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GRID-VIDEO MEASUREMENT METHOD FOR A-UGV'S SMALL OBSTACLE AVOIDANCE PERFORMANCE

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ABSTRACT

With the advancement of factory logistics into the autonomous era comes the need to validate the safety and performance characteristics of Autonomous-Unmanned Ground Vehicles (A-UGVs) working in these application spaces ASTM Committee F45 has been developing standards for A-UGV performance measurement in various domains. The object detection and obstacle avoidance performance of A-UGVs in factories needs to be managed carefully as the action may cause severe damages, particularly when obstacles are either not detected or erroneously detected. In this paper, the grid-video measurement method is proposed to measure the small (e.g., short and/or thin) obstacle avoidance performance of A-UGVs. First, this paper describes the need for measuring the A-UGV performance through examples of small obstacles and the required A-UGV capability to avoid them. Next, the grid-video measurement method is introduced as a low cost, standard method to measure the small obstacle avoidance performance of A-UGVs. An experiment using blocks demonstrates how the grid-video measurement method can be used effectively to measure the A-UGV obstacle avoidance performance, and it shows that the performance changes upon A-UGV specification, obstacle sizing, and environmental conditions quantitatively. The method and experimental results proposed in this paper will be used to support ASTM F45 standard development.

Keywords: A-UGV, Grid-video measurement, obstacle avoidance

NOMENCLATURE

A-UGV	Autonomous-Unmanned Ground Vehicle
ASTM	American Society for Testing and Materials
LADAR	Laser Detection and Ranging

1. INTRODUCTION

Factory logistics systems have been evolving through the introduction of recent technologies such as sensors, Internet-of-Things, embedded systems, and artificial intelligence [1]. With laser, vision, ultrasonic, contactless identification, positioning, or other tracking systems, the logistics equipment and materials can be identified and traced in real time [2], and various hardware and software information from device to factory level can be managed [3]. A logistics system can be directly involved in manufacturing tasks such as assembly in conjunction with production devices [4].

As the logistics system develops, the role of the industrial vehicle has been changed. Task creation, planning, execution, and analysis can be performed as well as delivery of materials, parts, and products. Various data can be transmitted to and from the vehicle and processed in real time [5]. Navigation and driving have evolved significantly, allowing the A-UGV to be operated automatically (i.e., pre-programmed path) or autonomously (i.e., no preprogrammed path), and to be actively introduced into factories [6]. For this paper, A-UGV will represent only the autonomous unmanned ground vehicles that can self-plan paths.

One of the potential uses of A-UGVs is the integration with the production system. When a logistics task occurs, A-UGVs can directly create an optimal path based on their capabilities and current status of manufacturing systems and send the path to the manufacturing system. In addition to tools, products, and materials, A-UGVs can deliver manufacturing equipment such as industrial robot arms (i.e., mobile manipulator). Therefore, A-UGVs are expected to travel and perform more functions with more diverse, dynamic, and complex routes and capabilities (e.g., self-awareness and path planning) than traditional industrial vehicles. Research to measure performance of mobile manipulators that include use of A-UGVs is being actively conducted [4,5,7].

Factory environments directly affect the performance characteristics of A-UGV systems. To describe and communicate the A-UGV performance in a common format among manufacturers, installers, and users, standard documentation of environmental conditions, obstacles, and test methods for evaluating safety, navigation, and obstacle avoidance are required. In line with technological developments and requirements, the ASTM F45 committee has been establishing standards for A-UGVs [8].

An obstacle is defined in the ASTM F45 F3200 standard [9] as "a static or moving object that obstructs the intended movement". Obstacles can affect the A-UGV performance in various ways [10]. Yoon et al. classified the characteristics of obstacles according to how they affect the driving performance of the A-UGV, including virtual, negative, lighting, moving, overhanging, and small obstacles [11]. In addition, Yoon et al. organized how each type of obstacle affects the navigation and driving of an A-UGV and proposed an obstacle information model accordingly [12].

Among the obstacle types, small obstacles have specific properties when measuring the A-UGV performance against them. First, the meaning of small is relative depending on A-UGVs. Second, the effect that the small obstacle has on the A-UGV varies depending on obstacle shape and size. Lastly, the A-UGVs' performance of detecting and avoiding small obstacles is significantly affected by factory environments. Because of these, the existing measurement methods [13] cannot sufficiently explain the interaction between A-UGV and small obstacles. To market A-UGVs to various industries, it is necessary to develop a common performance measurement method that can apply to all vehicles and factory environments when they include small obstacles.

In this paper, the grid-video measurement method is proposed for the small obstacle avoidance performance measurement of A-UGVs and based on this, the factors affecting the A-UGV performance are analyzed. As part of this, the characteristics of small obstacles are considered in terms of A-UGV performance, and an experiment is performed using the grid-video measurement method. In addition, the benefit, contribution, and expected use of the results towards the development of A-UGV safety and performance standards are discussed.

