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Roger Bostelman, Tsai Hong, Gerry Cheok

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Navigation Performance Evaluation for Automatic Guided Vehicles

Roger Bostelman
Intelligent Systems Division
National Institute of Standards and Technology
Gaithersburg, Maryland, USA
roger.bostelman@nist.gov
IEM, Le2i, Université de Bourgogne,
BP 47870, 21078 Dijon, France

Tsai Hong and Gerry Cheok
Intelligent Systems Division
National Institute of Standards and Technology
Gaithersburg, Maryland, USA
tsai.hong; cheok@nist.gov

Abstract—Automatic guided vehicles (AGVs), an industrial form of a mobile robot, typically navigate using a central computer commanding AGV movement on predefined paths. How well they follow these paths is not well-defined in research articles and their performance is reported in non-standard manufacturer specifications. Furthermore, AGV technology is advancing towards vision guidance to map and localize their position from onboard the vehicle, whereas performance evaluation of advanced navigation techniques is just beginning. This paper describes AGV experiments using ground truth measurement comparison for performance evaluation of AGV navigation. A generic test procedure and metrics, described herein, are recommended to ASTM F45, a recently formed committee on performance of AGVs, as a navigation test method for use by the AGV and mobile robot industries.

Keywords—automatic guided vehicle; mobile robot; performance measurement; ground truth; ASTM F45; test method

I. INTRODUCTION

Mobile robot navigation includes sensing the world, computing the next motion, and actuating the robot. A vast amount of research has occurred in this area and a brief summary of navigation methods are listed in [1]. Those methods include potential field methods that addressed the first sensor-based motions [2, 3], vector field histograms as the first alternative to doing obstacle avoidance with high-uncertainty sensors like ultrasounds [4], elastic bands as the first technique combining planning and reaction schemas in a unified framework [5], the dynamic window as the first technique to address kinematics and dynamics to carry out motion at high speeds [6], the curvature-velocity method as a similar method developed [7], and, nearness diagram navigation as the first technique to address motion in troublesome scenarios [8], among many other techniques discussed in [9]. Navigation-error reduction has been researched, uncovering a variety of successful and unsuccessful methods [10]. An example of the latter is dead reckoning, which can increase navigation position error. An example of the former is vision-based navigation combined with non-linear filtering techniques. Those techniques include Extended Kalman or Unscented Kalman Filters, which use a series of measurements observed over time; Gaussian Sum Filtering, which tracks filtering and predictive distributions encountered in dynamic, state-space

models; and, Particle Filtering, which implements a recursive Bayesian filter using Monte Carlo simulation.

Automatic guided vehicles (AGVs) typically include much less onboard sensing of the world. Instead, AGVs use, for example, position-calibrated fiducials with laser azimuth and range sensing. AGVs also use minimal computation to choose the next motion; and, they are commanded when to actuate by, typically, a central, off-board controller. As AGVs begin to navigate through unstructured environments or precisely position tools for manufacturing [11], they too may utilize some of the previously discussed mobile robot navigation techniques. Equipment manufacturers provide specifications for these techniques; for example, the AGV navigation laser sensor, which triangulates position using facility-mounted reflectors, has a range measurement resolution of 3.9 mm and angular resolution of 0.125° with statistical error distance of ± 10 mm. [12]¹ However, the mobile robot or AGV may not provide accuracy specifications for all navigation and positioning situations. Moreover, navigation-performance measurement methods for mobile robots and AGVs have been minimally defined in the literature.

To achieve navigation-performance measurement for mobile robots or AGVs, a set of metrics must first be defined. Use of quantitative metrics for AGV navigation is limited to measuring the length of the path or the time needed by the robot to complete the task. [1] Deviation from the path could also be used since the AGV may be required to navigate within a small tolerance in proximity to some infrastructure – sometimes called localization accuracy. As stated in [13], “the lack of consensus on how to define or measure these systems impedes rigor and prevents evaluation of progress in this field and compare its different capabilities.” One proposed method [14] for evaluating the localization accuracy of an indoor navigation system in arbitrarily large environments is to use onboard, mobile, robot vision and facility landmarks consisting of distinct patterns. This is instead of using externally mounted sensors, as required by most ground-truth systems. For this

¹Disclaimer: Commercial equipment and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

method, the combined mean position error was 15.2 mm and mean orientation error was 0.4° with maximum errors of 52.9 mm and 2.8° .

