Analysis of Automatic through Autonomous – Ummanned Ground Vehicles (A-UGVs) Towards Performance Standards

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***Abstract*— Automatic-through-Autonomous – Unmanned Ground Vehicles (A-UGVs), as termed by ASTM Standards Committee F45 for Driverless Industrial Vehicles, have much potential for use in manufacturing operations thanks to their versatility and flexibility. To utilize A-UGVs efficiently and effectively, it is needed to specify how the vehicle will be used, in what environment, and how best to control it. By understanding the detailed performance of the A-UGV and the facility environment, the vehicle can potentially operate with maximized productivity. In this paper, various parameters of the A-UGV are analyzed to measure navigation and obstacle avoidance performance. A-UGV aspects related to various facility environments are defined in structural form with organic relations. Performance test methods were developed and verified in a mock facility environment combining ramps and obstacles to measure navigation and obstacle avoidance performance.**

Keywords*— *Automatic through Autonomous – Unmanned Ground Vehicles (A-UGVs), vehicle environment, vehicle performance, test methods

I. INTRODUCTION

Automatic through Autonomous – Unmanned Ground Vehicles (A-UGVs) is a relatively new term defined by ASTM Committee F45 standard F3200 as “automatic, automated or autonomous vehicle that operates while in contact with the ground without a human operator” [1][2]. A-UGVs can be applied in a range of facility types as next generation vehicles. They are deployed to perform transport and other operations for various applications, such as assembly, painting, maintenance, material handling, and military assistance [3-6]. The type of vehicle varies depending on the vehicle task. Vehicle types include: loading-carrying, typically called unit-load, forklift, or tugger which pulls carts. A relatively new type of tugger is called cart transporter where the cart straddles and is mechanically fixtured to the vehicle. “Dock” is defined in F3200 as the target location where the A-UGV interacts with another object – i.e., in this case an object can be a cart, conveyer, load, etc. Cart transporters push, pull, and rotate a cart docked to the vehicle with nearly the same motion as the mobile base, as opposed to a tugger A-UGV that pulls carts from a single pivot point (e.g., trailer hitch).

Each A-UGV type also has unique sensor configurations for use with their varied applications. A-UGVs may include horizontal and vertical laser sensors, sonar sensors, and other sensors as with the A-UGVs tested and described in this paper. As A-UGVs can have many potential uses, the specific purpose of the vehicle must be defined by the manufacturer or requested by the user so that the A-UGV specifications align with its intended use. For example, in a dynamic facility environment where moving obstacles may be present in the vehicle path, relatively long-distance clearances are required for front and side sensors, while relatively short clearances are required in narrow path driving. If both cases exist in the facility, the A-UGV sensor configuration must be able to handle the variations.

There has been much research to measure and enhance the performance of the A-UGV [7]. The performance criteria includes path planning, stability, robot coverage, navigation system, accuracy and repeatability, time duration, task completion, efficiency, dexterity, autonomy, and exploration of unknown environments [8-13].

To effectively operate the A-UGV in a factory, it is necessary to measure the performance of the A-UGV, describe the environment in which the A-UGV operates, and evaluate how the A-UGV responds to each environmental factor. For example, most A-UGV manufacturers only generally specify that their vehicle can or cannot respond to floor gaps, undulations, and grade changes in the manufacturing floor. However, these environmental conditions can critically affect the vehicle performance. The user may therefore have difficulty selecting an A-UGV considering the specific task and operating environment.

To ensure expected performance, the user must define and measure: 1) the A-UGV performance on the task, 2) the manufacturing environment factor where the A-UGV will operate, and 3) the performance of the A-UGV's response to manufacturing environmental factors. Accordingly, ASTM Committee F45 was developed to standardize how the various A-UGV aspects are defined and recorded during standardized tests [1]. This allows employing the same methods for testing vehicles so that manufacturers can describe their product’s performance accurately and users and potential users can compare candidate A-UGVs to their task requirements. As the A-UGV term encompasses automatic guided vehicles (AGVs) and mobile robots, performance test methods within ASTM F45 are currently being developed to address generically automatic through autonomous industrial vehicles. Test methods tailored for specific vehicle types are left for future developments.

This paper defines criteria and describes the tests and results of A-UGV performance when they are used in mock facility environments. The criteria are defined as the environments in which the vehicle is to be driven and/or avoided. A description is provided for each criterion as to why each capability needs to be measured. Use cases were developed to demonstrate how the results can be applied in manufacturing processes or tested in even more complex environments that, for example, combine ramps and obstacles.