The paper first includes the definition and characteristics of a small obstacle in terms of A-UGV performance and described using examples. Second, the grid measurement method is introduced as a common measurement method for a small obstacle. Third, the A-UGV small obstacle avoidance performance is measured in experiments using an A-UGV under various conditions. How the A-UGV specification, obstacle size, and environmental conditions affect the performance are analyzed, and the usefulness of the grid-video measurement method is validated. Finally, a summary and future research are described as a conclusion.

2. NEED FOR SMALL OBSTACLE AVOIDANCE PERFORMANCE MEASUREMENT

To specify the measurement method objective, it is important to address why A-UGV small obstacle avoidance performance is needed. In this section, examples are provided where the A-UGV fails to detect the small obstacles due to their size and therefore, cause the A-UGV to collide with the obstacle and have navigation errors. Next, a small obstacle is defined reflecting the characteristics shown from the examples. Then, the A-UGV performance when interacting with small obstacles is summarized.

FIGURE 1: THE A-UGV COLLIDES WITH THE PALLET (TOP), THE PALLET IS ALIGNED IN A LESS DETECTABLE POSE (MIDDLE), AND THE PALLET BLOCKING A PORTION OF THE PATH (BOTTOM)

2.1 Small obstacle examples

The most common small obstacles in a factory environment are cardboard boxes and toolboxes [11]. ASTM F45 provides examples of obstacles in factory environments, among which pallets can be classified as small obstacles [10].

Figure 1 (top) shows the case where an A-UGV[1] fails to detect a pallet and collides with it. The A-UGV includes single-line scanning, LADAR sensors as the main detection sensors, and infrared depth sensors as secondary sensors. The pallet height is lower than the LADAR, so it failed to detect the pallet. Also, the surface area, as shown in Figure 1 (middle), is significantly reduced (i.e., as opposed to the adjacent side) according to the alignment of the A-UGV to the pallet making it undetectable by the depth sensor. In turn, the A-UGV collided with the pallet and pushed the object a considerable distance,

[1] 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

FIGURE 2: THE A-UGV CLIMBS THE DOOR CHOCK (TOP) AND ROTATES BY THE UNBALANCED WHEEL (BOTTOM)

which also caused an impact to the A-UGV body. The A-UGV did not recognize the collision and continued driving along the original route until it reached its destination. Figure 1 (bottom) shows a case where the pallet is blocking a portion of the initial A-UGV planned path. In this example, the A-UGV stopped at a very close distance to it after detecting the left-solid-side of the pallet using 3D sensor. In this case, the A-UGV generated a bypass route around the short obstacle (pallet). In other similar cases, the controller displayed a navigation failure and stopped driving.

Another small obstacle example is a door chock, a small wedged object commonly used to hold open a door. Figure 2 (top) shows the case where the A-UGV climbs up the door chock without recognizing it. As such, when a part of the A-UGV climbs up an obstacle, it makes the A-UGV tilted, and leads to lost navigation due to LADAR orientation changes. Additionally, climbing can result in uneven wheels and a tilted A-UGV, resulting in a wrong navigation plan, or a fall from a steep obstacle edge. Figure 2 (bottom) shows a case where the A-UGV rotated clockwise due to the unbalanced wheels.

2.2 Small obstacle definition and A-UGV performance

The above examples suggest the need for A-UGV capabilities to detect and avoid small obstacles. The first capability is obstacle detection. Small obstacles are difficult to detect when using only the main laser and are often detected by additional sensors such as 3D LADAR, vision, or sonar sensors. When searching with additional sensors, the A-UGV needs to be close enough to the obstacle or it needs specific conditions such as a brightly lighted environment or slow vehicle speed. The second capability required is navigation. The A-UGV needs to change the path when small obstacles are detected, to keep enough distance from small obstacles for safety when navigating, and to apply an emergency stop when too close to small obstacles. The third capability required is to respond appropriately to a collision. It is necessary to recognize the collision and notify the user and upper control system levels (e.g., high level planner).

Meanwhile, the above example also suggests the characteristics of a small obstacle. As defined in ASTM F3200 [9] and from the perspective of the navigating A-UGV, a general obstacle can be described as an object in the A-UGV path which an A-UGV can identify its relative location and size, generate a bypassing path, and navigate around it. However, in contrast to a general obstacle, a small obstacle can be defined as an obstacle having the following perspectives: First, the obstacle size is small enough to possibly not be detected by A-UGVs; second, the obstacle size is large enough to disturb navigation of A-UGVs; and third, when the A-UGV collides with the obstacle, the safety of the obstacle or A-UGV is affected and in turn, could cause harm to nearby workers.