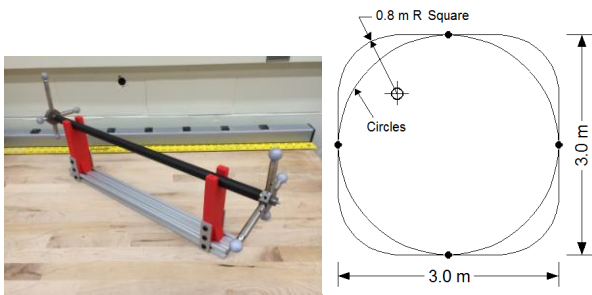
A committee has recently been formalized as ASTM F45, Driverless Automatic Guided Industrial Vehicle.[15] This committee will establish the performance criteria for AGVs and mobile robots through five subcommittees: Environmental Effects, Docking & Navigation, Object Detection & Protection, Communication & Integration, and Terminology. Committee F45 will provide information and guidance for AGV and mobile robot manufacturers and users through the development of a variety of consensus-based documents, including standard test methods. Navigation test methods will be one of the first areas for F45 consideration. Of particular concern are test methods that potentially do not require purchasing relatively expensive ground-truth measurement equipment with accuracy that is at least 10 times better than the system under test. However, development of standard test methods do require accurate ground-truth measurement systems as suggested.

This paper describes experiments utilizing a multi-camera, ground-truth measurement (motion capture) system to analyze AGV-acquired, tracking-measurement data acquired during navigation. Analysis and experimental results are then discussed and added to an navigation test method to be recommended to ASTM F45. The paper closes with a summary and conclusion with future plans.

II. EXPERIMENTS

Two types of experiments were performed: Ground-truth measurement system as compared to a metrology bar and AGV as compared to ground truth. The metrology bar (shown in Figure 1 (a)), designed at NIST with known dimensions, was used to measure the uncertainty [16] of the 9 m W x 22 m L AGV lab so that measurement uncertainty of the ground-truth system could be established. The bar was moved throughout the space where the AGV was to be used.

Fig. 1. (a) NIST metrology bar used to measure ground truth system uncertainty. (b) Commanded AGV paths.

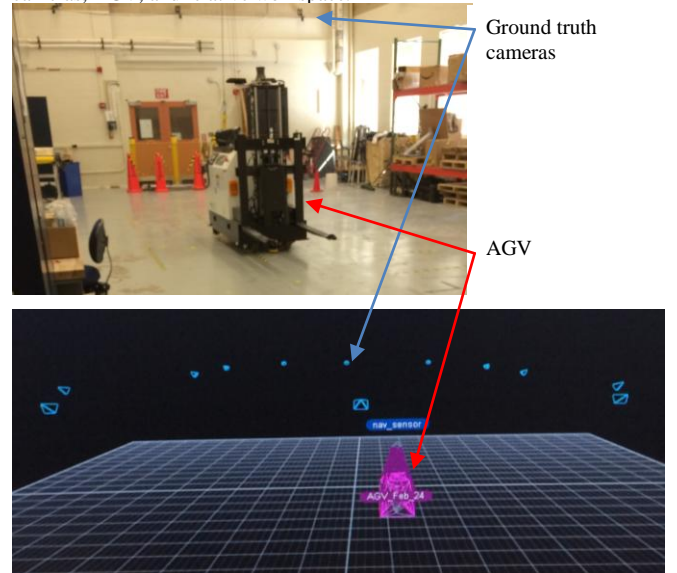


Experiments were then performed using a 1.7 m W x 2.9 m L x 3.1 m H AGV programmed to navigate simple geometric shapes, including lines (point-to-point), circles, and squares, and using an All-Wheel Steering (AWS); i.e., the vehicle body rotates when wheels are steered, although at different angular rates. AGV position information is achieved via spinning laser triangulation, time-of-flight measurement at 6 Hz to facility-mounted reflectors that have been calibrated to known