II. Driving performance

First, it must be considered that generally A-UGVs have different driving modes, including: speed-based; heading-based; purpose-based; autonomous driving; and/or automatic driving. In this paper it is assumed that the vehicle generally drives in autonomous driving mode with normal speed. Normal speed is the speed chosen by the vehicle controller up to a user-defined maximum that the vehicle will travel based on sensor and location inputs. Performance measurements of A-UGVs with specific mode configurations, such as maximum driving speed and acceleration are not considered in this study.

A. Narrow Path Driving and Curved Path Driving Performance

Paths that are slightly wider than the vehicle can define the test criteria for minimum passable area through which the A-UGV can navigate. Path width and navigation speed can be changed (dependent upon the facility and user requirements) according to vehicle configuration and capability. When moving from one path to a perpendicular path, as shown in Fig. 1, these criteria must be combined with curved path criteria.

Curved path driving performance describes how well the vehicle can follow an intended curved path and under what conditions – in this case, 90^{o} to another path. Usually A-UGVs generate paths under the shortest path protocol resulting, in this case, in the curved path maintaining minimal clearance from the inside radius of the corner. In our tests, sometimes the vehicle, with a large turning radius, emergency-stops (or e-stops) when it reaches a specific proximity to the wall. When the A-UGV attempts to navigate the curve and detects the corner, the vehicle rotates with a small rotation radius, requiring more space and time to make the turn. The vehicle performance criteria can therefore be evaluated as measuring: maximum rotation radii, required inside clearance to the corner, and required outer area to complete the turn.

B. Grade Driving Performance

Grade, or ramp, is listed in ASTM F3218 as an environmental condition for A-UGVs, that affects mobility performance [14]. The primary performance criteria are whether the vehicle can: 1) navigate from a level surface and transition onto the ramp, 2) navigate on the ramp, and 3) transition onto a level surface from a ramp.

The secondary performance criteria include whether or not the A-UGV can identify a ramp when navigating on a level surface. When creating the vehicle navigation map, it is typically known where ramps are located. However, if the navigation system does not support ramps, ramps are typically

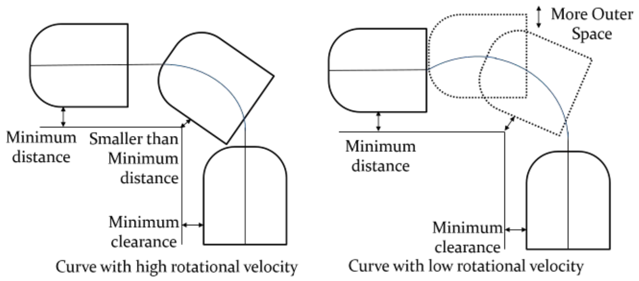

Fig. 1. Curved vehicle paths at high (left) and low (right) velocities.

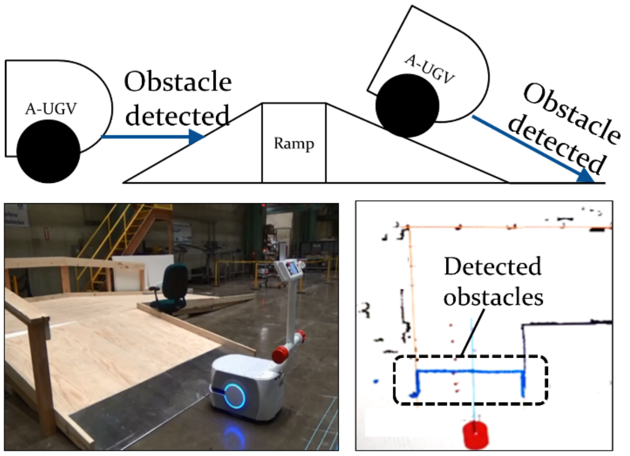

Fig 2. (top) Drawings of the ramp detected as an obstacle by the A-UGV. (bottom) Picture of the A-UGV in front of a ramp (left) and the ramp detected by the vehicle sensors (right).

detected as an obstacle by some sensors (e.g., line scanner range imagers) when the vehicle passes or enters the ramp. Similarly, when the vehicle travels down the ramp, the ground level surface is recognized as an obstacle by the front-facing laser sensor as shown in Fig. 2.

The common method to allow ramp-use by A-UGVs is to temporarily turn off low-mounted sensors which mainly detect the ramp as an obstacle when the A-UGV is on the level floor. Some other approaches can instead be applied to detect ramps both in software and hardware. For example, comparing the distance to the detected obstacle by various sensors can be used, and angle sensors can be used to measure vehicle tilt.

