load, runtime, charging method and time, navigation performance, etc.

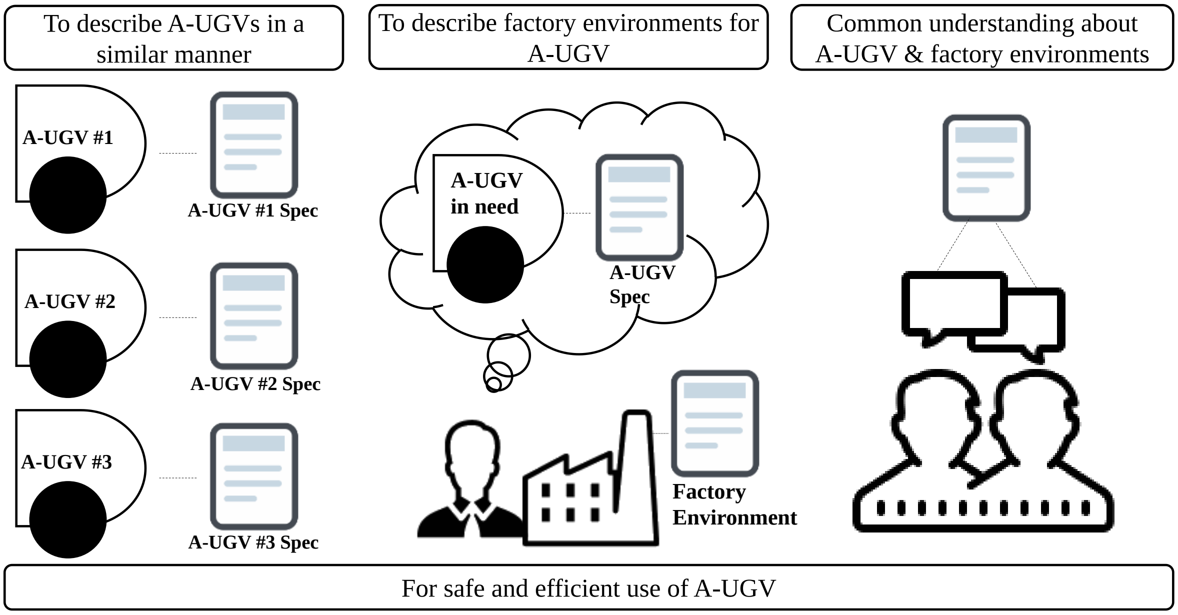

FIGURE 1: STANDARDS NEEDS SUPPORTING A-UGV USERS AND MAKERS

In addition, physical components specs such as drive wheel(s), motor, amplification, and battery can be numerically expressed. In terms of software, it shows what can be controlled including driving mode, driving function, map making, navigation, and monitoring. In terms of communication, it shows how the user can control the A-UGV including remote control, monitoring, fleet mode control, etc.

Meanwhile, there is less information about A-UGV performance under specific conditions. It is impossible for an A-UGV maker to test all manufacturing environments in the world, so they assume the general manufacturing environment and test the performance of the A-UGV in their facilities. However, this general environment may not equate well to factories in the world. Therefore, A-UGV makers need a method to express A-UGV performance under specific conditions.

From the user side, the first thing to consider is whether A-UGVs can perform the task in their manufacturing environment, rather than just purchasing A-UGV's based on their mechanical specifications. Manufacturing environments include basics such as temperature, humidity, brightness or lighting conditions, energy supply, and floor conditions. Open or closed space, workspace size, obstacles, pedestrians, floor level transitions (e.g., ramps), doors, gates, or steps (e.g., thresholds) should be considered. Safety, health, and quality should be protected and maintained.

The information provided by a maker alone is not enough to determine whether A-UGVs can operate in the user's manufacturing environment. Factory workers are not typically A-UGV experts although they know their process. The A-UGV installer must use their expertise to integrate the vehicle into the facility. However, once the installer leaves, many issues can arise that affect the A-UGV performance where user-knowledge is gained only during A-UGV use, instead of cost- and time-saving A-UGV performance knowledge gained prior to the installation. A-UGV users therefore need a means to express how the environment affects the A-UGV performance.

Figure 1 depicts overall needs for standards consisting of one base objective and three detailed objectives to resolve the issues. The base objective upon introduction of A-UGVs is that they are used safely and efficiently. To do this, first, standards need to describe the A-UGVs performance using a standardized method so that all A-UGVs are similarly described. Example A-UGV performance standards are ASTM F3244 navigation [13] and WK57000 docking. The A-UGV performance can be described for the A-UGVs being made or as requirements from users. Next, standards need to describe the factory environment using a standardized method. Here, the factory environment includes only elements that affect the A-UGV performance. An example environment standard is ASTM F3218 [14]. Based on the described factory environment, users can identify requirements of A-UGVs needed. Lastly, there needs to be a common understanding of A-UGV performance and the factory environment between makers and users, which these standards should provide. ASTM WK65139 A-UGV Capabilities standard includes both A-UGV performance and environmental conditions in which the A-UGV can prove or assert capabilities. The next section describes how standards are used and support common understanding.

