Mobile Robot and Mobile Manipulator Research Towards ASTM Standards Development

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Abstract

Performance standards for industrial mobile robots and mobile manipulators (robot arms onboard mobile robots) have only recently begun development. Low cost and standardized measurement techniques are needed to characterize system performance, compare different systems, and to determine if recalibration is required. This paper discusses work at the National Institute of Standards and Technology (NIST) and within the ASTM Committee F45 on Driverless Automatic Guided Industrial Vehicles. This includes standards for both terminology, F45.91, and for navigation performance test methods, F45.02. The paper defines terms that are being considered. Additionally, the paper describes navigation test methods that are near ballot and docking test methods being designed for consideration within F45.02. This includes the use of low cost artifacts that can provide alternatives to using relatively expensive measurement systems.

Keywords: mobile manipulator, reproducible performance, smart manufacturing, ground truth, test methods, artifact

1 INTRODUCTION

United States [1] and European [2] safety standards for industrial vehicles have evolved to protect people working near automatic guided vehicles (AGVs). However, performance standards for AGVs[2] and mobile robots have only recently begun development. Similarly, safety and performance of these industrial vehicles with onboard equipment, such as robot arms, are beginning to evolve.

The National Institute of Standards and Technology (NIST), Robotic Systems for Smart Manufacturing (RSSM) Program [3] is currently researching both AGV and mobile manipulator performance. The Program develops and deploys advances in measurement science that enhance U. S. innovation and industrial competitiveness by improving robotic system performance and other aspects to achieve dynamic production for assembly-centric manufacturing. NIST has recently been measuring performance of AGV navigation towards development of test methods that can allow vehicle manufacturers and users to match their systems to tasks such as for safe, material handling. Additionally, advanced mobile manipulators are being sold as useful tools for unloading trucks [4] and for delivering, placing, and manipulating semiconductor waferpods within wafer fabrication facilities [5]. In these two cases, both AGVs and mobile robots support onboard manipulators to provide smart navigation and docking capabilities.

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In 2014, ASTM Committee F45 for Driverless Automatic Guided Industrial Vehicles [6] was established to develop standardized nomenclature and definitions of terms in this area. ASTM F45 is developing a terminology working document [7]. Some terminology will be briefly discussed in this paper.

ASTM F45 also recommends practices, guides, test methods, specifications, and performance standards for driverless automatic guided industrial vehicles. The Committee encourages research in this area to facilitate the development of such standards. In support of ASTM F45, NIST is currently developing test methods for navigation and docking. Navigation test methods for “defined” areas, such as within barriers or along pedestrian paths, are being developed by the Task Group within ASTM F45.02 Docking and Navigation. These methods are described in a working document [8] and they are being reduced to practice at NIST. Additionally, performance test methods for vehicle docking and vehicle-with-onboard-equipment (e.g., mobile manipulator) docking are being developed at NIST and proposed to F45.02. The experiments and results that support the test methods are described in section 4. Conclusions end the paper and provide next steps for ASTM F45 standards development.

2 ASTM F45.91 TERMINOLOGY

The term ‘AGV’ has been used throughout industry and research since the 1950’s [9]. ‘Mobile robot’ has been used throughout the research community for perhaps the same length of time and the term ‘unmanned ground vehicle (UGV)’ has been used in the military and industrial security organizations. A single term is ideal to limit confusion by vehicle users and so that various performance test methods developed can be considered for any vehicle type, potentially independent of autonomy level and vehicle capability.

The ASTM F45.91 Terminology [7] task group is developing a working document to address this disparity of terms. As stated in the F45.91 scope: “For the terminology to be harmonious with the practices in the field, definitions have been drawn from the literature or other public sources when possible. When no definition is available, or definitions are in dispute, a consensus-based approach will be employed to resolve definitions”. For example, the task group decided on a core term, ‘UGV’, that provides levels of autonomy instead of several different terms being used to define the variety of industrial vehicles. The proposed UGV term, associated sub-terms, and definitions are as follows:

- Unmanned Ground Vehicle (UGV), noun -vehicle that operates while in contact with the ground without a human operator (see: Automatic – UGV, Automated – UGV, Autonomous – UGV)
    - automatic - UGV, noun -vehicle capable of following a pre-programmed path and that does not deviate from the path without human intervention; see A-Unmanned Ground Vehicle.
    - automated - UGV, noun -automatic vehicle with limited ability to deviate from the pre-programmed path; see A-Unmanned Ground Vehicle.
    - autonomous - UGV, noun -self-guided vehicle that is able to travel without a pre-programmed path and operates independently to navigate around fixed and moving obstructions; see A-Unmanned Ground Vehicle.