According to these perspectives, an unfolded cardboard box is not an example of a small obstacle although the height is short. When an A-UGV climbs on an unfolded cardboard box, no damage occurs to the vehicle or possibly to the obstacle. The cardboard will most likely not interfere with A-UGV navigation when driving on or off the cardboard. Therefore, an unfolded cardboard box is not classified as a small obstacle unless A-UGV users find that the A-UGV performance is affected. Similarly, small floor cracks, a small string or a piece of plastic wrap, or short raised concrete expansion joint material are negligible obstacles and would not be considered small obstacles.

Considering the characteristics of an A-UGV's capabilities relative to small obstacles, a small obstacle avoidance measurement method is required to provide the following performance: First, detecting performance regarding how well the A-UGV detects or does not detect the obstacle during travel; second, navigation performance regarding how efficiently the A-UGV drives while avoiding obstacles; and third, collision response performance regarding whether the A-UGV senses collision with the obstacle and responds or not. In addition, it is necessary to describe the vehicle specification and the environmental conditions during the A-UGV performance evaluation.

3. GRID-VIDEO MEASUREMENT METHOD FOR SMALL OBSTACLES

In this section, a grid-video measurement method is introduced that satisfies the requirements of the A-UGV small obstacle avoidance performance measurement considerations. The grid-video method was initially designed and demonstrated for automatic guided vehicle (AGV) safety performance evaluation, and the test method was published in ASTM F45 standard F3265 [14]. The grid-video measurement method traces the AGVs' and moving obstacle positions simultaneously using overhead-mounted cameras and reference grids on the ground covering a 4 m x 1 m rectangular area. The method can be used to measure the time and trajectory of the AGV at a specific event, such as a worker suddenly traversing within the stop-zone (i.e., area needed to stop the vehicle without collision with the obstacle). The grid and recording concept can also be applied to

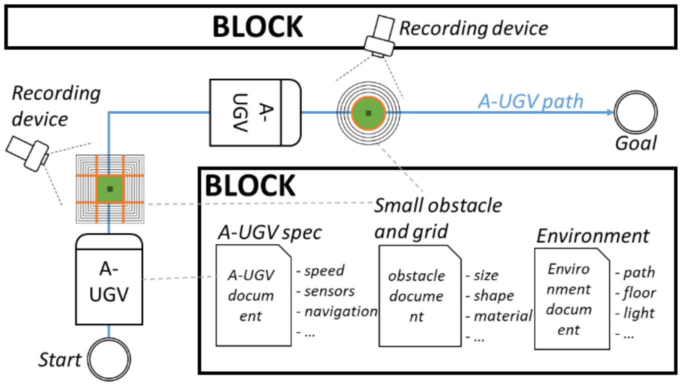

FIGURE 3: THE CONCEPTUAL PICTURE OF THE GRID-VIDEO MEASUREMENT METHOD FOR SMALL OBSTACLE AVOIDANCE PERFORMANCE MEASUREMENT

A-UGV performance measurement against stationary small obstacles.

Compared to the AGV experiment, the grid-video method for measuring A-UGV small obstacle avoidance performance has some different characteristics. It is not necessary to generate an event when testing the small obstacle avoidance performance. Since the observation range can be limited around the obstacle, the grid size can be minimally reduced. Also, the grid shape can change depending on the experiment purpose.

The grid-video measurement method proposed in this paper is based on an existing standard, simple to implement, low in cost to replicate, and can be applied to any A-UGV or manufacturing environment. Figure 3 shows the grid-video measurement method concept. The method begins by designing and documenting the A-UGV specifications, obstacles, and environment. First, the environment is defined in which the A-UGV performs tasks. Next, the A-UGVs' speed, sensor setup, navigation setup, and other specs are defined to allow navigation in the corresponding environment. Then, the obstacle is defined with location where it is placed on the A-UGV path. It is common to place it in the center of a straight-line A-UGV route. Or it can be placed anywhere that affects A-UGV driving, such as near the start point, near the goal point, and in the corner.

A grid is installed around obstacles. The grid is used to measure the distance when the A-UGV detects the obstacle and stops and/or navigates around the obstacle, and provides the closest distance when the A-UGV passes the obstacle. The grid is also used to determine collisions with an obstacle or the inability to sense obstacle motion and/or A-UGV direction change. When measuring the A-UGV-to-obstacle distance, a camera is used as the recording device mounted with a top-down view.