Therefore, grade driving performance can be described by: the ability to detect ramps, the ability to recognize being on a ramp; the required force or speed to enter a ramp; the minimum vehicle-to-ramp distance before transitioning onto a ramp; the transition capability from a ramp; the ability to drive on the ramp forward and backward; and the ability to rotate, drive, dock, and undock while on a ramp.

C. Driving Performance upon Gap and Threshold

Because not all factories are made up of just one uniform floor surface, there can be gaps and/or thresholds between surface areas. Separations between surfaces are gaps and adjacent floor height differences are thresholds. A crack in the factory floor is a typical example of a gap, irregular in shape. A concrete abutment with a grate inserted that is raised slightly (e.g., 1 cm) within a uniform floor surface is an example threshold.

Often, A-UGVs are expected to traverse gaps and thresholds. There are three possible results in this case: 1) the A-UGV successfully passes over it and detects or does not detect it (not detecting it could be considered a sensor failure), 2) the A-UGV fails to pass over it but does not detect it, or 3) the A-UGV fails to pass over it although recognizes it. The second case occurs when a vehicle wheel is stuck in the gap or at the threshold. In this case, the vehicle cannot move as planned although one or more driving wheels may keep moving. The vehicle controller inputs wheel encoder changes without vehicle body movement and as a result, vehicle position errors appear in the navigation system. Fig. 3 shows

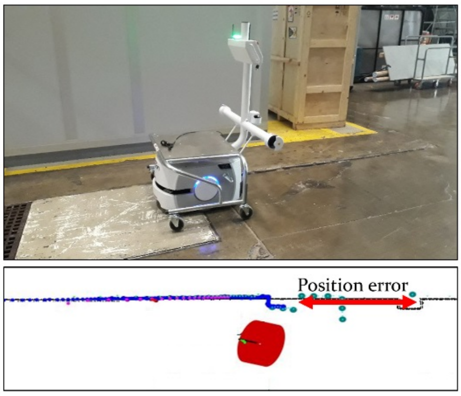

Fig. 3. A-UGV stuck on a raised surface resulting in vehicle position error.

an example of a position error from the A-UGV being stuck on a threshold.

Gap and threshold performance criteria can be described by: the ability to detect a gap or threshold, maximum length of a gap to pass over, maximum height of a threshold to pass over, minimum driving speed to pass over the maximum length of gap and height of a threshold, the ability to recognize position error caused by a gap or threshold, and the ability to recognize being stuck from a gap or threshold.

D. A-UGV Performance Caused by Floor Conditions

Factories can have different floor conditions. The most widely used floor materials are concrete and steel. However, as the types and purposes of factories vary, other floor materials, such as wood, tile, or carpet, may exist. Additionally, miscellaneous materials may be lying on the floor, such as plastic wrap, liquid, thin film, or tape. It may be intended that the A-UGV has the capability to drive over these materials. In which case, any of these floor conditions may cause the vehicle to perform unexpectedly.

A-UGV performance affected by floor conditions can be described by: the feasibility to drive on specific floor surfaces and the feasibility to drive over materials on floor surfaces.

III. Obstacle Avoidance performance

One of the most critical issues concerning A-UGVs is safety. To protect nearby humans, equipment, facilities, and the A-UGV itself, the A-UGV performance detecting obstacles and avoiding collisions is very important. However, if the vehicle is under strict obstacle detection and avoidance or is to stop when detecting an obstacle in the vehicle path, the A-UGV may fail to drive to the goal. To continue production, a trade-off between drive performance and safety may therefore occur. Of course, external approaches, such as facility-based obstacle sensors, can be effectively applied to enhance both performance and safety. Instead, this study aims to analyze the obstacle detection and avoidance issue from the perspective of the vehicle itself as discussed in this section.

A. General Obstacle

In ASTM F3200, obstacle, also referenced from ISO 8373, is defined as: static or moving object or feature, on ground, wall, or ceiling, that obstructs the intended movement [2][15]. A discussion that adjoins the obstacle definition also states: Ground obstacles include steps, holes, uneven terrain, and so forth. For this study, obstacles are considered to be every detectable object which is not registered in the A-UGVs navigation system.

Beyond preprogrammed automatic guided vehicles, A-UGVs with higher intelligence should be able to detect general obstacles and continue driving toward the goal while avoiding the detected obstacles. Usually there are three obstacle types as in the definition: 1) obstacles on the floor, such as workers, objects, products, pallets, or other A-UGVs; 2) obstacles attached to the wall, such as wall-mounted tools or open doors; and 3) obstacles suspended from the ceiling, such as an overhead crane. Fig. 4 shows typical examples of these.