2.2 How standards are used

A-UGV users can check the manufacturing environments defined in the ASTM F3218 standard and whether they exist in their manufacturing system. By measuring the vehicle workspace, including all possible conditions that could affect the A-UGV performance, the environment can be replicated. For example, the user can not only define narrow paths and turns but also potential challenges (e.g., low lighting, floor defects) with their exact locations noted from, for example, an intersection

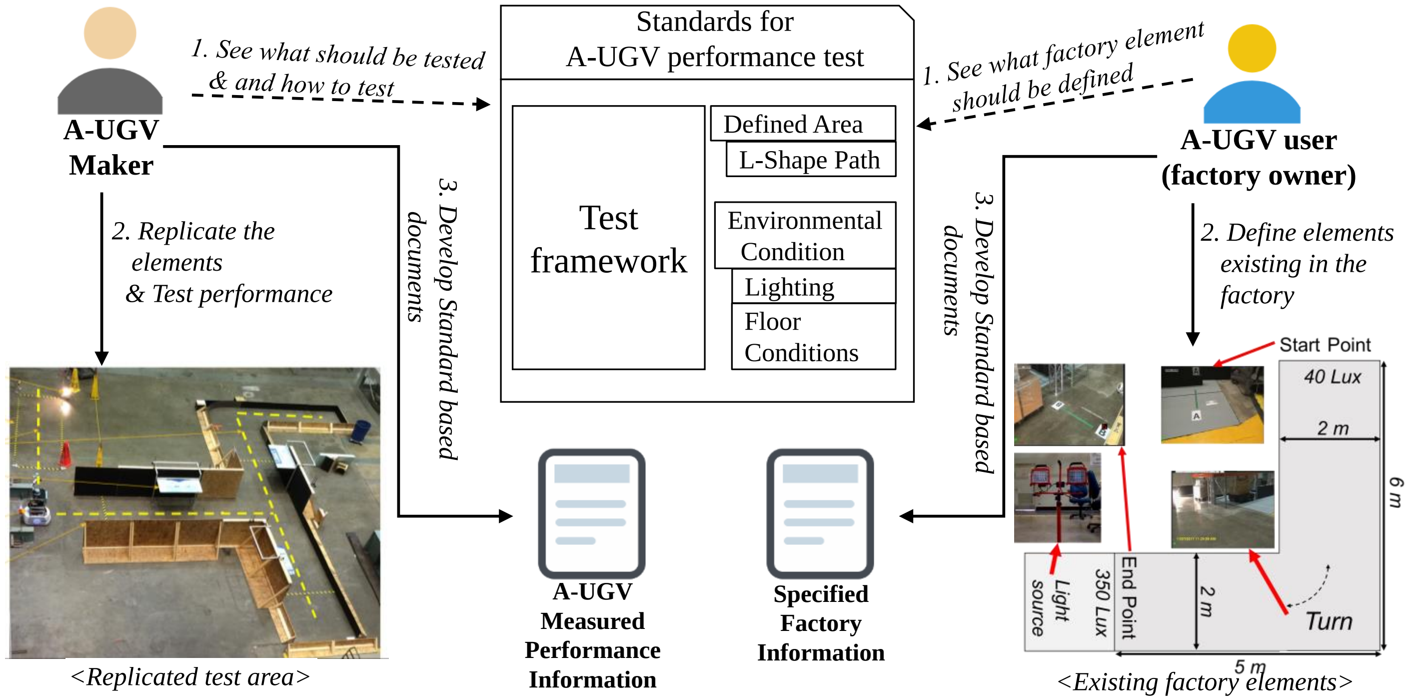

FIGURE 2: EXAMPLE OF A-UGV PERFORMANCE MEASUREMENT STANDARD USAGE IN CASE OF L-SHAPE PATH

(Fig. 2 right). Then, users can ask makers about the expected A-UGVs performance at user's factory by providing detailed operating environment information.

An A-UGV maker can build a test system to evaluate the performance of A-UGV for items defined in the standard. For example, in order to evaluate driving performance on narrow paths and turns, they can measure and evaluate the performance of an A-UGV by establishing the narrowest path environment in which their A-UGV can travel, as shown in Fig. 2 left. In addition, it is possible to measure the obstacle avoidance performance by making obstacle models and installing them in the driving path.

With the process shown above, the user and maker can communicate efficiently and effectively. The user can provide more exact A-UGV operating environment information and the maker can provide A-UGV performance values for the relevant environment. The user can find the A-UGV model that best suits their manufacturing environment and the maker can sell the A-UGV to users who have environments where their A-UGVs can operate.

In addition to helping to communicate between the maker and the user, standards help to clarify what to discuss. The standards provide the list of items that may affect A-UGV performance. The next section discusses items to be defined as standards.

2.3 Standards items to be defined

There are numerous factors that affect the A-UGV performance and many performance indexes. According to the purpose of this study, the standard items include only factors that: 1) can describe the operating environment, 2) can affect A-UGV functionality, especially navigation and docking, and 3) can commonly exist in factories. Items in ASTM F45 standards include the A-UGV performance descriptions, tests, and measurements that: 1) describe functionality against the factors, 2) test and document navigation, docking, and/or other vehicle tasks and capabilities, and 3) measure the A-UGV performance regardless of technology (e.g., automatic or autonomous). There are two types of factors, referred to as environmental factors and obstacles.