The grid size provides a specified distance around the obstacle. It may improve readability by highlighting at larger intervals (e.g., every 10 marks is bold). Depending on the obstacle type, an obstacle base may be needed. In this case, the size and shape of the base must match the grid so the base is regarded as part of the grid. For example, the length of the base can be 100 mm and the grid interval is 10 mm. A circular grid and a square grid are typical grid shapes as shown in Figure 3,

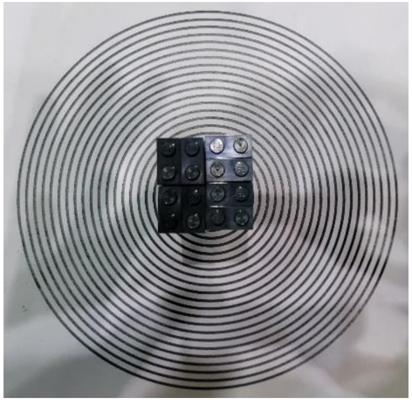

FIGURE 4: A CIRCLE GRID ON A PAPER WITH A SMALL OBSTACLE

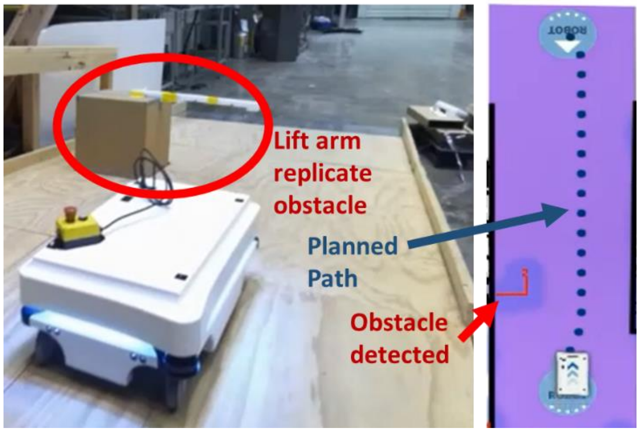

FIGURE 5: A PATH TO AVOID THE FORKLIFT ARM OBSTACLE

and dependent upon the obstacle feature to be referenced (e.g., center post vs. the entire obstacle).

The advantage of the circle grid is to measure accurately the distance from the obstacle center to the vehicle. Regardless of the obstacle size and shape, the circle grid can be used to measure the distance to the obstacle center. Figure 4 shows a small obstacle on a paper circle grid.

The square grid is useful when measuring the closest distance to a small square obstacle, such as a box or pallet. It also has a benefit when the grid aligns with the A-UGVs' forward axis. A-UGVs begin path planning by generating a combination of straight lines connecting each waypoint [15]. As shown in Figure 5, the A-UGV establishes a path avoiding the obstacle (forklift arm replicate) when sufficient detection and navigation space is available. The method using a square grid can provide the A-UGV-to-obstacle distance, which can then be verified as the appropriate passing distance. Other benefits by using the square grid are its simple design, installation, and expanse as needed in a specific direction.

There are several ways to make and install grids. The printed grid on a paper can be attached to the floor and then an obstacle can be placed on it. The obstacle can be placed first, and then a grid can be taped to the floor around the obstacle. Grids can be displayed on the floor using a projector or lighting (e.g., laser

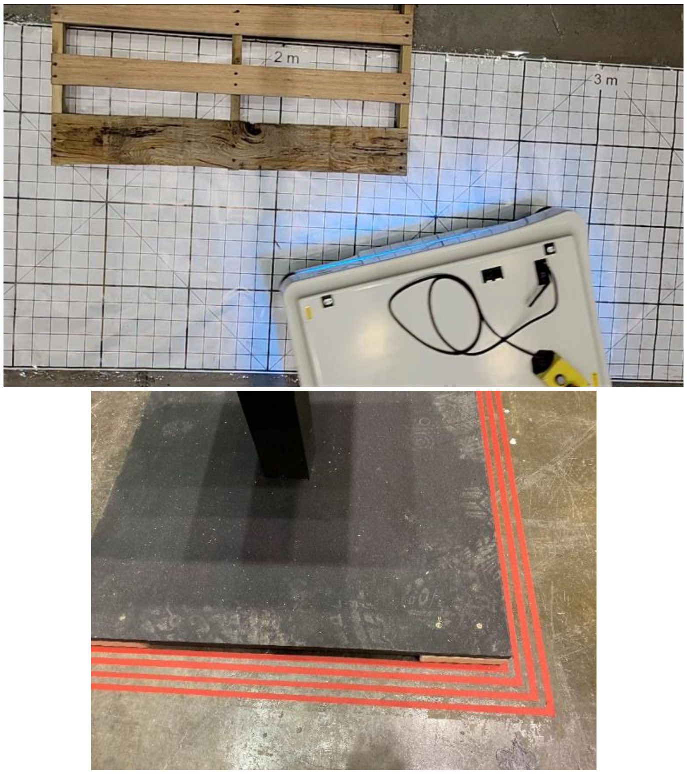

FIGURE 6: A PALLET ON A PRINTED PAPER GRID (TOP) AND THE TAPED GRID AROUND A WIDE BASE WITH CENTER POLE (BOTTOM)

lines). Figure 6 (top) shows a pallet on a printed grid paper taped to the floor and with an A-UGV passing by and Figure 6 (bottom) shows tape lines in a grid pattern around a wide base supporting a center pole.