locations using a laser-tracking, position-measurement system. Computer aided design models of the AGV paths (5 m long path between two points and 3.0 m squares and circles – see Figure 1 (b)) were pre-programmed using an off-board vehicle computer and sent to the vehicle to be traversed. The AGV command software cannot draw a complete circle and instead draws quarter arcs from each of the four points as shown. The AGV command software also forced AWS traversed squares to include rounded corners with 0.8 m radii whenever the non-stop velocity was 0.25 m/s or less. The controller can also track the vehicle position during navigation at 60 Hz.

The AGV navigates using an approximately-central vehicle point (minus the forks) that follows the programmed path. The central navigation point is located at floor level, at the center of the vehicle width, and halfway between the front and rear wheels.

Fig. 2. (top) Test setup showing the AGV traversing a path and cameras mounted to walls and (bottom) virtual multi-camera system display of the cameras, AGV, and relative workspace.



The navigation center point, used as reference by all AGV navigation and docking control programs, is very difficult to access; and, therefore, it may not be correctly input into the controller as navigation reference. For our tests, the point was approximated at floor level and transferred to the vehicle top using squares, tape measures, and straight edge instruments. Ideally, a standard AGV calibration exposes this point for measurement reference in vehicle control software to minimize path-following uncertainty. We instead modeled the vehicle parameters, including the origin and the orientation of the AGV, and used a mathematical solver on collected data to solve the parameters.

A twelve-camera, ground-truth measurement system was used to track reflective spheres mounted to the AGV at a variety of locations, where one reflector was mounted above and as close to the AGV navigation center as feasible. Figure 2 shows the AGV, three cameras mounted to a wall (of 4 walls), and the virtual ground-truth system display of the cameras, AGV, and relative workspace. Eighteen reflective spheres were also mounted 1) to the fork tines (although not used); 2)

the fixed, 2 m high fork mast and surrounding the navigation sensor;3) the AGV body top and bottom sides; and, 4) the AGV top plate. The reflectors were combined in the camera system software to form a rigid model of the AGV so that the orientation could also be measured. Twelve cameras were mounted to the lab walls 4.3 m above the floor and several meters from the AGV path so that the camera fields-of-view(FOVs) maintained continuous sight of most reflectors, except those reflectors that were occluded by the AGV during navigation tests.

A laser tracker was also initially used to obtain ground truth measurements although was determined not to be useful since the laser tracker requires continuous line of sight to its target and the line of sight was interrupted during AGV rotation. Therefore, this paper only considers the multi-camera measurements.

III. ANALYSIS AND RESULTS

A. Performance Measures and Data

A set of performance measurements was developed for evaluating the navigation performance of an AGV. Before describing the performance measurements, we discuss the data obtained from the experiments and registration between the data from the Ground Truth(GT) system and the System Under Test (SUT).

Input data: The data obtained from the experiments forms the inputs to the analysis. There are two types of input files expected. All of the files are in comma-separated-variable(CSV) format. The GT and SUT data files contain a time stamp and six degrees of freedom (DoF) information which includes x, y, z, and orientation.

Sensor Registration: The GT system and SUT typically produce data in different coordinate systems. Several registration techniques were investigated and evaluated. There are two approaches to evaluate the SUT. The first approach is to determine the transformation between the SUT data to the GT coordinates. This approach is required to register the SUT data and GT data. Several algorithms were investigated which include closed-form solutions[15] [18] and the CeresSolver[19] - an open source C++ library for modeling and solving large, complicated, optimization problems. The Ceres Solver was selected to automatically register between the GT system and the SUT using timestamp and 6DoF data.

