

**NIST Technical Note 1965**

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Roger Bostelman  
Ya-Shian Li-Baboud  
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**NIST**  
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Roger Bostelman  
Ya-Shian Li-Baboud  
*Intelligent Systems Divison  
Engineering Laboratory*

Steve Legowik  
*Robotics Research, LLC.  
Gaithersburg, MD*

Tsai Hong  
*Intelligent Systems Divison  
Engineering Laboratory*

Sebti Fofou  
*College of Engineering  
Qatar University  
Doha, Qatar*

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## Abstract

The National Institute of Standards and Technology, Intelligent Systems Division has collected data measuring the performance of a mobile manipulator; i.e., an automatic guided vehicle (AGV)<sup>1</sup> with onboard robot arm, from two different manufacturers. The performance measurement concept uses a novel artifact and method that have been verified using an optical tracking system (OTS), which can measure AGV position, manipulator motion, and position uncertainty. The data needed to make these three measurements was collected during two tests; both tests have corresponding timestamps relative to global positioning system (GPS) time, where the computer clocks are synchronized using the Network Time Protocol. This paper provides detailed explanation of the data from mobile-manipulator, performance-measurement tests. It is expected that the user of the information within this document and the data files that accompany this document will have sufficient knowledge to implement mobile manipulation testing and evaluation.

Keywords: mobile manipulator, AGV, robot arm, optical tracking system, GPS timestamp, performance measurement

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<sup>1</sup> Disclaimer: NIST does not endorse products discussed within this paper nor manufacturers of these products. Products mentioned are for information purposes only and are not expressed as an endorsement for them or their manufacturer.

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## Introduction

Science-based measurements of the performance metrics of mobile manipulators performing standard tasks (poses and motions) are non-existent. Usually, measurements are used to simply ensure that tasks have been ‘more or less’ completed. Typical, robot-performance measurements include path drawing, path comparisons, Cartesian and polar coordinates, triangulation, optical tracking, and inertial measuring. Additional measurements are associated mainly with how well the end of arm tooling deviates from the commanded robot position and orientation or pose.

Making ground-truth measurements using different motion-tracking systems provides robot-joint, segment, and tool-point position information. This information is accurate enough to make comparisons to the commanded pose summarizing review of robot, mobile robot, and mobile manipulator performance measurement research shows this as being relatively new to the research community [1]. The National Institute of Standards and Technology (NIST) Robotic Systems for Smart Manufacturing (RSSM) Program [2] has been researching methods for measuring the performance of mobile manipulators for several years. The data collected during two tests that are described in this paper provides an extension of the RSSM publications referenced here and provides publicly-accessible experimental data to further this research.

This paper discusses the use of the NIST reconfigurable mobile manipulator artifact (RMMA) in measuring mobile manipulator performance. The concepts of using artifacts for measurement and programmed algorithms to control the manipulator are described. Two mobile manipulator performance measurement tests, their procedures, and logged data files are discussed to inform the reader about the accompanying data. Optical tracking system data of the two tests is also provided, along with ground truth data, to allow the user an additional measurement method beyond the artifact method.

## Mobile Manipulator Performance Measurement Concept

NIST has been developing a mobile manipulator, performance measurement concept over the past two years [3, 4, 5]. This concept, which evolved from the experiments described in [6], consists of using 1) a NIST-developed, reconfigurable, mobile manipulator artifact (RMMA) (see Figure 1) with 2) interchangeable and varying sized fiducials to be detected by a sensor carried by the mobile manipulator.

Researchers pre-programmed the forklift automatic guided vehicle (AGV) movements to ten different (see Figure 2) positions and orientations (poses). AGV orientation angles were programmed to be at 45° with respect to the RMMA. The AGV moved from a home position away from the RMMA to the first pose next to the RMMA, stopped and waited until the manipulator registered to RMMA reflectors, and then detected a pattern of fiducials mounted in a circle and a square pattern.