4. A-UGV SMALL OBSTACLE AVOIDANCE TEST WITH GRID-VIDEO MEASUREMENT METHOD

The A-UGV was tested to measure the small obstacle avoidance performance using the grid measurement method described in the previous section. The test measured whether the A-UGV collided with the obstacle and the distance when the A-UGV detected the obstacle and stopped. Then, the small obstacle avoidance performance as affected by the A-UGV specification, environmental conditions, and the size of the small obstacle was analyzed. Through the test, the grid-video measurement method was verified to measure the A-UGV small obstacle avoidance performance at intervals of 25.4 mm.

4.1 Experiment setup

The A-UGV used in the experiment is a logistics vehicle mainly being used to work in a warehouse loading up to 100kg. Single line scan LADARs with 270 degree detection angles are attached to the front and rear as the main sensing system. The LADARs are mounted 190 mm height from the ground. Two depth cameras are attached to the front 140 mm height from the ground as a secondary sensing system to find nearby obstacles. The A-UGV was commanded to navigate a 6.0 m straight path. Figure 7 shows the A-UGV, the environment, the obstacle, and

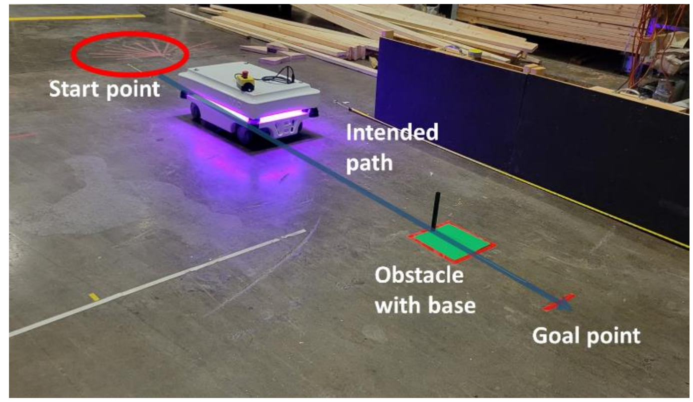

FIGURE 7: EXPERIMENT SETUP BEFORE A GRID INSTALLATION

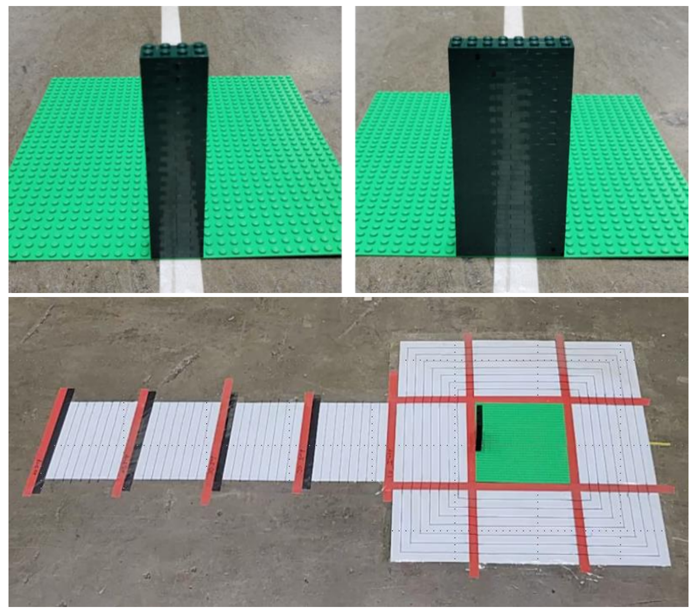

FIGURE 8: THE SMALL OBSTACLES WITH BASES (TOP), AND A GRID INSTALLED (BOTTOM)

the path before the grid installation. An A-UGV navigation map was created for the experimental space. The A-UGV speed was set to 0.3 m/s and to 1.0 m/s, and all the other navigation options were set to default values.

Stackable toy blocks were used as a small obstacle. The toy is a small plastic brick and can be reconfigured into various shapes. The toys were stacked until it was small enough to not be detected by the main A-UGV sensor, but large enough to interfere with driving. Since the toy material is light, it didn't affect the A-UGV when colliding, however there were occurrences where the toy pieces split into smaller pieces or fell down.

The obstacle height was set to 130 mm including the base, which is the maximum height not to be detected by the A-UGVs' main sensor. The obstacle depth was set to 15 mm. The obstacle width was set to 31.5 mm and 63 mm by using two and four stacked blocks, respectively. Accordingly, the obstacle used in this experiment can be defined as a plastic toy block with size of 31.5 mm x 15 mm x 130 mm (width x depth x height) and 63 mm x 15 mm x 130 mm. Since the obstacle base does not affect