The concept allows for the ‘automatic guided vehicles’ term to keep the sub-term ‘automatic’ in Automatic – UGV, while mobile robots with typically increased autonomy and capabilities may be considered as Autonomous – UGVs. A vehicle with more capability and autonomy than an Automatic – UGV, yet less than an Autonomous – UGV would be considered an Automated – UGV. However, all three terms have a single, base ‘A-UGV’ term that will be used throughout ASTM F45 subcommittee test methods as they are developed. The generic test methods can therefore, focus on a single test to be performed by all types of A-UGVs where applicable.

Terms within the F45.91 working document are based on three sources: American National Standards Institute/Industrial Truck Standards Development Foundation (ANSI/ITSDF) B56.5 [1], International Standards Organization (ISO) 8373 [10], and the Material Handling Industry of America [11] list of terms. The term ‘robot’ was removed from the original draft working document during pre-ballot comment resolution to limit confusion, since ‘manipulator’ was expected to be used more frequently, and to minimize confusion of an onboard A-UGV robot arm.

3 ASTM F45.02 DOCKING AND NAVIGATION

As briefed in the Introduction section 1, NIST is developing navigation and docking performance test methods as part of the RSSM Program and in support of ASTM F45. Specifically, navigation test methods for defined areas and both vehicle docking and vehicle-with-onboard-equipment (e.g., mobile manipulator) docking are being developed at NIST. The standard does not address safety concerns. These are covered in B56.5 [1]. The following sub-sections detail the navigation and docking test methods.

3.1 Navigation

As stated in the ASTM F45.02 Navigation: Defined Areas working document, statistically significant test results are to demonstrate that the A-UGVs traverse paths that are typical in manufacturing facilities and warehouses having defined and undefined areas that are structured and unstructured. A single performance test method is expected to evaluate whether or not an A-UGV deviates from its intended path. Additionally, the same test method will also allow vehicles to use local environment features as input for navigation as needed.

The scope in the current F45.02 Navigation working document includes the proposed test method to evaluate an A-UGV "capability of traversing through a defined space (e.g., navigation areas with limited A-UGV clearance)". It is expected that A-UGV manufacturers, installers, and users will use F45.02 to evaluate industrial vehicles that navigate between structures defining the vehicle path with typical constraints such as walls, equipment, and pedestrian paths and other user application requirements.

The F45.02 navigation performance test method consists of traversing scalable areas defined by physical barriers, virtual barriers, and/or floor markings. The defined navigation test is a straight corridor followed by a 90 degree turn into a second corridor. The corridors are constructed with a width sufficient for the A-UGV to traverse them. The path width is incrementally reduced during A-UGV evaluation. The corridor is reduced and the A-UGV is tested, "until the most constrained testing pathway is accomplished for the specified number of repetitions". The A-UGV configuration of software, hardware, and other characteristics are to remain the same during the entire test. During the test, the A-UGV traverses the path from the start point to the end point, and then returns back to the start point. For the return trip, the A-UGV can either drive backwards, or turn around. The full start-to-goal-to-start traversal of the test course is considered one full repetition.

Figure 1 shows three test method configurations proposed in F45.02 and evaluated at NIST. The three configurations include physical barriers, virtual barriers (e.g., laser beams), and floor markings. Physical barriers, shown in Figure 1a, are temporary walls used for the experiments were made of painted, 1.2 m square oriented strand board mounted to 0.6 m bases. The barriers were aligned to form a corridor approximately with a length of four vehicle lengths, 8 m, and a variable width. The initial width is chosen to provide a certain buffer from the A-UGV sides defined by the safety sensor side distance plus a chosen uncertainty (standard deviation) distance (e.g., 10 cm). After each test, if no wall detection occurs during traversal, the walls are moved towards the A-UGV sides by a chosen amount, e.g., 2 cm. When the wall is detected during a test, the detection is logged in a report and the test is repeated. A statistically significant number of trials (a minimum of 30) are done by the A-UGV provider dependent upon the confidence and probability of success threshold (PST) desired (e.g., 0.95 confidence with 0.95 PST = 118 trials). Additional details of the barrier test setup are provided in [12].