For all three types, it is required that the A-UGV measure the distance to the obstacle in real time to decelerate and/or plan an appropriate path around the obstacle. The A-UGV should then determine whether to ignore the obstacle or not. Surely when the obstacle is far away from the path, the obstacle can be ignored. The obstacle can also be ignored when it is mounted on the wall or suspended from the ceiling if it is higher than the vehicle height. Industrial Truck Safety Development Foundation (ITSDF) B56.5 safety standard [16] states that test pieces testing the onboard sensors must be detected "within the contour area of the vehicle (including onboard payload, equipment, towed trailer and/or trailer payload)." Thus, the vehicle should be able to determine these conditions. As stated in the previous section, the ability for the A-UGV to distinguish obstacles and ramps from the environment is also important.

A-UGV performance criteria when detecting general obstacles can be described as: minimum and maximum detectable range from the vehicle, obstacle detection time, obstacle measurement uncertainty (i.e., obstacle size and location), and time spent detecting an obstacle. A-UGV performance criteria when avoiding a general obstacle can be described as: minimum required space to avoid an obstacle, the ability to determine avoidance feasibility, the ability to generate an alternate route, and the ability to stop before a collision.

B. Virtual Obstacle

There are areas where vehicles are prohibited, such as pedestrian walkways or human work areas. In these areas, although there is no physical object for sensors to detect, the vehicle is expected to avoid them. The virtual obstacle may therefore constrain the A-UGV path. A-UGV navigation software may be configured with forbidden lines or areas for the vehicle to avoid. As with general obstacles, the vehicle should keep a minimum clearance to the virtual obstacle. Also, when no path can be generated because of virtual obstacles, the vehicle should stop driving.

A-UGV performance criteria for nearby virtual obstacles can be described as: the ability to put virtual obstacles in the

Fig. 4. Typical examples of general obstacles: cone (left), open door (middle), crane hook (right).

vehicle map and the ability to react correctly to virtual obstacles.

C. Negative Obstacle

Negative obstacles are areas where the floor is lower than the surface on which the A-UGV drives (e.g., a hole). Similar to ramps, ASTM F3218 considers negative obstacles as a ground surface condition, called a gap, where depth and length of the gap are recorded. However, ASTM F45 is considering whether to specifically define a negative obstacle or to add further condition information since gaps can have width that is larger than what may be considered a floor gap (e.g., manholes and loading docks). Since negative obstacles can cause severe damage to the A-UGV and without the obstacle being placed in the vehicle map as infrastructure to avoid, the A-UGV should detect and avoid negative obstacles that may be within its path.

The A-UGV needs to at least detect the length and width of the negative obstacle that is within the vehicle path to safely avoid it. Fig. 5 shows a negative obstacle caused by a grate removed from a manhole. Typically, the grate covers the hole and therefore it is not placed in the map. However, when the grate is removed the A-UGV should safely avoid it if the size of negative obstacle is correctly measured and placed in the vehicle map.

As discussed in section II-B, other types of negative obstacles (e.g., platform-to-ramp transitions) are generated by sensing changes to elevation in the flooring. When an A-UGV is on the level platform at the ramp top and ready to go down the ramp, the vehicle must detect that there are changes in floor level to vary vehicle velocity and/or apply downhill braking. Those floor height changes may be incorrectly sensed for both ramps and negative obstacles. However, the vehicle performance is dramatically affected where it should keep driving for the ramp case and should avoid the negative obstacle in that case.

A-UGV performance criteria when detecting a negative obstacle can be described by the ability to detect a negative obstacle and the minimum detectable length, width, and depth of a negative obstacle. A-UGV performance criteria when avoiding a negative obstacle can be the same as for the general obstacle. It may also be required to measure the vehicle performance that is capable of driving over the maximum length, width, and depth of the negative obstacle.

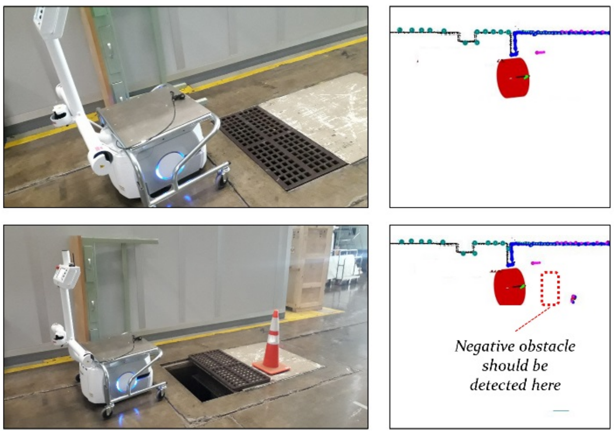

Fig. 5. A-UGV attempting to navigate across a covered (top) and uncovered (bottom) man-hole. The bottom image shows a negative obstacle not being detected by stock A-UGV sensors.