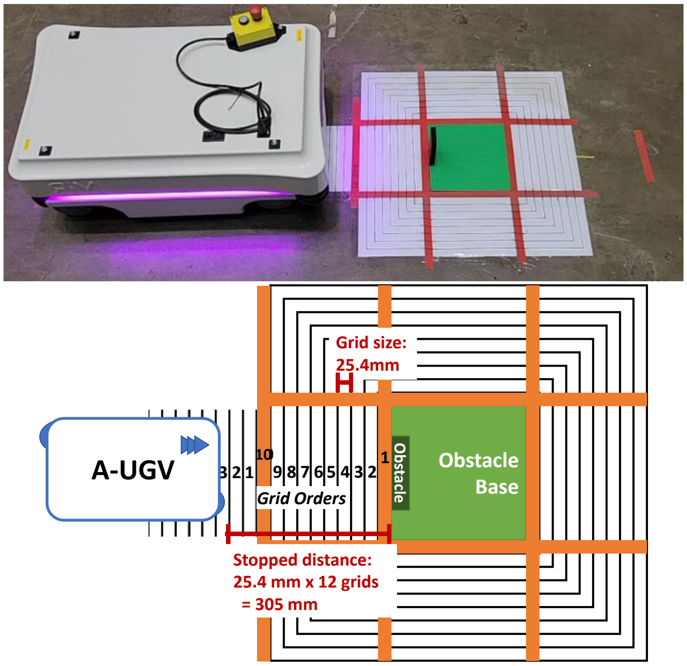

FIGURE 9: THE A-UGV STOPPED BETWEEN THE 12TH and 13TH MARKS(TOP), AND ITS PLANAR VIEW

A-UGV navigation, it was only included in the obstacle height. The obstacle was placed about 760 mm from the A-UGV goal point. The width center of the obstacle was horizontally 260 mm away from the front LADAR, and 70 mm away from each of the depth sensors. Figure 8 (top) shows the obstacles with bases.

Graph paper was used as the grid. The paper has an auxiliary line drawn every 25.4 mm. The grid was installed radially with a length of 254 mm centered on the obstacle base. A grid with a length of 1,016 mm was additionally installed in the A-UGV approaching direction. For easy distance measurement viewing, red masking tape was attached to the grid at intervals of 254 mm. The obstacle was placed closest to the A-UGV approaching direction for accurate distance measurement of when the A-UGV stopped. Figure 8 (bottom) shows the obstacle, the obstacle base, and installed grid.

The environment of the test was as shown in Figure 7. It was a factory-type laboratory shared by many people, and there existed various undefined objects. The floor was concrete and flat. There were some cracks in the floor, but they didn't cause noticeable issues in A-UGV navigation. The laboratory had a main and a secondary ceiling lighting system. In a dark environment, the main lighting system was used and measured to be 46 lux. In a bright environment, the secondary lighting was added and measured to be 246 lux. The distance from the floor to the light sources was about 30 m and the brightness was measured by a lux meter laying on the floor with the sensor facing upward.

The distance between the obstacle and the A-UGV was measured by a top-down view video camera in units of 25.4 mm. For example, as shown in figure 9, since the A-UGV stopped between the 12th and 13th markers, the measurement distance is 12 multiplied by 25.4 mm, which is approximately 305 mm.

4.2 Result and Discussion

The A-UGV was tested 30 times in each of the eight experimental conditions. The results are shown in Table 1. The collision metric indicates the number of times the A-UGV collided with the obstacle under each lighting condition. Mean distance indicates the average distance from the A-UGV to the obstacle when it detects the obstacle and stops, where collision cases are excluded. Standard deviation, minimum distance, and maximum distance were derived in the same way.

In the case of the bright condition, no collision occurred except for the case of small obstacle width and 1.0 m/s A-UGV speed. On the other hand, in the case of small width, 1.0 m/s A-UGV speed and dark condition, the obstacle was never detected. Accordingly, statistical analysis on distance cannot be performed for that condition.

The largest mean distance was shown at wide width, 0.3m/s A-UGV speed, and bright condition, and the smallest was small width, 1.0m/s A-UGV speed, and bright condition. The smallest standard deviation was small width, 0.3m/s A-UGV speed, and bright condition, and the largest was wide width, 0.3m/s A-UGV speed, and dark condition. In the 0.3 m/s A-UGV speed and dark condition, the difference between the maximum and minimum distance was much larger than in other cases.

To see the effect of the A-UGV specification, the obstacle size, and the environment, three pairs of tests were compared and analyzed. To minimize the combinational impacts, the test in which wide width obstacle, 0.3m/s A-UGV speed, and bright condition was set as a base, and the tests in which only one condition differed among the variables, vehicle speed, brightness, and obstacle size for each trail.