Figure 1b shows the virtual barrier test setup which makes use of a laser breakbeam aligned along the vehicle path. The test setup and procedure are similar to the physical barrier setup where the laser line is initially set and moved using a procedure similar to that of the physical barriers. However, to break the laser beam, as opposed to detecting a physical barrier, a bar measuring the desired width is clamped perpendicular to the vehicle. The bar protrudes from the vehicle at the laser breakbeam height. The distance the bar projects is determined by the lane width plus the chosen uncertainty (e.g., 2 cm). Similar trial repetitions are then completed as with the physical barriers.

Figure 1c shows the floor marking test setup that includes a bar similar to that used in the virtual barrier test setup. This supports a laser pointer or marking pen pointed at or touching the floor, respectively. The test setup and procedure are similar to the virtual barrier setup where the laser line is initially set and moved using a similar procedure to that of the physical barriers. A line is attached to the floor (e.g., pedestrian marker, painted or taped line) at the location of a virtual barrier laser breakbeam. Additionally, the laser pointer/marker is incrementally moved closer to the A-UGV along the bar for each successful trial. Again, similar trial repetitions are then completed as with the physical and virtual barrier test setups.

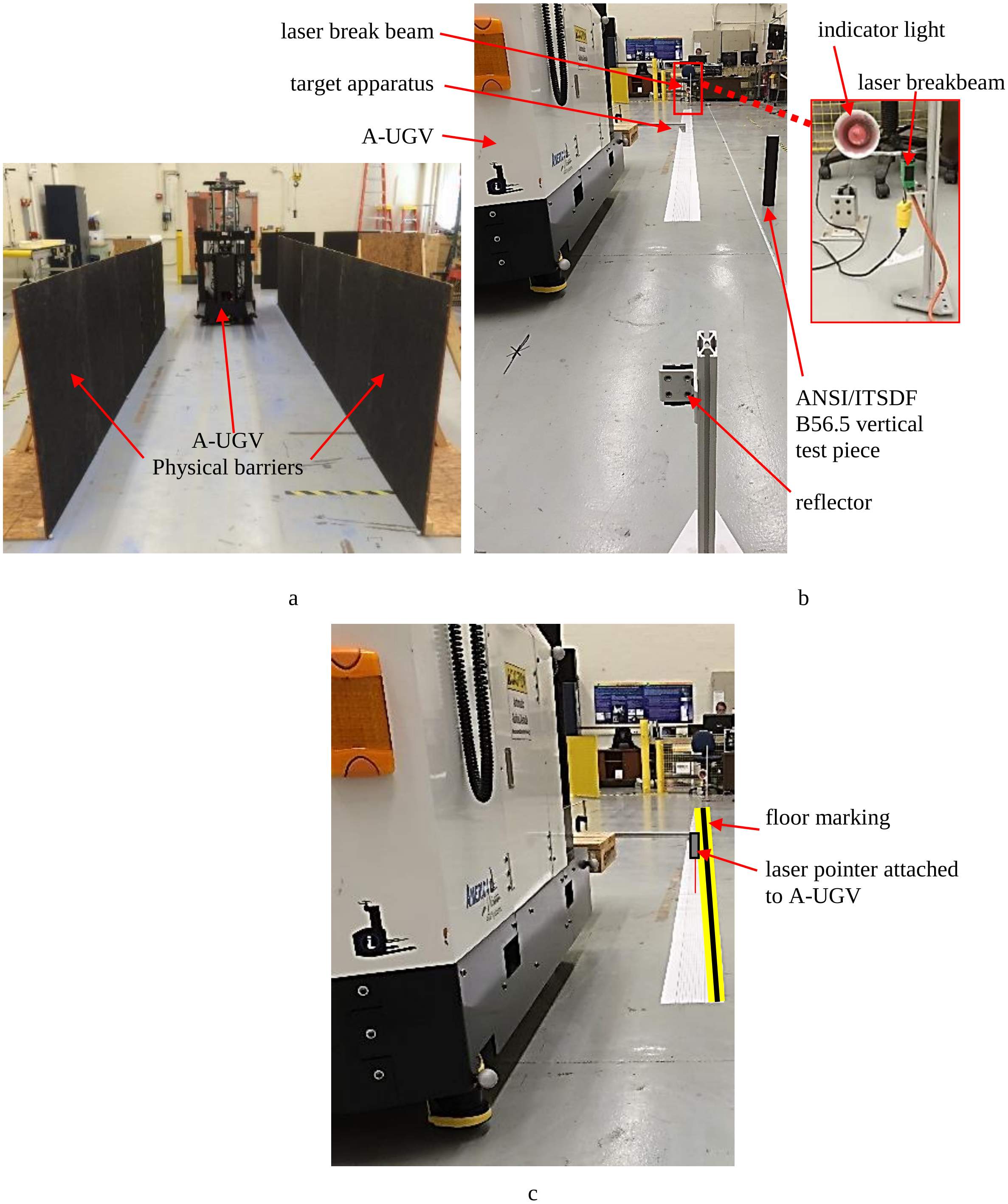


Figure 1. Example A-UGV navigating within a) physical barriers, b) virtual barriers (e.g., laser beams), and c) floor markings.