D. Atypical Obstacles

A-UGVs typically detect obstacles by light (e.g., laser detection and ranging (LADAR), vision) and/or acoustic sensors (e.g. sonar). LADAR and vision sensors are naturally affected by light. Similarly, acoustic sensors may be affected by loud noise. When bright light is directed or is flashed towards vehicle light sensors, the vehicle controller may interpret the light source as an obstacle as in Fig. 6. Common bright light examples in factories are uncovered windows that allow bright sunlight to pass through or high intensity work lights used by maintenance personnel. ASTM F3218 provides a brief description and method for recording several aspects associated with environment light conditions, including: ambient lighting type and source, direct highly-concentrated, directional lighting, ambient lighting source location, lighting intensity level, spectrum, and light exposure (i.e., continuous or transitional).

A-UGV performance criteria for robustness to light conditions could be described as maximum light intensity and light direction that the vehicle can withstand before it considers the light source as an obstacle.

E. Moving Obstacle

Detecting and avoiding moving obstacles requires more advanced technology as compared to stationary obstacles. Most common moving obstacles in a facility are humans and equipment (e.g., carts, forklifts).

Multiple A-UGVs can detect each other as moving obstacles and they can avoid one-another with appropriate moving-obstacle sensing and/or a central controller planning vehicle path as shown in Fig.7.

F. Overhanging Obstacle

Overhanging obstacles are general obstacles with obstacle parts detected or undetected causing the obstacle to appear to float in the path. Typical examples are folklift tines, pipe laying on and overhanging a cart, and stretched arms of worker. Because of the vehicle sensor detection capability and mounting location, the entire obstacle in the vehicle path may go undetected.

Overhanging obstacles may be undetected when: 1) objects are thin and long, 2) objects are mounted above or below A-UGV's horizontal sensors, and/or 3) objects are mounted between the A-UGV's vertical sensors. These conditions cause high collision risk with severe damage to the objects or A-UGV.

Fig. 8 shows overhanging obstacles at three different heights. Polystyrene obstacles were placed and an A-UGV was programmed to move straight forward toward each. Only the 2nd level obstacle was detected due to the vehicle sensor mounting height being in-line with the obstacle and the

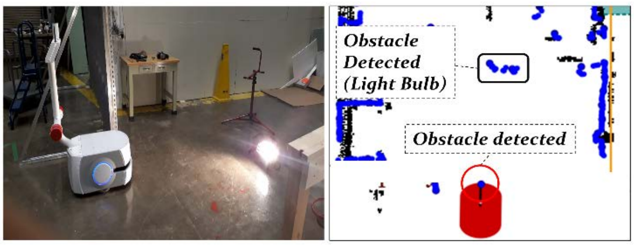

Fig. 6. Bright light detected as a (false) obstacle by the A-UGV obstacle detection sensors.

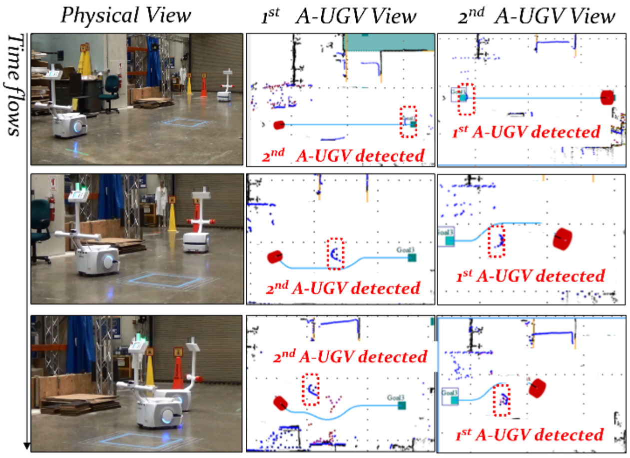

Fig. 7. Two vehicles approaching one another and recognized as obstacles by each other.

vehicle stopped before collision. The 1st and 3rd level obstacles were not detected causing A-UGV collisions with the obstacles.

Similar to general obstacles, A-UGV performance criteria with overhanging obstacles in the vehicle path can be described as the ability to detect obstacles that are within the facility – i.e., if there is a possibility of facility obstacles being within the A-UGV path, they must be detected and avoided. This includes the removal of sensor blind spots.

G. Small Obstacle

When two-dimensional (2D) A-UGV sensors are installed in only vertical or horizontal orientations, they may not detect obstacles that are shorter than, for example, a horizontal 2D LADAR sensor and narrower than the distance between right and left vertical sensors. Many obstacles fit this scenario (see Fig. 9), such as: worker tools and toolbox, cardboard packages, and tape rolls.