Figure 10 (top) shows the distance distribution in 76.2 mm increments when the A-UGV stopped, comparing the 0.3 m/s and the 1.0m/s A-UGV speeds under the wide width obstacle and the bright condition. The number of stops for each distance are

TABLE 1: THE EXPERIMENT RESULT

Obstacle width	63.0mm				31.5mm			
Vehicle Speed	0.3m/s		1.0m/s		0.3m/s		1.0m/s	
Lighting	**Bright**	**Dark**	**Bright**	**Dark**	**Bright**	**Dark**	**Bright**	**Dark**
Collisions	0	8	0	23	0	21	3	30
Mean Distance(mm)	977.90	873.99	319.19	391.89	844.13	485.42	248.36	N/A
Std Distance(mm)	100.00	234.72	81.06	107.62	71.74	226.63	109.89	N/A
Min Distance(mm)	762.00	381.00	127.00	228.60	711.20	228.60	76.20	N/A
Max Distance(mm)	1219.20	1270.00	457.20	508.00	965.20	914.40	482.60	N/A

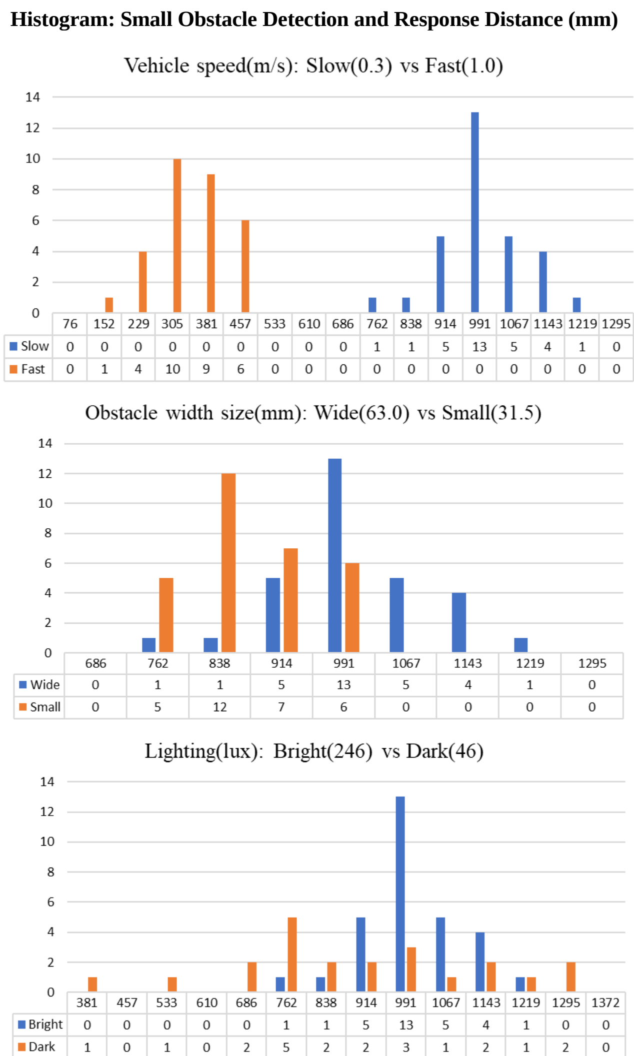

FIGURE 10: THE DISTANCE DISTRIBUTIONS COMPARING THE VEHICLE SPEED (TOP), THE OBSTACLE WIDTH (MIDDLE), AND THE LIGHTING (BOTTOM)

displayed in numbers and bars. For example, at 1.0 m/s A-UGV speed, the vehicle stopped once at a distance between 76 mm and 152 mm. There was no failure in avoiding the obstacle in both the slow and fast speeds. The average distance was less by 658 mm at high speed. Standard deviation was as small as 19.04 mm at the high speed, and they were the closest standard deviation from the comparisons. The data showed that the faster A-UGV speed decreases the expected mean distance to find small obstacles.

Figure 10 (middle) shows the distribution of the distance when the A-UGV stopped comparing the 63.0 mm and the 31.5 mm obstacle width under the 0.3 m/s vehicle speed and the bright condition. There were no failure cases for both widths. The average distance was less by 133 mm when the obstacle width was smaller and the standard deviation was less by 28.4 mm. The data showed the obstacle width gives small changes in the expected mean distance to detect small obstacles.

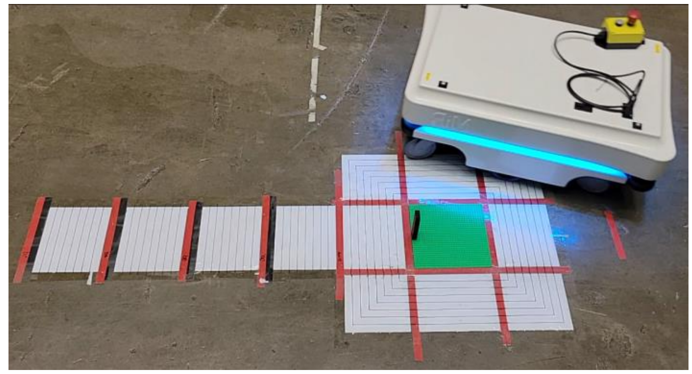

FIGURE 11: THE MOMENT WHEN THE A-UGV PASSES BY A SMALL OBSTACLE

Figure 10 (bottom) shows the distribution of the distance when the A-UGV stopped comparing the environmental illuminance between the 246 lux and the 46 lux with the 0.3 m/s vehicle speed, and with the 63.0 mm obstacle width. Under the 46lux illuminance, the collision occurred eight times. The distance when stopped decreased by an average of 104 mm, and the standard deviation increased by about 134 mm. Figure 10 bottom shows that the distance distribution was between 381 mm and 1270 mm. The data showed the lighting condition changes the variability of the expected distance to detect and respond to small obstacles. In addition, the brighter condition may increase the probability to detect small obstacles.