3.2 Docking

3.2.1 Vehicle Docking

A-UGVs "dock" with different devices in their work area. Vehicles with forks typically dock with pallets. Unit load vehicles dock with tray stations. Tugger style vehicles dock with hitches. These vehicles have different but related positioning requirements for docking. Fork-style vehicles must align their forks perpendicular to the openings of a pallet. Unit load vehicles must align properly with a tray station in order to allow a tray to roll between the onboard-vehicle roller table and a facility roller table. The vehicle roller table has right and left edges that align with the corresponding edges of the facility tray station. Docking for these two types of vehicles can be generalized into the act of aligning two points on the vehicle with two points on the device. Similarly, tugger vehicle docking can be generalized as aligning one point on the vehicle with one point on the device (representing the hitch).

A-UGV users might assume that their vehicles remain calibrated from vehicle installation, although these vehicles can become uncalibrated. An experiment using a two year old, uncalibrated A-UGV that was programmed to stop at various points yielded an uncertainty range of approximately 1 mm to 50 mm [12] as measured by a laser tracker. Docking was measured again after the A-UGV was calibrated using the manufacturer's procedures. During tests, the A-UGV approached similar dock locations and after A-UGV calibration, provided consistent 5 mm uncertainty (standard deviation) from several dock points in the lab.

NIST and the F45.02 subcommittee have begun investigating A-UGV docking performance test methods. The generic concepts of vehicle docking, aligning one or two points, was tested at NIST [12] and proposed to the ASTM F45.02 subcommittee. Figure 2(a) illustrates the candidate tests. Three vehicles are shown, represented as rectangles. Vehicles 1 and 2 each have two points, i and j, that must align with the two points on the device, I and J. Vehicle 3 has only one point that must be aligned with one point on the device, either I or J.