Upon completion of the circle or square pattern fiducial detections for one location, the AGV moved to the remaining nine other locations and poses. The AGV completed the test by moving towards the home position. Emergency stops, which are common in industrial uses of AGVs, occurred twice during the first test and once during the second test to add a semblance of reality.

A laser retroreflector was mounted in-line to the manipulator end-of-arm-tool joint and used as a reflector detection device. A circle pattern and a square of 2 mm diameter fiducial reflectors were mounted to the RMMA. Additionally, two large (42 mm) diameter reflectors were mounted within the two patterns (four total) and used as registration devices for the mobile manipulator. A “bisect with search” registration method for registering the mobile manipulator to the RMMA was developed. Once the registration was completed, the mobile manipulator was expected to then detect all fiducials within a local pattern (circle or square) to the current AGV pose. Upon completion, the manipulator stows and the AGV moves to the next pre-taught pose until all ten poses are completed.

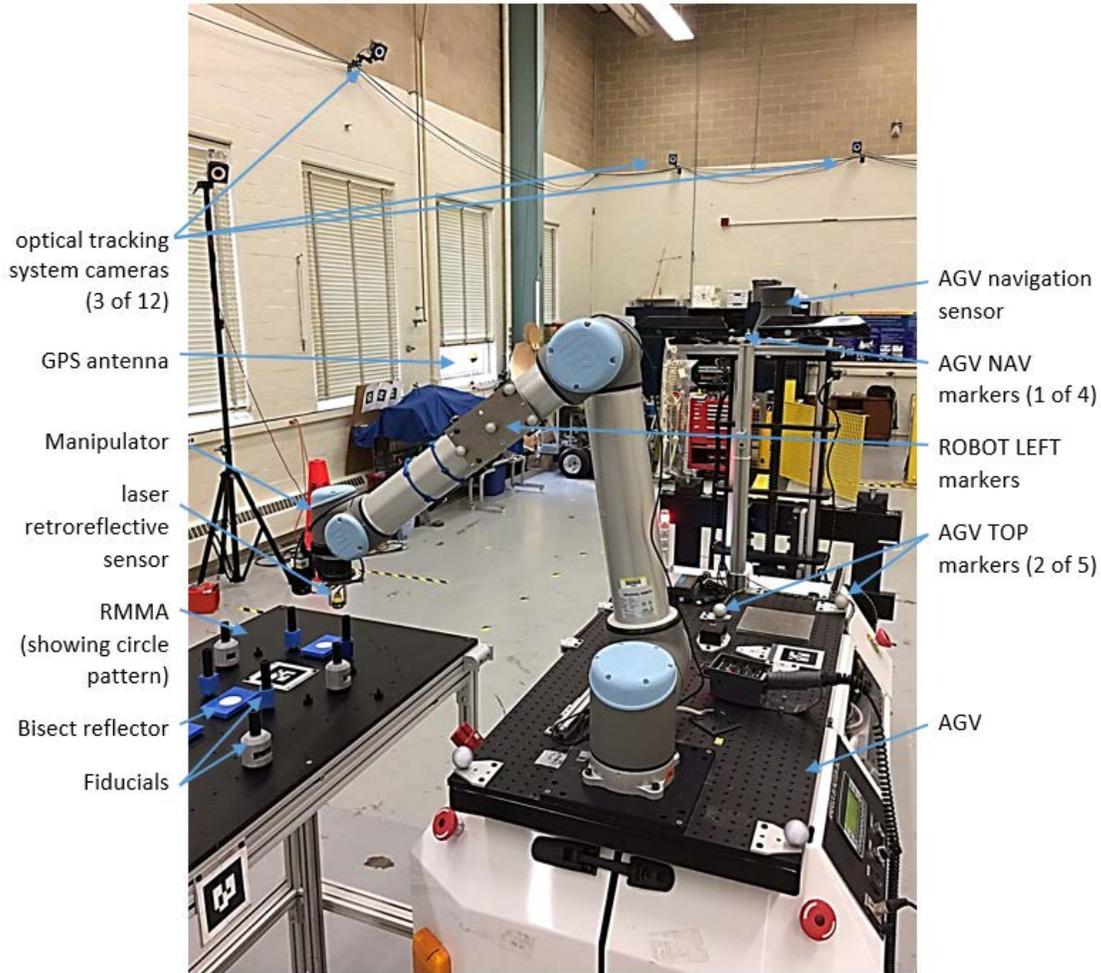


Figure 1 – Mobile Manipulator positioned next to the reconfigurable mobile manipulator apparatus (RMMA)