The mean distance of the dark condition is longer than that of the bright condition when the obstacle width is 63.0 mm, and the vehicle speed is 1.0 m/s. It is counter intuitive and comes from the small sample size due to 23 collisions in the dark condition. Out of the 30 tests, excluding 23 collisions, there are seven available samples in the dark condition, and five of them are longer than 400.0 mm. In the bright condition, there are six samples longer than 400.0 mm from the 30 available samples. This can be interpreted as the A-UGV rarely detects the small (63 mm wide) obstacle within 400 mm, traveling at 1.0 m/s speed, and in the dark condition. Results of the biased samples (i.e., collisions) made the mean distance in the dark condition longer than that of the bright condition.

4.3 Grid-video measurement method validation

As described earlier, a measurement method for A-UGV performance to detect and react to small obstacles should be able to evaluate detecting performance, navigation performance, and collision response performance, and to manage environment and vehicle specification. In this section, the grid-video measurement method is validated to be suitable for these purposes based on the data and result acquired from the test.

Detecting performance can be confirmed by measuring the distance between the obstacle and the vehicle. In the test described in this paper, the grid-video method was able to measure the distance when the A-UGV detected and reacted to the small obstacle since the grid was extended along the A-UGV path.

Navigation performance can be confirmed through travel time and travel distance. The navigation time and distance can usually be measured by the A-UGVs' monitoring system. The grid-video measurement method can also provide the approximate travel time and distance to verify the measurements from the A-UGV. The process of avoiding an obstacle can be divided into three states: (1) obstacle detection, (2) obstacle avoidance, and (3) arriving at the goal. The second state is affected by the A-UGV interaction with the small obstacle, and the grid-video measurement method can measure the length of the time of the second state. Figure 11 shows the moment when the A-UGV passes by the small obstacle using the grid.

Collision performance can be confirmed through whether an obstacle moves from the grid origin, and whether an A-UGV responds to it. The test in this paper concluded that the A-UGV did not recognize the collision in all cases.

Vehicle specification, obstacle characteristics, and environment can be described based on ASTM F45 standards [9, 10, 16] and the standard based information model [12]. Vehicle speed, obstacle width, and environmental light intensity were selected and used as test variables. As each variable changed, the test was able to quantitatively analyze how individual variables impact the A-UGV small obstacle avoidance performance. It was shown that the grid-video measurement method can measure how the performance changes upon differences in environment, vehicle specification, or obstacle size.

5. CONCLUSION

In this paper, A-UGV small obstacle avoidance performance is described and a grid-video measurement method is proposed to measure the performance. The grid-video measurement method is low cost, intuitive, and easy to use, and it can be applied to any A-UGV or operating environment. The method meets the requirements to deal with the small obstacle avoidance performance. As standard documents and procedures are well reflected, the grid-video measurement method has sufficient value to be used as a standard tool. Industrial indoor A-UGVs and environmental conditions were targeted in this paper, and the measurement method can be extended to the fields of for example, outdoors, public service, or medical facilities.

The study was conducted to measure the small obstacle avoidance performance of an actual A-UGV to validate the grid-video measurement method. The test showed that the A-UGV specification, the obstacle size, and the environmental conditions have effects on the A-UGVs' detection and interaction capability with small obstacles. The study demonstrated that the grid-video measurement method can be readily applied to a factory environment.

This study contributes to A-UGV adoption by providing a low-cost small obstacle avoidance performance measurement method. In addition to the measurement method proposed in this paper, the examples, the experiment, and the considerations on small obstacles are being applied to ASTM F45 standard developments.

There are two major plans for future efforts. The first is to expand the method for various obstacles. It is necessary to develop a methodology that can be applied to the obstacles defined in ASTM F45 as well as small obstacles. It is expected the unified method to measure the interactions with objects will contribute to the market of A-UGVs in the manufacturing industry. The second is to further analyze the effects of A-UGV specification, obstacle characteristics, and environmental conditions with multivariate statistical approaches. Interactions between the factors will be considered as the number of failures rise when they are applied together as demonstrated in this study. The detail analysis of the performance changes will be incorporated including the performance segmentation into sub-systems such as LADAR, depth, and sonar sensor.

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