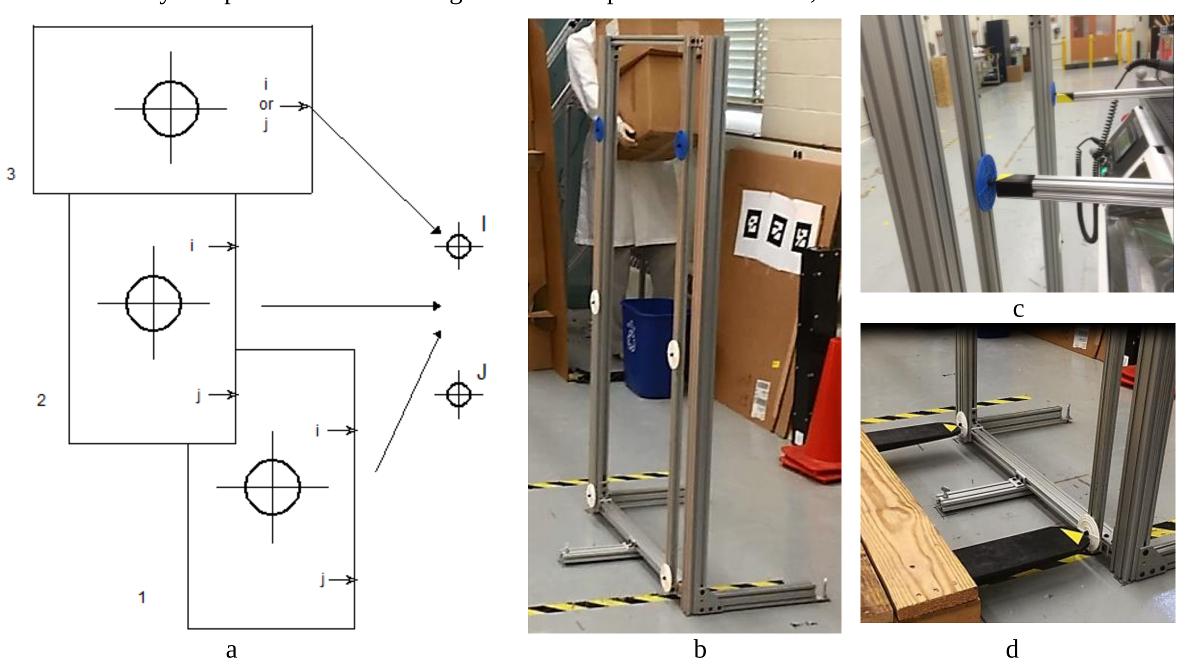


Figure 2. Docking Test Method. (a) Conceptual docking test method for use with various A-UGVs. The three rectangles represent three different vehicles, each with one or two points, i and j, that must be aligned with one or two target points on the device, I and J. (b) Docking apparatus with multiple alignment target points, lower and middle white targets and upper blue targets. (c) Unit-load A-UGV docked with the Docking apparatus. Two bars

represent roller table edges that should align with the two blue targets. (d) Fork-type A-UGV docked with the Docking apparatus. The forks should align with the two white targets.

Figure 2(b) shows the NIST Docking apparatus. It has leveling feet and targets moveable in both lateral and vertical directions used to test one- and two-point docking with the targets. Targets have a center point with 3 mm spaced concentric rings to visually detect relative alignment uncertainty. The targets can be sized for other specific desired relative alignment uncertainty.

3.2.2 Vehicle with Onboard Equipment Docking

Vehicles with onboard equipment, such as robot arms (manipulators), are typically called mobile manipulators. NIST has also been developing performance test methods for mobile manipulators that will be affordable by manufacturers and users. These test methods are also useful to ASTM F45.02 as docking test method reference experiments of vehicles with onboard equipment. The method is feasible for measuring performance of mobile manipulators. The mobile manipulator positions a relatively inexpensive laser retroreflective laser to detect smaller and smaller reflective targets accurately positioned on an artifact.

NIST developed a test apparatus for measuring mobile manipulator performance [13]. The apparatus, shown in Figure 3, is called the Reconfigurable Mobile Manipulator Apparatus-1 (RMMA-1). It has a circle pattern of six fiducials and square pattern of four fiducials. The potential for artifacts to be made using three dimensional (3D) printing could lower the cost by perhaps 200 times, as demonstrated through machining costs of the RMMA-1 and the 3D printing of parts used with the artifact.

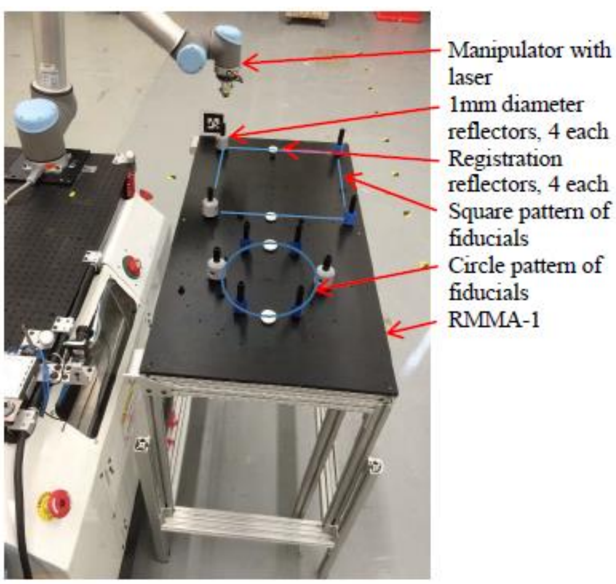


Figure 3. RMMA-1 showing circle and square patterns of fiducials for the mobile manipulator to index between.

The test A-UGV can access the artifact from any pose (position and orientation). In [13], a calibrated vehicle carried the onboard manipulator to a point with 5 mm position uncertainty. The manipulator was able to register (determine its position with respect to the artifact) using a circular-spiral search and repeatedly locate 6 mm diameter targets when the manipulator was positioned by the AGV at a static location and next to the square pattern on the RMMA-1.

Recent research [14] demonstrated registration of the mobile manipulator to 1 mm diameter fiducials from any vehicle orientation with respect to the RMMA-1. The registration method incorporated a 0.5 mm step, square-spiral search pattern, and higher resolution A-UGV pose information (0.01 mm position and 0.01° orientation). The research also demonstrated "indexing" between RMMA-1 circle and square patterns as opposed to static positioning of the manipulator at a single pattern. Indexing allows the mobile manipulator to be repositioned to reach each pattern.