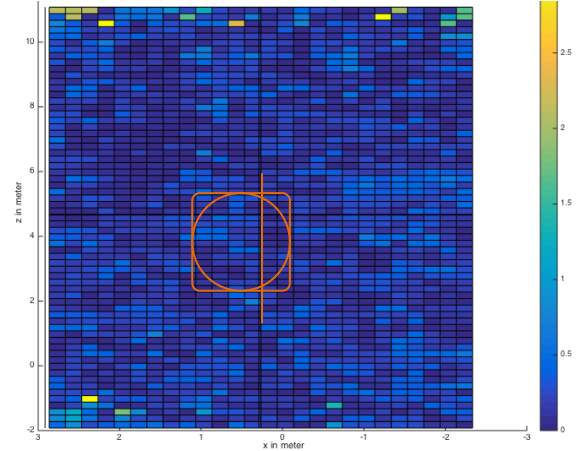
We present several types of performance evaluation metrics for an AGV programmed to navigate simple geometric shapes, including straight lines, circles and squares, and using AWS. The performance metrics that we used included mean, maximum, and standard deviation of the errors for x, y, z, distance and angle between GT and the SUT.

B. Performance Analysis

Initially, a measure of the performance of the Ground Truth (GT) system was made throughout the laboratory where the SUT or AGV was tested. This resulted in submillimeter uncertainty in the test area. Measurement standard deviation (σ) (uncertainty) of the distance is 0.26 mm and σ of the angle

is 0.10° . Figure 3 shows graphed data of the distance uncertainty throughout an approximate 5.5 m W x 13 m L area. The data graphed for angle uncertainty appeared similar and is not included due to space limitations.

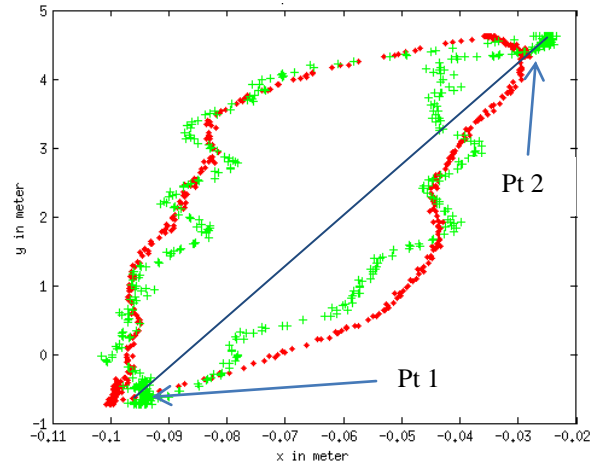
Fig. 3: Graphed data of the distance uncertainty for the AGV lab. The orange straight line, circle, and rounded square depict the approximate size and location for AGV tests.



The navigation experiments were to command an AGV to navigate each path (straight, circular, and square) 10 times where circle and square paths were traversed with AWS and all experiments were repeated three times resulting in a total of 9 data sets. All GT system and SUT data were then analyzed and the metrics described in section III A were computed.

The first AGV experiment was a “straight line path test” with the AGV navigating at 0.25 m/s maximum. The results are shown in Figure 4 where X and Y axes scales are in meters, although X is expanded to clearly show the AGV performance as compared to ground truth. Maximum GT and SUT deviation from the commanded path, represented by the blue line, was approximately ± 25 mm.

Fig. 4. Ground Truth (red) and AGV (green) data of the straight line path tests. Scales for X and Y axes are in meters where the X axis shows only -0.11 to -0.02 range to clearly show the AGV performance as compared to Ground Truth measurement. The blue line represents the commanded path from pt 1 to pt 2 and back.



The second AGV experiment was a “circle path test”. The results are shown in Figure 5 and in Tables 1 and 2 for the AWS tests. The raw data and fitted ellipses are shown in Figure 5.

Tables 1 and 2 show the uncertainty (mean and maximum errors and σ) for the AGV using the Ground Truth system. Each table entry shows the results of navigating the circle 10 times and for each of three different tests. Table 1 shows uncertainty results without adjusting and Table 2 shows the results after adjusting for the potential AGV origin and rotation offsets. Table 2 shows a clear need to adjust for these offsets. Ideally, the offsets are then reprogrammed into the AGV.

Fig. 5. Ground Truth (blue) and AGV (green) data of the 3 m diameter circle path tests for AWS steering.