Sonar or other sensor types can be used to detect obstacles. Low-mounted sensors can detect obstacles just above the floor. Higher-mounted or adjustable-mounted sensors can detect obstacles in other locations.

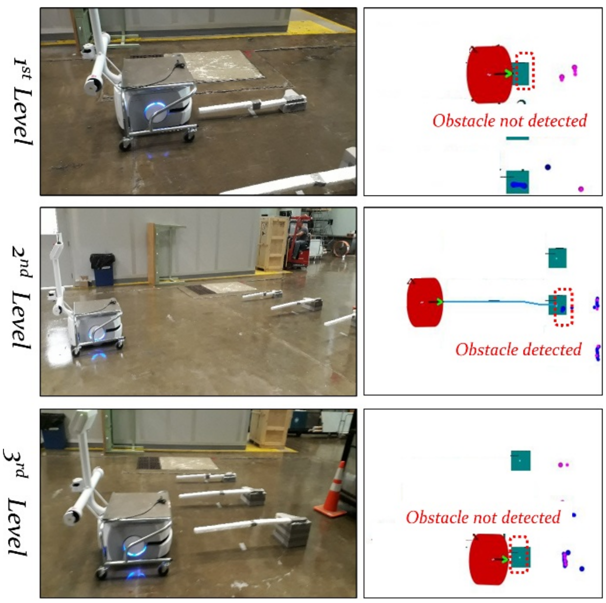

Fig. 8. Three overhanging obstacles with different heights being undetected (1st and 3rd level) and detected (2nd level) by the A-UGV sensors.

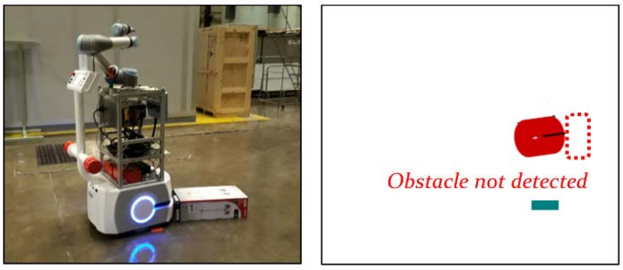

Fig. 9. A large, short box undetected by the A-UGV sensors.

As with overhanging obstacles, A-UGV performance criteria when detecting small obstacles can be described as the ability to detect obstacles that are within the facility.

IV. A-UGV Performance Case Study

In sections II and III, A-UGV performance considerations with respect to environmental effects and obstacles are discussed. There are many cases that combine these elements affecting A-UGVs. In some cases, there can be issues beyond those described previously that are caused by these complex conditions. In this section, a case study is presented where an A-UGV is programmed to avoid a general obstacle placed on a ramp and vehicle performance is measured.

A. Ramp with Obstacle

Given the information presented in section II-B, the addition of obstacles on the ramp can also affect vehicle performance, especially dependent upon their location on the ramp. Therefore, the effect of obstacle location will be analyzed.

The A-UGV was programmed to drive from the floor to the top platform of a 5° ramp measuring 2.4 m wide x 4.8 m long. An obstacle (cone) was then placed at 8 different ramp locations 1 m apart and from the top edge, namely Ob.1 to Ob.8, as shown in Fig. 10. The A-UGV was driven manually by the operator as a reference, and then 30 times in autonomous mode for the test. Manual mode includes direct human-machine interface (e.g., joystick) control and autonomous mode includes vehicle self-driving control. Throughout the test, 1) the A-UGV performance was measured and recorded, and 2) general issues were recorded when unexpected events occur.

The obstacle was placed in a position that can 1) interfere with A-UGV, and 2) allow enough space for the A-UGV to drive around. Each obstacle was therefore placed at 300 mm from the center of the ramp with the vehicle being aligned with the ramp center.

Through preliminary research, it was determined which A-UGV configurations affect driving performance. The A-UGV drives best on this ramp when 1) the low laser sensor obstacle detection is ignored, 2) vertical sensors are ignored, 3) local path fail distance is low, and 4) driving velocity is higher than 300 mm/s. These properties were applied and minimum driving velocity was set at 450 mm/s. Local path fail distance is the distance allowed to approach a sensed area blocked from navigation.