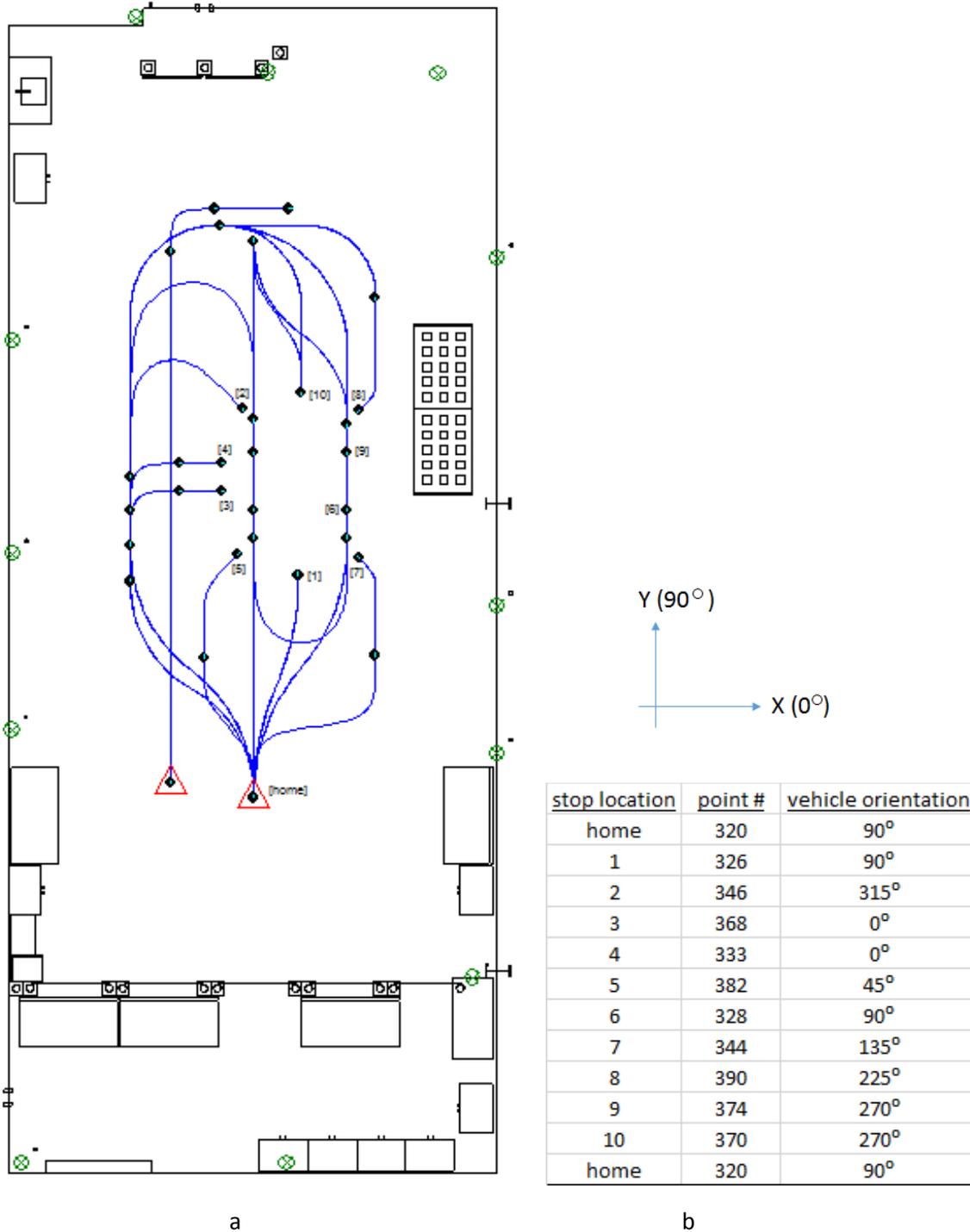


Figure 2 – (a) Map of AGV reference point paths (blue lines) and stop points (black dots on paths), and approximate locations of AGV wall-mounted reflectors (green circles with X's) used for navigation. (b) AGV stop location corresponding to the map, point number corresponding to the transport structure point, and vehicle orientation at each stop location. The left straight-to-right turn only path beginning at the unlabeled home triangle was not used.

A square search pattern provided the best search method [5] for detection of the 2 mm or smaller fiducials. An example of the square step pattern is shown in Figure 3 where the search begins away from the reflector at the chosen start point (yellow arrow dotted end). Each step moves along the small white or gray arrows until the laser retroreflector detected the fiducial reflector with the red arrow step.

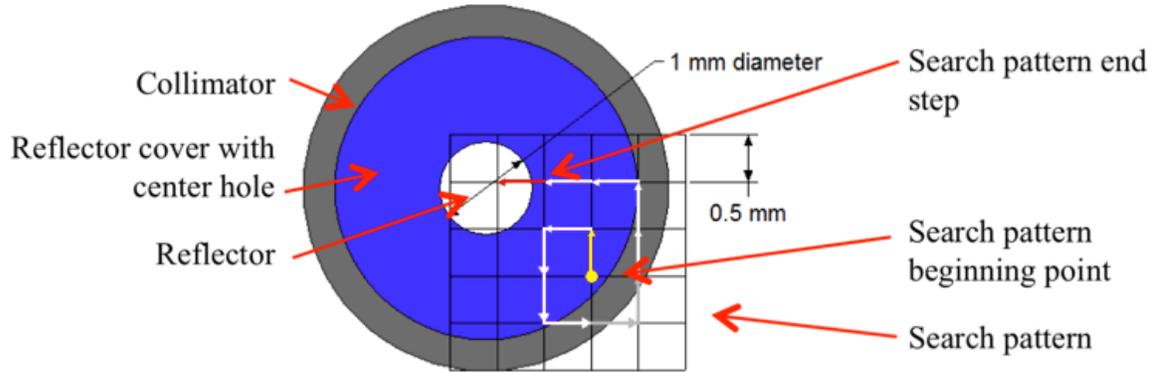


Figure 3 – Example square step search pattern drawing. The pattern begins with the yellow arrow dotted end and ends when the reflector is detected with the red arrow search step.

### Mobile Manipulator Algorithm

The Mobile Manipulator program controlled the manipulator during the tests. It interfaced with the AGV directly to obtain the current AGV position and orientation. It also interfaced with the NDC8 [12] AGV control program (Transport Structure) running on the NDC8 Order Manager application to coordinate the motion of the arm with the motion of the AGV. The AGV control program signaled the Mobile Manipulator program when it arrived at one of the stop or test locations. The AGV control program also sent the identification number of the test location. The Mobile Manipulator program read the current AGV pose and used it to compute the initial search for the locations of the two registration reflectors in the target pattern (circle or square). Additional patterns could also have been used in the Mobile Manipulator program.

The manipulator was first moved from a stowed location over the body of the AGV to a staging location directly in front of the AGV. The manipulator was then moved from the staging location to the first of the two registration reflectors. The staging location was chosen so that the manipulator could make a straight-line motion from the staging location to a registration reflector - located in front of, or to either side of, the AGV - without colliding with its shoulder joint. After moving to the first registration reflector, the manipulator performed a square spiral search to determine the exact location of the reflector. When it determined the location of the first registration reflector, the program repeated the process with the second registration reflector. When the locations of the two registration reflectors were determined, the program had sufficient information to compute the locations of the other fiducials in the square or circular patterns. The initial registration number of iterations count was logged and included in results. Repeatability is a common metric in robotics and can be compared to the registration number within this log.