A computer aided design model of paths and docking points was used by a vehicle control program to move the A-UGV from one docking point to another. This programming method is inherent in the A-UGV type used. The manipulator control program moves the robot arm from the stowed location to each fiducial and searches for the exact position using a laser retro-reflector detector. The vehicle control program positioned the vehicle at various orientations with respect to the RMMA-1 and the manipulator program corrected for vehicle position and rotation allowing it to quickly find, pre-taught, target registration.

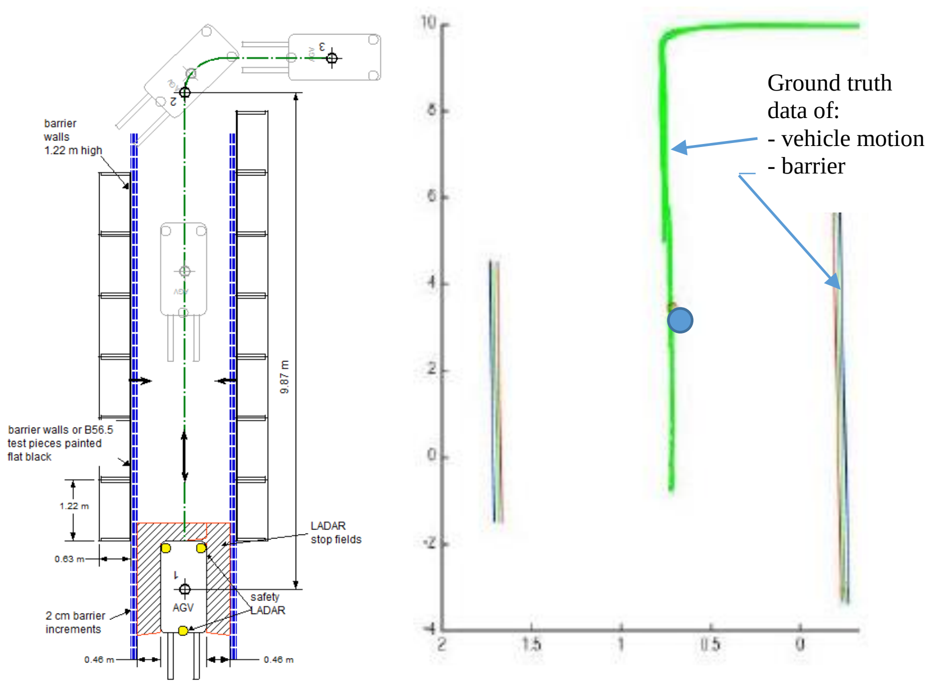
Current research at NIST included a bisecting or "crisscross" search of two large-diameter registration reflectors within each circle and square pattern. Each pattern had a 35 mm and a 30 mm diameter reflector mounted across the pattern edges. The reflectors were detected eight of ten times by the laser retroreflector when perpendicular and pointed at them. The bisecting search concept was to allow the manipulator to rapidly move from the pair of large-uncertainty reflector registration locations to the 1 mm fiducials representing assembly access points. A more refined registration-reflector sizing is a topic for future research. The propagation of manipulator position error will be theoretically examined to optimize the registration speed of mobile manipulators by selection of optimal reflector and search step sizes. As such, using the above explained, relatively inexpensive procedures and apparatus demonstrates a feasible performance measurement test method for mobile manipulators.

4 EXPERIMENTS AND RESULTS

This paper has described new low cost test methods for measuring the performance of A-UGVs. During development, an optical tracking measurement system [14, 15] was used as ground truth. The optical tracker could simultaneously measure the position of all system components. The ground truth system has positional accuracy of 0.02 mm (static) and 0.2 mm (dynamic). The tracking system measured the locations of the vehicle, manipulator, and artifact within the same reference frame. However, more cost-effective means are needed to enable performance tests to be used by A-UGV manufacturers and users. Therefore, the optical tracking system provides verification of the test methods being developed. This section discusses the results of navigation and docking experimental data analysis performed at NIST where several of the tests were initially compared to optical tracking system ground truth for validity while others used only artifacts. The thrust for ASTM F45 performance test methods is the use of replicable and cost effective artifacts.