For each test, drive pass/fail, travel time, and travel distance were measured. A test was deemed as passing when the A-UGV successfully reached the goal. Otherwise, it was determined to be a failure. Overall A-UGV driving

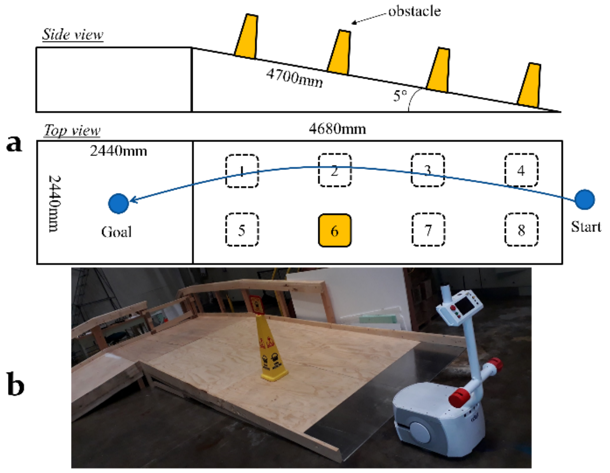

Fig. 10. (a) Drawings of eight different obstacles on a 5° ramp and (b) picture of an obstacle at location 6 on the ramp. The approximate A-UGV path avoiding the obstacle is shown from start to goal.

performance was evaluated, including: whether the vehicle could recognize the ramp as not being an obstacle, if it was able to transition to and from the ramp, and could drive on the ramp and avoid the general obstacle.

B. Results and Discussion

Table I shows the experimental results. In most cases, the A-UGV reached the goal. Failures occurred in only Ob. 5 and Ob. 6 obstacle locations - once for each. The A-UGV successfully drove up the ramp and approached the goal, although it kept spinning around the goal. These failures were self-errors of the A-UGV navigation system and can be treated as independent of the object avoidance performance.

The A-UGV therefore showed a success rate of 99.1% including the two failures. Compared with manual drive, travel time increased by 20.6 % and travel distance increased by 1.9 % on average. Ob. 8 and Ob. 4 showed the greatest increase in travel time, and Ob. 1 showed the least increase. Ob. 2 showed the largest increase in travel distance and Ob. 4 showed the least increase in travel distance.

Travel time was determined to be more critical than travel distance. There is no major difference in travel distance and the A-UGV drove in the allowed area for all cases.

Ob. 4 and Ob. 8 showed 40 % more travel time than the other obstacle locations. This was caused by the A-UGV's detection of the ramp and obstacle (see Fig. 11).

The ramp was detected as an obstacle crossing most of the available travel space. This was considered a general obstacle in the middle of the ramp but only occluded part of the ramp, allowing a path to be planned around the general obstacle and behind it in an S pattern, resulting in inefficient performance. It is possible to extend this issue of obstacles blocking other obstacles. For example, there can be a case that tricks the vehicle where it plans a path to a closed area.

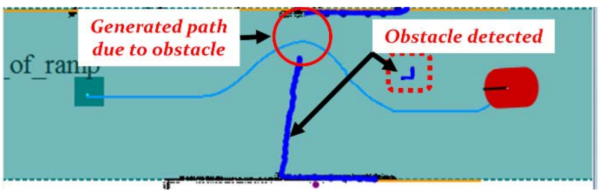

Fig. 11. Inefficient path generated due to obstacle (right) and ramp (left).

TABLE I. CASE STUDY EXPERIMENTAL RESULT

	Manual Drive (1 time)		**Autonomous Drive (30 times), mean [std]**	
	Time(s)	*Distance(mm)*	*Time(s)*	*Distance(mm)*
Free	16.3	6488	17.8 [0.8]	6491 [63]
Ob.1	18.2	6655	19.5 [1.1]	6734 [89]
Ob.2	16.4	6464	20.9 [1.5]	6802 [83]
Ob.3	16.9	6664	18.7 [0.5]	6697 [68]
Ob.4	17.5	6924	23.9 [2.1]	6872 [103]
Ob.5	16.8	6616	19.1 [0.9]	6757 [74]
Ob.6	16.8	6621	18.8 [0.7]	6722 [85]
Ob.7	16.6	6537	19.1 [1.6]	6658 [103]
Ob.8	17.1	6752	24.4 [5.3]	6999 [213]

The test case can be summarized as: 1) the vehicle was able to drive on the ramp with 99% success rate, 2) travel time was strongly influenced by the position of the obstacle while the travel distance does not change significantly, and 3) the travel time greatly increased when the obstacle was close to the ramp entrance.

A-UGV performance was measured through a series of experiments, and important issues were found for various situations. The A-UGV reacted differently depending on the circumstances (e.g., obstacle placement) and was verified that it can be measured quantifiably. The test was deemed successful for measuring the A-UGV performance using the testbed and test methods outlined.