Environmental factors refer to the environmental conditions in which the A-UGV operates. If an A-UGV navigates successfully under an environmental factor, the A-UGV is determined to provide the expected performance for the factor. Environments can be classified into floor factors such as: ramps, gaps, gouges, and steps, and non-floor factors such as: lighting, temperature, humidity, and blocks.

ASTM F3200 defines obstacle as: "static or moving object that obstructs the intended movement" [15]. Obstacles in the vehicle path must be avoided (e.g., stop or navigate around) to not cause collisions or other unexpected A-UGV performance. To avoid obstacles, automatic A-UGVs stop, whereas autonomous A-UGVs can have the ability to recognize, measure the size of, and regenerate path(s) to avoid obstacles. There are various kinds of obstacles in factories depending on target products and processes of manufacturing systems. Since the A-UGV performance is affected by the obstacle characteristics (e.g., size, shape, reflectivity), it is necessary to analyze obstacles in with regards to how they affect A-UGV performance.

A-UGV performance refers to, among other capabilities, what the vehicle measures and reacts to in the presence of

TABLE 1: ENVIRONMENT AND OBSTACLE FACTORS, THEIR IMPACT TO THE A-UGV, AND THE REQUIRED A-UGV FUNCTIONS

Factors	Impact to A-UGV	Required A-UGV functions
Environment		
narrow curved path	stuck at the corner	to control minimum clearance from boundaries
grade (ramp)	obstacles by floor level change negative obstacles by floor level changes stuck at the entrance stuck before exit navigation error (vehicle location lost)	to recognize presence of a ramp to recognize being on a ramp to transit from floor to a ramp to recognize being stuck to recognize location lost
gap, step	stuck by gap or step floor detected as obstacle by tilted vehicle	to pass a gap, to recognize a gap or step and avoid to recognize being tilted
floor materials	docking / undocking failure by wheel slip	to drive on a surface without slip
transparent curtain barrier	blocked by barrier collide with obstacles near barrier	to pass barrier to detect obstacles near barrier
Obstacle		
general obstacle	fail to navigate due to collision damage to vehicle from collision	to detect obstacles before collision to measure the size and location of obstacles to stop before collision to bypass obstacles
small obstacle	fail to navigate and damage from collision	to detect obstacles near floor
overhanging obstacle	fail to navigate and damage from collision	to detect obstacles above floor below A-UGV height
moving obstacle	fail to navigate and damage from collision	to control time to reserve detected obstacle to detect obstacles frequently to predict next move of detected obstacle
lighting obstacle	stuck in front of lighting obstacle	to detect objects against direct light
transparent obstacle	fail to navigate and damage from collision	to detect transparent obstacle
negative obstacle	fail to navigate from fall severe damage to vehicle from fall	to detect negative obstacle to determine feasibility to pass negative obstacle
virtual obstacle	invade to human work or walk spaces	to behave against virtual obstacle as general obstacle

environmental factors and obstacles. The simplest navigation test result is pass or fail and in many failure cases, it is worth noting why it failed. For example, when an A-UGV is navigating a narrow path with an obstacle, the A-UGV performance can be evaluated differently. Failure examples could include: fails to measure the size of the obstacle, fails to determine a bypass route, fails to regenerate a route, approached and became trapped between the obstacle and the wall, or failed to pass narrow path. Alternatively, the vehicle may have performed as expected and simply stopped and alerted a supervisor of the issues.

Standards that document A-UGV performance should allow test requestors to clearly and concisely describe under which condition the vehicle is expected to pass against factors. Thus, standards should expect the test requestor to clearly document minimum and maximum values of measurable factors. For example, an A-UGV may be expected to successfully drive over 0 mm to 5 mm maximum steps.

Through previous studies [7], various environment and obstacle factors affecting A-UGV performance were identified and their characteristics were analyzed. Through subsequent research, several factors affecting A-UGV performance and the functions required for the A-UGV to respond are summarized in Table 1.

For each factor listed in the table, impact to A-UGV means there is a possibility that it may occur, and not all A-UGVs may be affected. Required functions for A-UGV means the capability is needed to respond to the factors. However, current F45 performance standards only provide test methods to measure the A-UGV performance regardless of how the vehicle technology is designed and handles factors. The intent in F45 standards is to allow the test requestor flexibility to determine how their A-UGV should handle each factor. For example, to solve a the situation when an A-UGV is stopped by a step, any solution making the vehicle surpass the step can be introduced. And, through standard tests requested, it is to be proven that the A-UGV can in fact do so.

In this paper, the effect of A-UGVs responding to a single factor, i.e., environment or obstacle, is described. However, more complex cases exist at factories where both simultaneously exist. Through various experiments, it was confirmed that the combination of both environmental factors and obstacles had additional effects to lower A-UGV performance. The method for defining such a complex situation and evaluating the corresponding A-UGV performance will be carried out through subsequent studies.