Once the locations of all reflectors in the pattern were computed, the manipulator cycled through them a set number of times – one time for the circle pattern and two times for square pattern. At each

fiducial reflector, the laser retroreflector checked to see if the manipulator was aligned with the reflector.

When the test was completed, the manipulator was moved to the staging location and then to the stow location. When the manipulator was back in the stow location, the Mobile Manipulator program signaled to the AGV control program that it was clear to move.

The positions of the circle and square patterns of fiducials were recorded prior to performing the repeatability tests. The AGV was first moved to a location where it could reach both patterns of fiducials. The current location and orientation of the AGV were recorded. The arm was repositioned manually until the sensor detected alignment [3, 5, 6] with each of the index fiducials, and the manipulator position was recorded. This information, along with the position of the manipulator base relative to the vehicle's coordinate system, allowed the correct manipulator coordinates for the index fiducials to be calculated for an arbitrary AGV location. This allowed the AGV to approach the target/work area from any direction and to compensate for variations in the AGV's stopping pose.

The calibration of the manipulator base location involved recording the position of one or more fiducials from a variety of locations. Both the AGV location and the manipulator coordinates of the fiducials were recorded. This data was processed using an iterative, non-linear model [13] to find the best value of the base position and orientation.

### Independent Measurement System

An independent measurement system was used to verify the mobile manipulator, performance measurement concept that uses an artifact. Data collected from both the NDC8 AGV Vehicle Diagnostics Tool (VDT) and the robot control program include much information about their motion and position and are provided with the accompanying data set. However, the data set sometimes is not complete; missing data or other information that may be useful to the system designer, researcher, or user is, for some reason, not included. See the Data Collection Anomalies section for these occurrences during tests.

An optical tracking system (OTS) manufactured by NaturalPoint was used for this research. There are several, similar systems on the market; these systems can be located using a simple online search. In addition to using the manufacturer's method for calibrating the OTS used for this mobile manipulator data collection exercise, research at NIST [7, 8] has led to developing a calibration method for these systems that has recently been standardized<sup>2</sup>. We include this information here as potentially useful background information for users of optical tracking systems. Markers were mounted to the AGV and to the robot as shown in Figure 4 and are described in the Procedures.

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<sup>2</sup> <https://www.astm.org/Standards/E3064.htm>