4.1 Navigation Experiment and Results

The ASTM F45.02 working document navigation test method was constructed using the barriers as shown in Figure 1a. The barrier experimental setup is shown in Figure 4(a) where the A-UGV begins at the lower start point, traverses between the barriers to the top, makes a right turn, stops, and then backs up to the start point. Performance measurement results as compared to the optical tracking ground truth system are shown in Figure 4(b) and show that the A-UGV drove off of the path ± 18 mm.



a b

Figure 4. a) CAD drawing of navigation test method using barriers. The dotted lines are barrier positions for several tests that reduced the A-UGV corridor width. b) Ground truth measurement data of a navigation test showing (blue circle) the vehicle stop location when barrier detection occurred in the reverse direction. The thicker A-UGV path navigation lines are from different forward and reverse paths.

The measurements demonstrate a need for users and manufacturers of these systems to understand their A-UGV capability and that test methods should be developed that are inexpensive and easily replicated for their use. Figure 4(b) shows results from running the ASTM F45.02 draft test method compared to ground truth.

4.2 Docking Experiments and Results

The navigation sensor [16] for the vehicle used in this research has a manufacturer's stated "best-in-class angle accuracy of 1 mrad (0.057°)". When this specification is applied to the A-UGV navigation sensor distance to the closest reflector, a maximum A-UGV docking uncertainty of 0.5 mm would be expected. However, many factors, such as the location of the navigation sensor relative to the vehicle reference point, wheel wear, and the servo control algorithms, impact the vehicle performance. No manufacturer's vehicle specified performance was provided with the experimental vehicle as is fairly common on industrial vehicles. The following docking experiments were performed and associated results provided.

4.2.1 Vehicle Docking Experiments and Results

Experiments using a fork-style A-UGV and the Docking apparatus shown in Figure 2(b) were performed to measure vehicle docking repeatability. A triangular piece of yellow tape was placed on each fork tip as shown in Figure 2(d). Prior to the experiment the apparatus location was set by moving it to the dock location, since the experiment measured repeatability. The vehicle was programmed with the path as shown in Figure 5 to move forward from home to point 1, stop, and move in reverse with the fork tines pointing at the apparatus. The tines were automatically raised or lowered at stop point 2 to match the chosen apparatus target heights. The vehicle moved to dock with the apparatus at one fork tine height and the next trial moved the tines to the other height. The target heights were set for both upper and lower fork tine positions. Note, to measure vehicle docking accuracy, as opposed to repeatability, the apparatus would have to be placed at a new location whose position is determined independently of the A-UGV and the A-UGV would then be commanded to dock at that position.

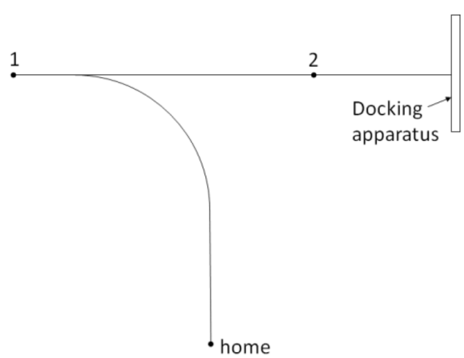


Figure 5. Vehicle path for docking with the apparatus.

The tests were iterated several times with the vehicle moving from a home position to the docking position. The targets measured 76 mm in diameter, which is similar to the height of a pallet opening. Pallet opening widths are much greater than their heights due to their overall pallet widths. Opening widths are typically ½ pallet widths minus their support structure widths (e.g., (1.2 m wide – 0.1 m structure)/2 = 550 mm wide openings). The test results for all iterations showed that the fork tips, marked with the tape points, repeatedly aligned within the approximate 10 mm target centers for both lower- and upper-height white targets, matching experimental results previously determined using the ground truth tracking system. The experimental results demonstrated that the test method provided reproducible docking repeatability results through use of a relatively simple Docking apparatus.

4.2.2 Mobile Manipulator Docking Experiments and Results

The mobile manipulator shown in Figure 3 was used for onboard equipment docking experiments building on previous research [12, 13]. Three recent indexing experiments were performed, as described in section 3.2.2 Vehicle with Onboard Equipment Docking. The three experiments measured 1) detection of 1 mm fiducials used for registration to the artifact, 2) re-registration using detection of two 1 mm fiducials after bisection (crisscross) registration of large reflectors, and 3) repeatability after registration. The main metrics for these tests were success rate and the number of 0.5 mm steps required to detect the first and second points after registration. These metrics are similar to what manufacturers and users may consider when matching a mobile manipulator to assembly tasks. Experiment one docking results after 10 trials using two 1 mm registration fiducials were that the success rate averaged 91 %, although an average of 794 steps in the square-spiral search were required to detect the first assembly point after registration followed by 12 steps to detect the second point.