3. INFORMATION MODEL

A-UGV performance factors should be addressed in terms of target factories and A-UGVs rather than individually. In other words, each factor should be expressed as a property of the

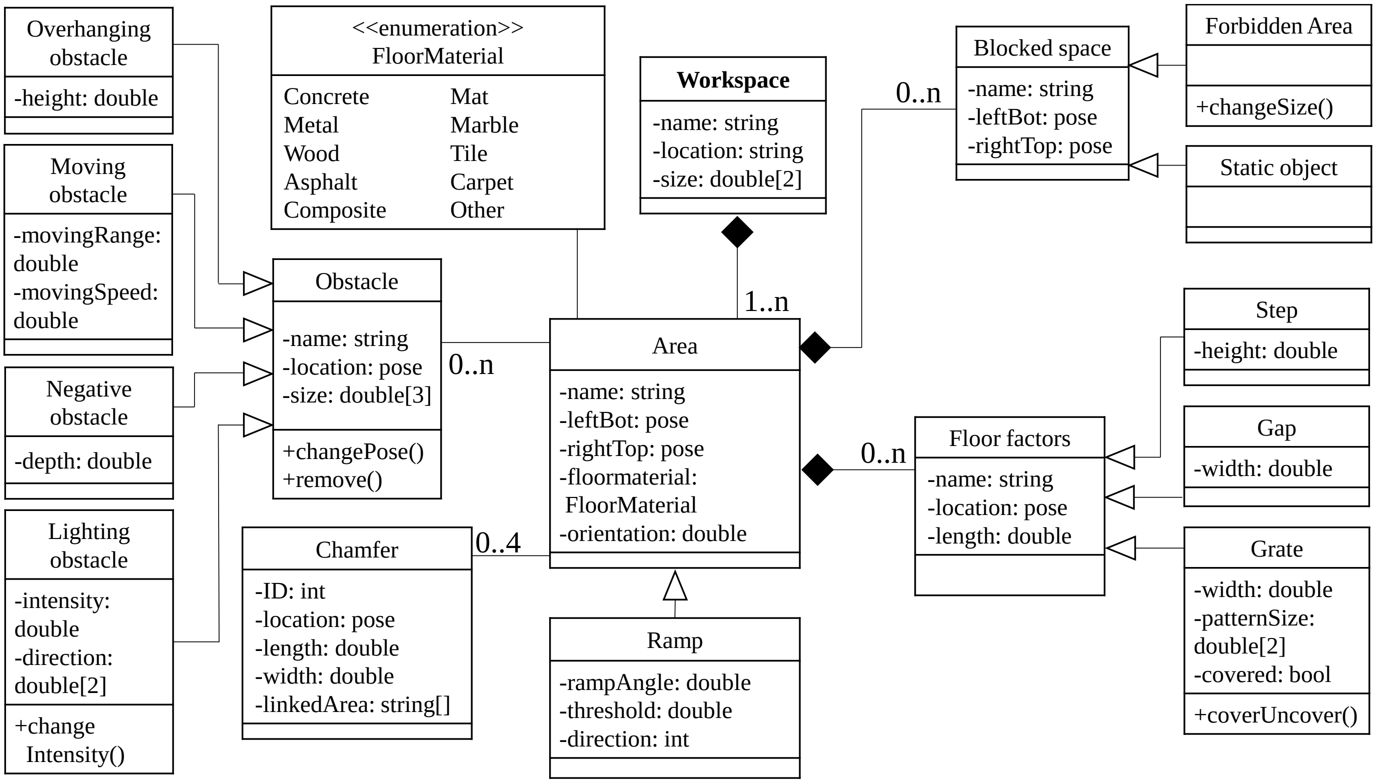

FIGURE 3: A-UGV WORKSPACE INFORMATION MODEL

factory or the A-UGV. At the same time, it must be able to express the factory elements (defined here as factory environment and obstacle(s)) independently, and relationships between the elements should also be revealed. The same is true of the A-UGV performance.

Accordingly, this section develops information models to support development of A-UGV performance measurement standards. The information model lists the elements necessary for the performance evaluation of A-UGVs and expresses how each element is related. The information model follows the class diagram of UML.

In this model, a class represents independent factory elements or the performance of an A-UGV. For example, obstacles in a factory can be defined as one class. Each class can have attributes describing the class. For example, obstacle class has location and size attributes. Each class is connected to other classes with relationship(s). For example, obstacle class is connected to area class, which means an obstacle exists in a factory area. Each class can define actual factory elements (see Fig. 6) or A-UGV performance (see Fig. 7) by specifying attribute values, called instances or objects. For example, a safety cone can be an obstacle class object that embodies size and location information.

An information model representing both the factory and A-UGV performance was developed to focus on classes to be defined and their relationships. Several attributes associated with factory elements can be added for each class, but those only suitable for this paper (i.e., considering only environmental and obstacle factors) are listed based on Table 1.

3.1 Workspace information model

In terms of A-UGV introduction, the most important part of a factory is navigation areas. From the perspective of the A-UGV, an area can be referred to as a confined space where A-UGVs can drive. Other spaces independent of A-UGVs are not included in the model even though they may play an important role in manufacturing processes. This paper uses the term ‘workspace’ as where the A-UGV can automatically navigate as specified by the user. The workspace can consist of one or more areas and the A-UGV can move freely between areas within the workspace. Therefore, the factory information model needs to be built in units of workspaces. Figure 3 shows the workspace information model.