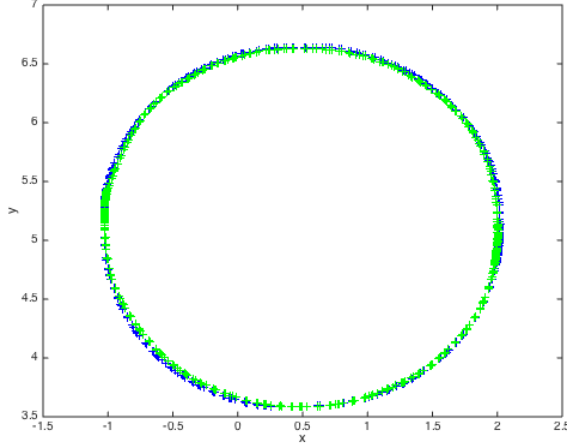


Table 1: Statistical uncertainty (in mm) of the AGV navigating circle paths without adjusting the AGV's origin or rotation.

<u>Circle A,B,C</u>	<u>X</u>	<u>Y</u>	<u>Distance</u>
Mean Error	-0.04; -0.01; -0.027	0.01; 0.015; 0.019	10.8; 11.0 10.9
σ	9.7; 9.9; 9.8	8.5; 8.6; 8.6	7.0; 7.1; 7.1
Max Error	21.3	17.3; 17.7; 17.1	31.3; 32.2; 32.9

Table 2: Statistical uncertainty (in mm) of the AGV navigating circle paths after adjusting the AGV's origin and rotation.

<u>Circle A,B,C</u>	<u>X</u>	<u>Y</u>	<u>Distance</u>
Mean Error	-0.010; -0.018; -0.008	0.02; 0.002; 0.019	5.00; 5.06; 4.98
σ	4.5; 4.5; 4.4	5.1; 4.4; 5.1	4.6; 4.5; 4.6
Max Error	23.8; 23.0; 8.9	8.9; 22.1; 22.1	23.85; 22.2; 22.2

The third AGV experiment was a "square path test". The results are shown in Table 3 for the AWS tests. The overlapped data between the GT and the SUT are shown in Figure 6.

IV. RECOMMENDED TEST METHOD

A test method, based on the measurements and analysis from our experiments, was recommended as an initial working document to ASTM F45.02 Docking and Navigation subcommittee. The test method includes: Apparatus, Calibration and Standardization, Procedure, and Reporting.

The navigation test method includes two types: Unconfined Space and Confined Space. Unconfined space is appropriate when virtual, pre-defined paths are used, i.e., the current technique used for AGVs and the experiments described in this paper.

Fig. 6. Ground Truth (blue) and AGV (green) data of the 3 m square path tests for AWS steering.

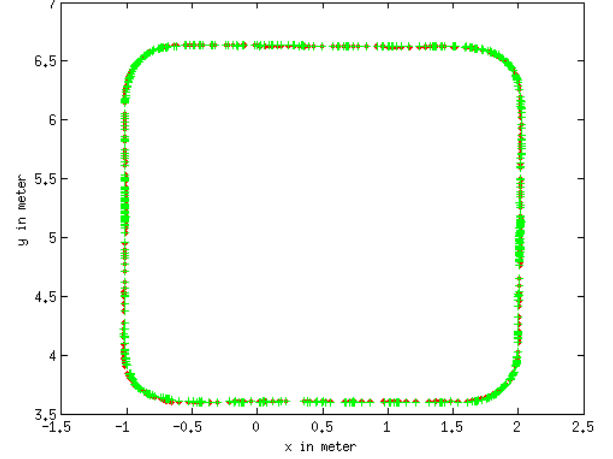


Table 3: Statistical uncertainty (in mm) of the AGV navigating square paths after adjusting the AGV's origin and rotation.

<u>Square A,B,C</u>	<u>X</u>	<u>Y</u>	<u>Distance</u>
Mean Error	-0.023; 0.002; -0.004	0.029; -0.039; 0.001	5.2; 5.0; 5.1
σ	4.5; 4.3; 4.4	4.4; 4.3; 4.4	3.6; 3.5; 3.6
Max Error	10.4; 8.8; 9.9	12.4; 12.0; 14.1	10.4; 18.3; 18.6

Confined space is suggested for mobile robots and some AGVs with simultaneous localization and mapping (SLAM) capabilities to navigate using walls or other landmarks. These test methods will be provided in future research publications.