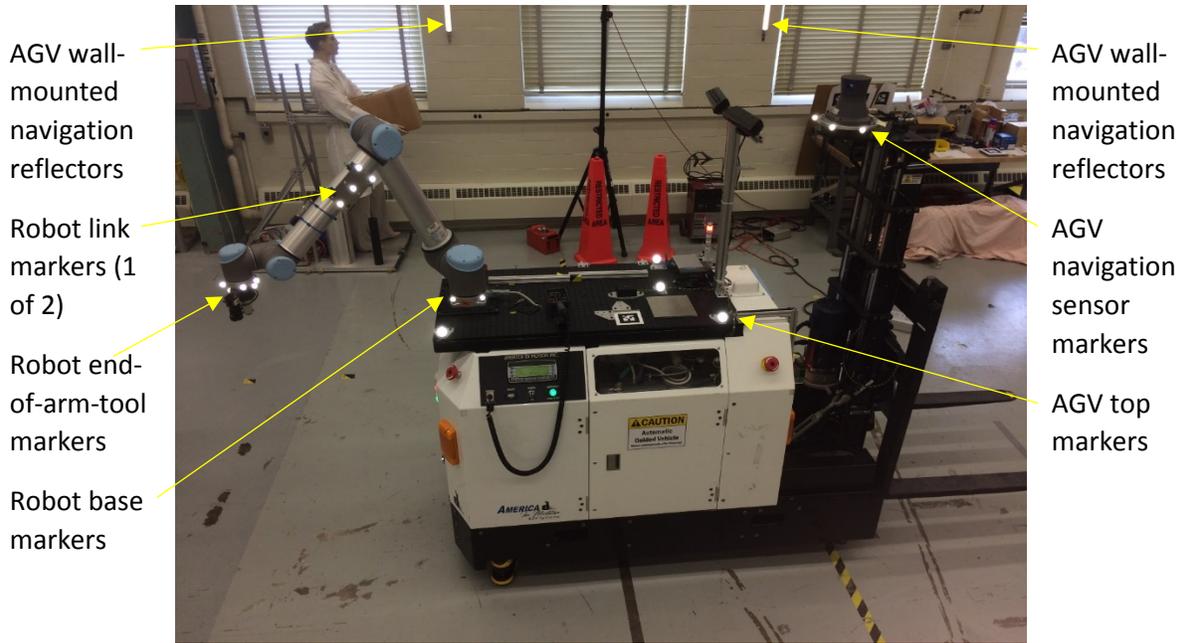


Figure 4 – Highlighted (white) AGV- and robot-mounted markers and AGV wall-mounted reflectors. Two robot link markers were used, one is shown and one on the opposite side of the link (not shown). Robot base markers were not included in Tests 1 and 2.

Ground truth of the RMMA was measured after the two tests. All fiducials and large bisect markers were unscrewed from the RMMA. A 19 mm diameter marker was placed on each screw hole where each fiducial and bisect marker was normally located (See Figure 5). Rigid bodies were created for the bisect reflector markers (BISECT), the circle pattern of markers (CIRCLE), and the square pattern of markers (SQUARE). Three data sets of approximately 30 s in duration were collected using the OTS of only the static RMMA markers. The OTS performed data collection at 120 Hz.

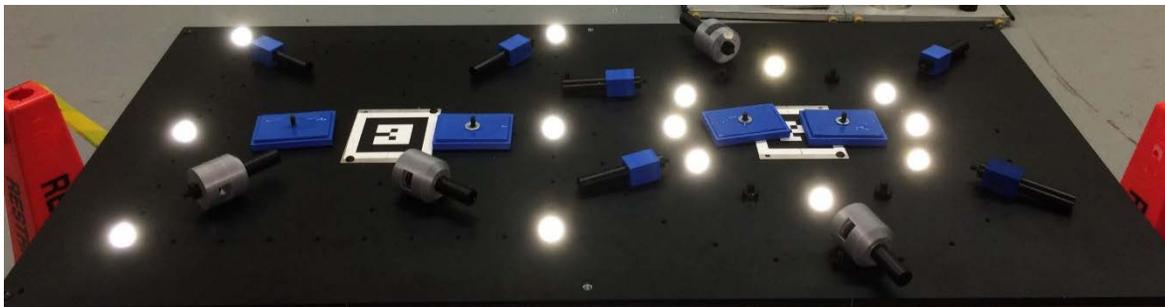


Figure 5 – OTS markers located on the bisect reflector, circle pattern fiducial, and square pattern fiducial locations of the RMMA measured for use as ground truth. The associated bisect reflectors and fiducials are lying next to their respective mounting locations.

Ground truth data was also collected for the robot base to allow static correlation of the base with respect to the AGV top markers. A rigid body was created for the robot base (called ROBOT BASE) and approximately 10 s of data was collected about it simultaneously with all other robot and AGV rigid bodies. Screenshots of the OTS rigid bodies developed for the AGV and robot and for the RMMA are

shown in the screenshots in Figure 6 a and b, respectively and correspond to Figures 4 and 5, respectively.