Workspace is defined as base class. It has name, location, and size as attributes. Location is used to describe where a workspace is in a factory and workspace must have at least one area.

Areas are defined as squares by default. The location and size of the area are described by the left-bottom and right-top coordinates in workspace. It is necessary to specify the floor material. Common floor materials are concrete, metal, wood, asphalt, mat, marble, tile, and carpet. Orientation is used when the reference origin of the area and workspace are different.

A ramp area is defined as a derivative of the area. A-UGV performance may be affected by a ramp, especially according to angle and ramp transition. The ramp information model includes direction properties to express incline or decline.

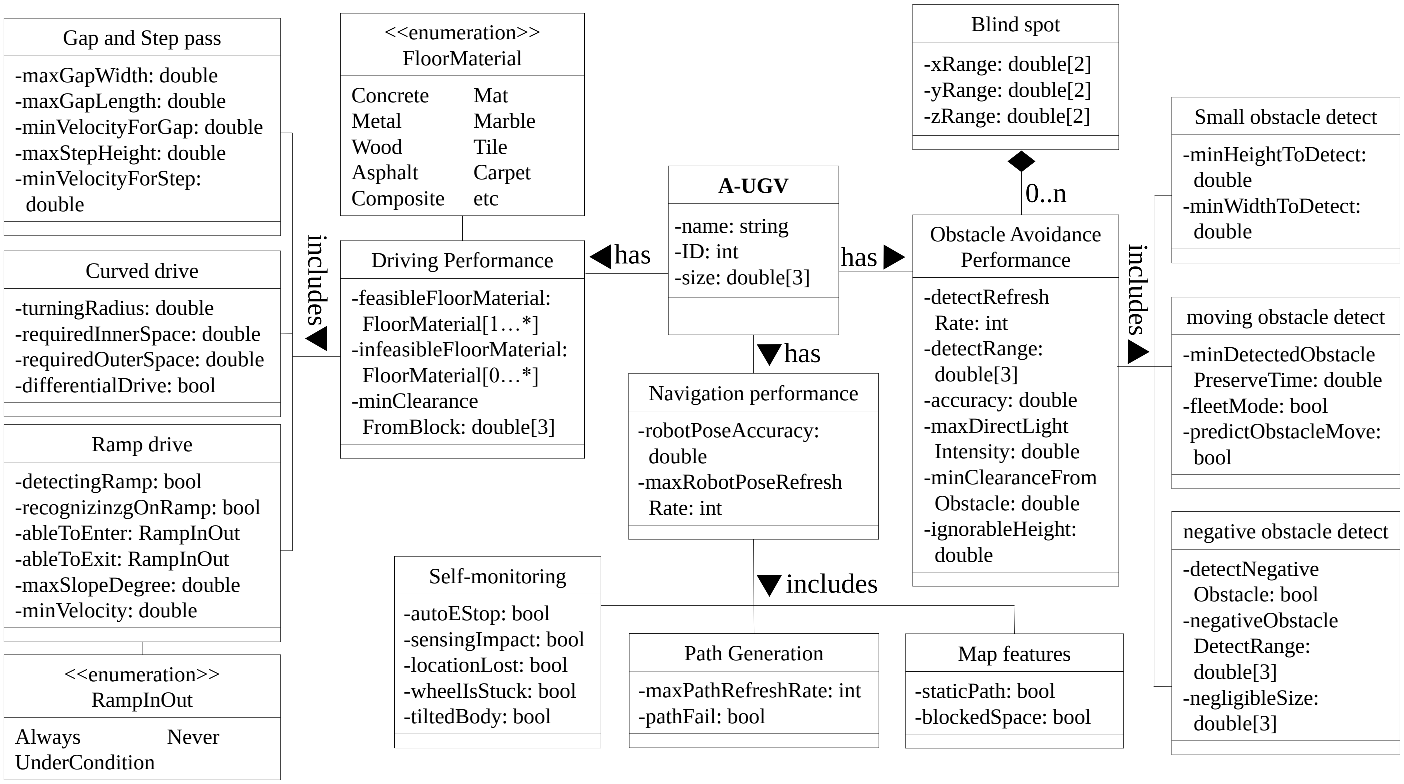

FIGURE 4: A-UGV INFORMATION MODEL

An area can have blocked space where the A-UGV should not access. Blocked space can be specified as a forbidden area or static object. A forbidden area is typically to prevent A-UGV collision with other objects, such as a pedestrian walkway. Static objects refer to those that are difficult to detect and rarely move, such as a workbench or a steel beam stacked on a shelf.

An area may have floor factors including irregular floor level changes. Gap, step, and grate are the typical types of floor factors. As floor factors may disturb and stop A-UGVs, their locations must be described. The size of floor factors should also be specified including height or depth information. Grates can be described as a set of patterned gaps. The pattern size describes the property of a grate. A grate can be changed to a negative obstacle when it is removed.

An area may have chamfered corners. The chamfer information model describes where it is, and to which area it is linked. The shape of a chamfer is described by length and width. Detailed measurement and expression methods are defined in the ASTM F3244 navigation standard [13].

An area may also have various obstacles. Each obstacle contains the location in the area and size information. Obstacles can be moved or removed. There are derivatives of the obstacle as the A-UGV may require further information to avoid them. They have additional attributes that may affect A-UGV performance.