A. Apparatus

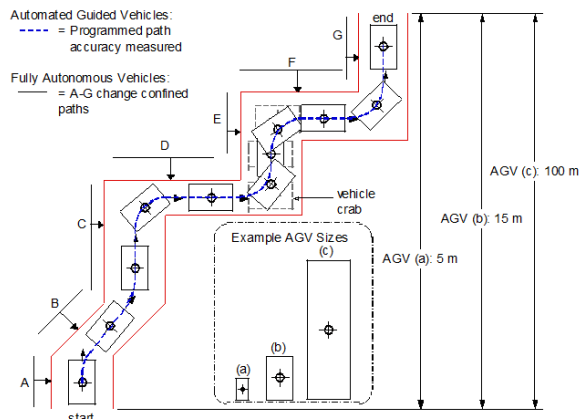
For the unconfined space apparatus, a virtual, computer-aided-design test path is defined for the AGV as a straight line, square path, or circular path. If needed, dependent upon the path sensing capability for the AGV, the test paths are marked on the ground in the necessary square and circular shapes. The size is fixed (set by the F45.02 subcommittee) for the appropriate AGV. The initial size shall be large enough to allow the AGV to traverse fully from the START to the END points. If needed, the material used to mark the path shall be strong enough to withstand AGV traversal.

The START and END points shall be co-located in a way such that the AGV path-coincident point (e.g., centroid or wheel axle midpoint) is located at the START and END during the respective points of the traverses. A 5 cm (2 in.) wide red line shall be painted at the respective center of the START/END location to delineate the AGV position.

The confined space apparatus, calibration, and procedures might be based on ASTM E2803-11 [20] where similar setup and materials are used. An example test setup is shown in Figure 7 for both unconfined and confined space tests.

The START and END points shall be located in their respective apparatus locations in such a way that the entire AGV is fully located in the START and END quadrants during the respective points of the traverses. A 5 cm (2 in.) wide red line shall be painted at the respective centers of the START and END locations to delineate the AGV positions.

Fig. 7. Example reconfigurable apparatus for navigation tests with various AGV sizes, types, and tasks and for open and confined areas.



Various test conditions such as 1) floor-surface types, conditions, wetness, and friction levels, 2) temperature and humidity, and 3) types of lighting shall be facilitated as appropriate for the AGV and the associated task. For example, for a test run in a dark environment, a light meter shall be used to read 0.1 lux or less. The darkness shall be re-measured when the lighting condition changes. The actual readings of these conditions should be recorded on the test form.

The darkness is specified as 0.1 lux due to the cost of implementing the apparatuses and due to the fact that AGV cameras are less sensitive than human eyes. Also, our experience indicates that any darkness below 0.1 lux would not make a difference in the cameras' functioning. It is recognized that the environments in real applications may be darker than the specified test condition. A stopwatch shall be provided to measure the timing performance. At least a 10X more accurate measurement system shall be used to measure ground truth for the AGV tests.

B. Calibration and Standardization

The AGV configuration as tested shall be described in detail on the test form, including all subsystems and components and their respective features and functionalities. The configuration shall be subjected to all the applicable test methods as determined by the test sponsor. Any variation in the configuration shall cause the resulting AGV variant to be retested across all the applicable test methods to provide a consistent and comprehensive representation of the performance.

Once an AGV begins a test, by starting to execute the task, its onboard AGV controller will monitor the execution of the

task for the specified number of repetitions through completion without leaving the path. During the test, the AGV shall not be allowed 1) to have the energy/power source replenished nor 2) to have any human physical or control intervention. The latter includes adjustment, maintenance, or repair. Any such actions shall be considered a fault condition.

The main metric for the navigation test method is path traversal accuracy- the minimum deviation from the path -for the specified number of continuous repetitions. In addition, other useful metrics include the elapsed time for successfully performing the task, and, the average number of tasks performed per minute for multiple repetitions. Both of these temporal performance indices reflect the combination of the AGV's capability, efficiency, and programmability. And, both are part of the test; this means that the results shall be recorded on a test form. The average number of tasks per minute rate is calculated based on the designed distances between the START and END points and not the actual trajectories of the traverses.