The re-registration concept, shown in Figure 6, includes a high level reference frame drawing of the system components and crisscross search. The initial bisection search location was measured with the vehicle parked at one of the test locations near both the circle and the square RMMA-1 patterns. The manipulator joystick was then used to jog the manipulator to detect a 1 mm fiducial at the center point where a large reflector was to be placed. The manipulator tool point location was recorded and the search was repeated for all four (two circle and two square) registration point locations. The large reflectors were replaced at the recorded locations and the vehicle was programmed to move to 10 different poses near the RMMA-1 as the manipulator performed the bisection registration. The bisection search used 3 mm steps to rapidly register the large reflector's center. Large step size on registration reflectors is perhaps one of the greatest uncertainties for this type of registration method, although lower tolerance steps provides much slower registration where a time/tolerance registration balance is a topic for future research.

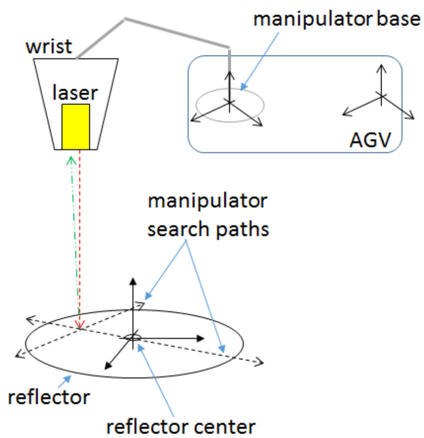


Figure 6. High level reference frame drawing showing the system components and bisection search concept.

The second experiment used the mobile manipulator to do crisscross registration to the RMMA-1 and then to re-register to two 1 mm fiducials. Afterwards, the manipulator was moved to detect the 1 mm fiducials and two more 3 mm fiducials on the square corners and four more on the circle. The experimental goal was to determine if the speed and success rate to detect the second registration were improved from experiment one. The experiment two test results were that success rate was averaged over 10 trials at 92 %. However the number of steps to detect the first and second 1 mm fiducials dropped to an average of approximately 11 steps and 4 steps, respectively. Two of the 10 trials included issues with detecting the large reflectors and were aborted and not included in the results. Future tests with the use of larger reflectors and a smaller, for example 0.5 mm, step search will replace the current large reflectors and 3 mm step search to help remedy this situation. Additionally, improved vehicle pose and manipulator base references will be researched.

The third experiment included the crisscross registration method followed by pattern registration to 1 mm fiducials and then performance measurement of repeatability. The square and the circle were repeated 32 times after registration where registration steps were not included in repeatability tallies. During repeated pattern detection, the success percentage averaged 98 %, detecting two 1 mm and two 3 mm fiducials on the square and two 1 mm fiducials and four 3 mm fiducials on the circle for a total of 1600 points. In all three experiments, the use of artifacts provided reproducible performance measurement methods verifying registration.

5 CONCLUSIONS

ASTM Committee F45 for Driverless Automatic Guided Industrial Vehicles is developing new terms and definitions for the community. The proposed term "A-UGV" provides a single term to span AGV and mobile robot systems. Also, ASTM F45 task groups and the NIST RSSM Program are developing performance test methods for navigation and docking. The navigation test method that is currently near ballot within F45.02 is used to measure an A-UGV's path following accuracy. The navigation test method demonstrates a simple, reproducible, cost effective solution to measure performance of a vehicle traversing, both forward and reverse, a straight path that includes a single turn. Experiments at NIST demonstrated that three different methods defining the path are feasible and useful for measuring navigation performance for A-UGVs.

Similarly, test methods for docking of A-UGVs, both without and with onboard equipment, such as robot arms, will help evaluate vehicle docking capabilities. Performance testing using a vehicle location, laser, and artifacts, such as the Docking artifact and RMMA-1, has proven to be useful and cost effective. Test method experiments at NIST for docking vehicles to an apparatus show repeatable results. Three experiments were performed on the mobile manipulator docking with an apparatus. The results showed that the test method being developed to dock a mobile manipulator with an apparatus provided various registration methods and uncertainties that can be measured using relatively simple and inexpensive components and concepts.

Future tests will be performed increasing the size of the initial reflectors that replace the current large reflectors, as well as improving the vehicle pose and manipulator base references. Also, a new performance artifact called RMMA-2 will be implemented for measuring mobile manipulator performance in dynamic vehicle and manipulator situations (i.e., the base and the arm are simultaneously moving).

6 ACKNOWLEDGEMENTS

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