3.2 A-UGV information model

The A-UGV information model begins by defining a target A-UGV class (Fig. 4). It includes basic information such as name, identification, and size. The A-UGV class has driving performance, obstacle avoidance performance, and navigation performance classes, and each of them have subclasses. Each class describes performance in each domain to respond to the factors defined in the workspace information model.

Driving performance class describes the environment in which the A-UGV can drive. Floor materials in areas where the A-UGV can or cannot drive should be specified. The class includes the minimum clearance from blocks required for safe driving. Driving performance includes gap and step pass, curved drive, and ramp drive classes.

Gap and step pass class describes maximum gap width and length, and maximum step height that the A-UGV can pass, and minimum velocities needed to pass the gap and step.

Curved drive class describes the required inner and outer radii in which the A-UGV can drive. The class also includes whether or not the A-UGV has differential steering which may allow the A-UGV to navigate tighter turns.

Ramp drive class describes abilities to recognize the presence of a ramp and that the vehicle is on a ramp. In addition, there are attributes to describe capabilities to drive on and off ramps. The class has attributes about the maximum ramp angle and minimum velocity required to climb the maximum ramp angle.

Obstacle avoidance performance class describes the capabilities for the A-UGV to detect and avoid obstacles. The ability to detect obstacles includes refresh rate, range, and accuracy. It includes lighting conditions in which sensors can operate normally. The ability to avoid obstacles includes minimum A-UGV clearance required to bypass obstacles and a minimum height value to ignore for overhanging obstacles under which the A-UGV can drive.

There are small, moving, and negative obstacles as subclasses of obstacle avoidance performance class. The small obstacle class describes the minimum height and width obstacle that the A-UGV can recognize. In the moving obstacle class, a minimum time to preserve detected objects in a navigation map is defined to avoid moving obstacles safely. A fleet mode support is defined to integrate other vehicles in a workspace. Predict function support is defined to predict next moves of moving obstacles. Negative obstacle class describes whether the A-UGV can recognize negative obstacles and the recognizable ranges. A-UGVs can ignore and pass over negative obstacles when one obstacle's depth, width, or length is small enough. Negligible sizes attribute describes their maximum values.

Depending on the type and arrangement of the sensors, blind spots exist where objects may be undetected. This usually occurs in spaces between A-UGV sensors. Blind spot class describes poses of A-UGV sensing volumes. An A-UGV may have no or multiple blind spots.

Navigation performance class is composed of the capability to monitor the current status and respond. Navigating begins with knowing the current pose of the A-UGV. Pose accuracy and refresh rate attributes are defined for the pose performance. Navigation performance class has self-monitoring, path generation, and map features subclasses.

Self-monitoring class defines several capabilities to recognize current status of the vehicle body and when an automatic emergency stop can occur. A-UGVs may be able to recognize physical impacts to the body, lost vehicle pose from the navigation map, drive wheels stuck from gaps, steps, or other floor factors, and vehicle tilt by a ramp, step, or uneven floor. Path generation class describes how frequently paths are updated and the capability to determine infeasible paths. Map feature class describes the capability to place paths and forbidden areas in the navigation map for efficient and safe A-UGV navigation.

4. CASE STUDY

As a case study, object diagrams were developed as information model instances for a National Institute of Standards and Technology (NIST) testbed having a similar environment to a factory. The testbed contains a lot of the spaces and objects including ramps, grate, steps, workshops, desks, chairs, machines, storage spaces, safety cones, etc. The main purpose of the testbed, in this case study, was to test A-UGV performance on and around ramps. It includes the abilities to undock from various points, to navigate to ramp entrances, to climb ramps, and to achieve a goal positioned at the level ramp top. The testbed has two ramps with 5˚ and 10˚ slopes. Figure 5 top shows the top view of the testbed and outlines the defined target workspace. Figure 5 bottom describes areas needed to be modeled. There are three steps and a grate as floor factors, and tires (T1 and T2), trash bins (B1 and B2), and safety cone (C) as obstacles.

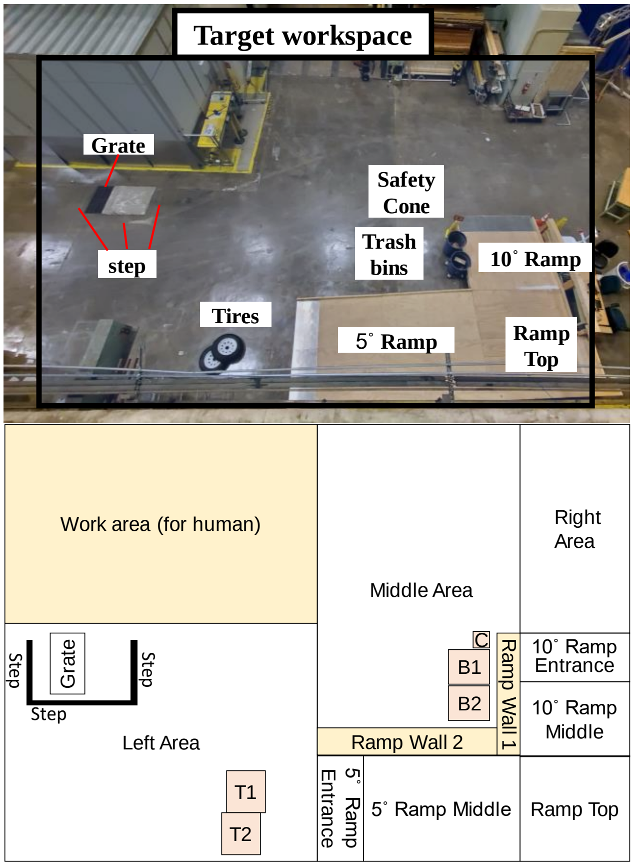

FIGURE 5: THE TARGET WORKSPACE PICTURE (TOP) AND DIAGRAM (BOTTOM)