The testbed can be expanded to a wider variety of situations. The configuration settings applied in this experiment were suitable for climbing the ramp, but there were several side effects. For example, it was difficult to find small and overhanging obstacles to place on the ramp because the lower and vertical sensors were not used.

V. CONCLUSION

This study analyzed an A-UGV's performance for typical facility applications particularly focusing on driving and obstacle avoidance. This study also considered the facility environment information for manufacturing system design and construction. Issues and requirements are defined to describe specifications of the A-UGV and facility environment. An A-UGV's performance was measured using a ramp with an obstacle in several locations on the ramp. Optimized configuration parameters were used while the test was performed. Results showed that for most trials the A-UGV drove well to the goal, although issues were uncovered when an obstacle was aligned with the ramp-detect location.

Standards for the A-UGV and its corresponding facility environment are under development by ASTM. For the negative obstacle and lighting issues discussed in this paper, specific hardware and software research activities are ongoing with help from the industrial and research communities. Future research should include a more detailed perspective of the facility environment. The A-UGV performance test methods should be standardized with the inclusion of irregular negative obstacles and dynamic negative obstacles (e.g., removable floor covers). Safety is an important issue and although there are many cases where safety and vehicle performance are conflicting, safety should be the primary consideration.

References

[1] ASTM F45, Committee F45 on Driverless Automatic Guided Industrial Vehicles, https://www.astm.org/COMMITTEE/F45.htm

[2] ASTM, ASTM F3200 Standard Terminology for Driverless Automatic Guided Industrial Vehicles, April 1, 2018, DOI: 10.1520/F3200-18A

[3] Hamner B, Koterba S, Shi J, Simmons R, Singh S (2010) An autonomous mobile manipulator for assembly tasks. *Auton Robot* 28(1):131-149. http://dx.doi.org/10.1007/s10514-009-9142-y

[4] Shunan Ren, ying Xie, Xiangdong Yang, Jing Xu, Guolei Wang, Ken Chen, A Method for Optimizing the Base Position of Mobile Painting Manipulator, IEEE Transaction on automation science and engineering, Vol 14, No1, Jan 2017

[5] Pin FG, Culioli JC (1992) Optimal Positioning of Combined Mobile Platform-Manipulator Systems for Material Handling Tasks. *J Intell Robot Syst* 6(2-3):165-182. http://dx.doi.org/10.1007/BF00248014

[6] Najjaran H, Goldenberg A (2007) Real-time motion planning of an autonomous mobile manipulator using a fuzzy adaptive Kalman filter. *Robot Auton Syst* 55(2):96-106. http://dx.doi.org/10.1002/j.robot.2006.07.002

[7] Bostelman, R., Hong, T., & Marvel, J. (2016). Survey of research for performance measurement of mobile manipulators. Journal of Research of the National Institute of Standards and Technology, 121, 342-366

[8] Tang CP, Miller PT, Krovi VN, Ryu JC, Agrawal SK (2011) Differential-Flatness-Based Planning and Control of a Wheeled Mobile Manipulator - Theory and Experiment. *IEEE/ASME Transactions on Mechatronics* 16(4):768-773.

[9] Wong SC, Middleton L, MacDonald BA, Auckland N (2002) Performance metrics for robot coverage tasks. In *Proceedings of Australasian Conference on Robotics and Automation*, vol 27, pp 29.

[10] Papadopoulos EG, Rey DA (1996) A new measure of tipover stability margin for mobile manipulators. In *Proceedings of the 1996 IEEE International Conference on*, vol 4, pp 31S11-3116. http://dx.doi.org/10.1109/ROBOT.1996.509185

[11] Papadopoulos E, Rey DA (2000) The force-angle measure of tipover stability margin for mobile manipulators. *Veh Syst Dyn* 33(1):29-48. http://dx.doi.org/10.1076/0042-3114(200001)33:1;1-5;Ft029

[12] Sprunk C, Röwekämper J, Parent G, Spinello L, Tipaldi GD, Burgard W, Jalobeanu M (2014) An Experimental Protocol for Benchmarking Robotic Indoor Navigation. In *Proceedings of the International Symposium on Experimental Robotics (ISER)*.

[13] Thibodeau BJ, Deegan P, Grupen R (2006) Static analysis of contact forces with a mobile manipulator. In *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*, pp 4007-4012. http://dx.doi.org/10.1109/ROBOT.2006.1642317

[14] ASTM, ASTM F3218 Standard Practice for Recording Environmental Effects for utilization with A-UGV Test Methods, July 1, 2017

[15] International Organization for Standardization (ISO), ISO 8373 Robots and robotic devices – Vocabulary, March 1, 2012

[16] ITSDF B56.5 Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles, www.itsdf.org, accessed February 2, 2019.