The test sponsor has the authority to specify the lighting condition and other environmental variables, which can affect the test results. All environmental settings shall be noted on the test form.

An AGV's reliability (R) of performing the specified task at a particular apparatus setting and the associated confidence (C) shall be established. The required R and C values dictate the required number of successful repetitions and the allowed number of failures during the test. With a given set of the R and C values, more successes will be needed when more failures are allowed.

A test sponsor has the authority to specify the R and C values for her/his testing purposes; otherwise she/he can elect to use the default values for this standard. The factors to be considered in determining the values are task requirements, consistency with the operating environments, ease of performing the required number of repetitions, and testing costs such as time and personnel. To meet statistical significance, for example, 80% reliability (probability of success) with 85% confidence at any given setting of a test apparatus, the number of failures (incomplete repetitions or occurrences of the fault conditions) in the specified set of repetitions shall be no more than the following:

- zero failures in 10 repetitions
- one failure in 20 repetitions
- three failures in 30 repetitions
- four failures in 40 repetitions
- six failures in 50 repetitions
- eight failures in 60 repetitions

The two-failure and five-failure situations are omitted in order to have the total repetition numbers increment in sets of 10 consistently to ease test administration. Additional repetition requirements can be calculated, if a test sponsor requires, by referring to general statistical analysis methods.

C. Procedure

For data traceability and organization purposes, the administrator shall obtain and record the pre-test information first. Pre-test information shall be collected, including: date/time,

facility, AGV model and make, environment (light, temperature, humidity conditions), AGV communication (i.e., control), etc. A set of specified fault conditions shall be followed during the test.

For the test method, the AGV operator either abstains or proceeds with the test. The administrator sets and verifies the apparatus or path setting and announces the number of repetitions to be performed. The administrator sets and verifies the test environmental conditions. The operator places the AGV behind the START point. The AGV may perform the traverse tasks in any order (e.g., maximum confined space or less than maximum confined space), but each task shall be performed for the required number of repetitions. The administrator instructs the operator to begin the task, starts the timer when the operator begins, and records the total elapsed time.

The operator initiates AGV control to perform the traversing task fully so that the entire AGV is at the END position. Return to the START point to complete one repetition. The administrator records the results on the test form. Information on fault condition handling is required and specified. Repeat the test until either the AGV fails to complete the task, or the specified setting is successfully negotiated for the specified number of repetitions. Test reporting on a standardized form is recommended.

V. ACKNOWLEDGEMENTS

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VI. SUMMARY AND CONCLUSIONS

AGV navigation-performance-measurement experiments were conducted and a multi-camera GT measurement system was first measured and then used for AGV navigation evaluation towards standard test method development. We tested a multi-camera measurement system, to be used as GT for the AGV, and compared the results to a metrology bar. We then compared the GT results to commanded data from an AGV. We conducted simple, geometrical, path-navigation experiments with an industrial AGV. Results show path deviation from commanded paths. Analysis of the AGV tracked data as compared to GT system data shows that the AGV is able to track to within σ between approximately 3 mm and 5 mm, for both the circle and square tests, while moving at 0.25 m/s. However, AGV calibration, tolerance, or other parameter adjustments in the vehicle controller may allow improvements to navigation performance. For example, we found that adjustment to the translational and rotational offsets would provide better navigation performance.

A test method was then developed intended for recommendation to the ASTM F45.02 subcommittee. Ideally, a minimalist, GT system, such as the metrology bar, or no ground truth (e.g., onboard AGV tracking, once evaluated) is used to measure AGV navigation performance. The results can help AGV manufacturers and users fully understand their AGV investment relative to its cost. Accuracy and repeatability of vehicle navigation must be better than the task tolerances. The next steps are to perform similar tests using crab steering,

mobile robot tests in unstructured environments (e.g., wall-following), and precision-tool (e.g., manipulator) positioning experiments, all including development of similar test methods.

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