Using the workspace information model defined in this paper, the instance for the target workspace is shown in Fig. 6 object diagram. A workspace object is defined as base with location and size information.

Four area and four ramp objects are defined under the workspace with name, location, and floor materials. Ramp structure consists of entrance, middle, and top objects. Entrances have 7 mm and 5 mm steps each, and a metal floor. Ramp middle and top have wooden floors. The direction attributes describe the direction of the ramp incline.

Left area object has forbidden area, obstacles, steps (i.e., in this case, small raised area) and grate objects. Forbidden area describes the location of the human work area. The Obstacle objects describe location and size of the folk lift and tires. The step and grate objects describe their locations and sizes.

Middle area object has obstacle and static object objects. Obstacle objects describe the location and size of trash bins and the safety cone. Static object describes the side of ramps, namely ramp walls, as they need to stop the vehicle when approaching the ramp from the wrong direction.

An A-UGV had been tested to measure its performance against the factors defined in the workspace object diagram. An object diagram is developed for A-UGV performance as shown

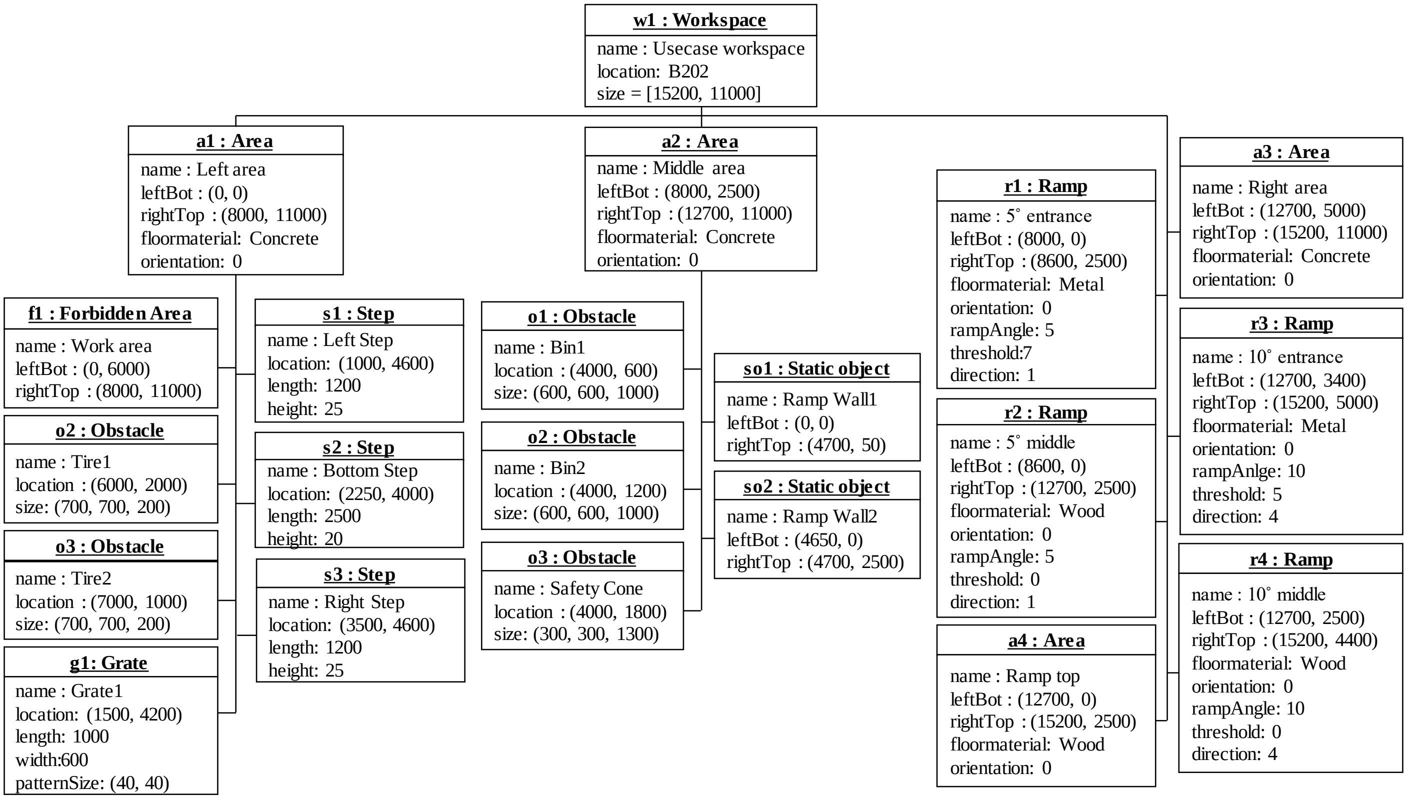

FIGURE 6: THE TARGET WORKSPACE OBJECT DIAGRAM

in Fig. 7. An A-UGV object is defined as base with name and size information. It has driving, navigation, and obstacle avoidance performance objects.

The driving performance object describes the performance against the floor factors. The A-UGV can drive on concrete, wood, and metal floor. The A-UGV required 50 mm clearance from blocks and succeeded to pass over a 20 mm height step at 500 mm/s velocity. When the A-UGV turned 180˚, it required 80 mm inside diameter clearance. The A-UGV could neither detect the ramp nor recognize being on the ramp. The A-UGV succeeded to enter and exit the ramp only when the side sensors were off. The A-UGV succeeded to climb 10˚ ramp with 300 mm/s speed.

The navigation performance object describes the performance of how the A-UGV perceives its status. The A-UGV had measured its pose under 100 mm error with 15 Hz refresh rate. The A-UGV stopped automatically when it failed to enter the ramp. The A-UGV could neither recognize that the drive wheels were stuck nor the tilted vehicle body by the steps. The A-UGV had set blocked spaces at the location of the ramp walls.

The obstacle avoidance performance object describes the performance against obstacles. The A-UGV had detected obstacles in the range of 8000 mm x 8000 mm x 1300 mm with 15 Hz frequency. The A-UGV detected obstacles correctly within 20 mm error and required 50 mm clearance to avoid obstacles. The A-UGV was able to detect obstacles equal to or larger than 200 mm x 300 mm. The A-UGV failed to detect the holes in grate, which are 40 mm x 40 mm x 1000 mm but the A-UGV could drive over the grate.

Through this case study, it is shown that the workspace information model can describe factors affecting A-UGV performance easily and efficiently. Also, it is shown that the A-UGV performance information model can describe its performance against those factors.

5. CONCLUSION

This paper analyzed needs of A-UGV performance standards and developed an information model for A-UGV performance. The information model supports A-UGV makers and users to describe and discuss the factors that affect A-UGV performance using a standard model, and the performance against them by providing the workspace model and A-UGV performance model. The workspace information model describes areas where A-UGV may drive with floor factors and obstacles information. The A-UGV information model describes the abilities to drive, navigate, and avoid obstacles responding to the factors defined in the workspace model. The case study was performed by applying the information model to the testbed having a mock factory environment. Through the case study, it was shown that the information model can describe the factory and A-UGV easily and efficiently in structured form for performance evaluation purposes.

This paper contributes to 1) help mutual understanding between A-UGV manufacturers and users through A-UGV and factory information models, 2) enable quick and structured

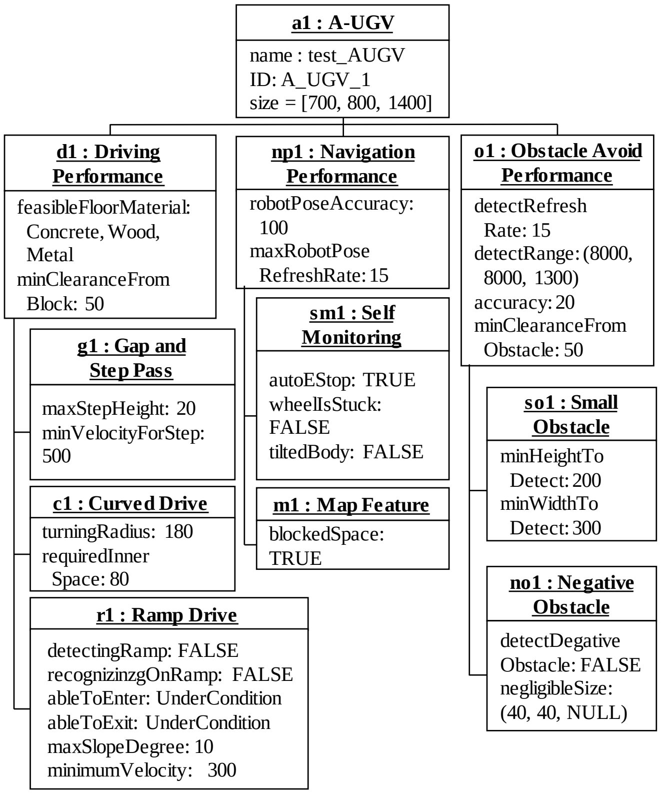

FIGURE 7: THE A-UGV PERFORMANCE OBJECT DIAGRAM

information delivery, and 3) provide a basis for testing various A-UGVs under the same environment in various locations.

A-UGV performance evaluation methods for more complex situations are planned to be conducted. This includes a combination of various floor conditions and obstacles and in a situation where multiple obstacles with different characteristics exist, such as transparent and luminous objects. Also, heterogeneous vehicles will be tested simultaneously in the same workspaces to see how the performance would change when they are grouped. The target and testing manufacturing system will be extended to larger scale with framework to manage the A-UGV in both hardware and software. The results of each study will be reflected in the information model and recommended to standards bodies.

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