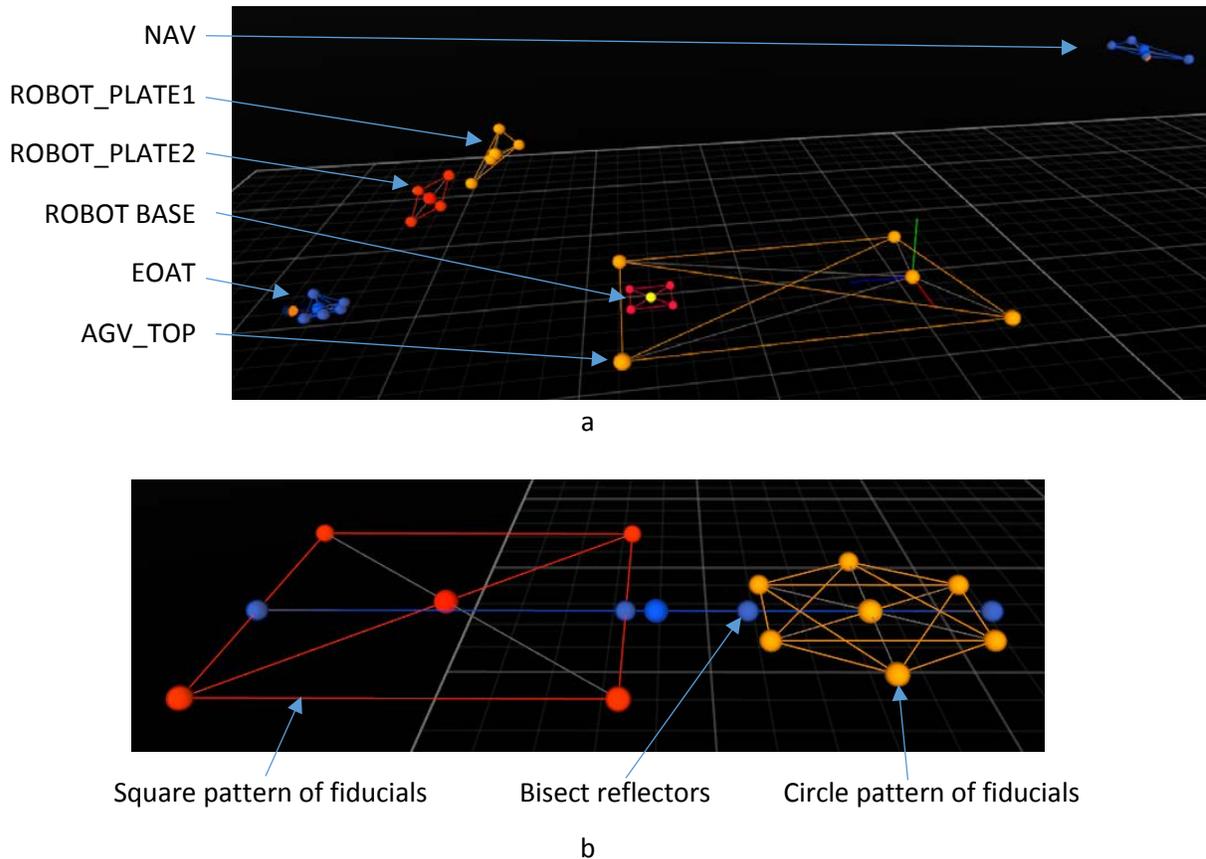


Figure 6 – Screen shots of OTS rigid bodies developed for the (a) AGV and robot and (b) the RMMA.

## Procedures

### Systems Setup

1. Passive optical tracking markers were installed on the AGV and the manipulator.
2. Within the Optical Tracking System (OTS) Software, two AGV rigid bodies were formed (i.e., a grouping of specific markers on an object) surrounding the navigation sensor (called NAV) and on the surface where the robot is mounted (called AGV\_TOP). Two robot rigid bodies were formed along the distal link (called ROBOT\_PLATE1 and ROBOT\_PLATE2) and on the end-of-arm-tool joint (called EOAT).
3. Extraneous markers within test area were covered, although there were perhaps five or so reflective spots shown on the OTS display from light reflected off the painted floor.
4. The four (two for the circle and two for the square) adjustable reconfigurable mobile manipulator (RMMA) fiducials (see Figure 3) were set to 2 mm diameter. The simplest method is to use a 2 mm diameter rod inserted within the aperture, closing the aperture until it contacts the rod, and removing the rod leaving the aperture opening set at a 2 mm diameter.
5. The manipulator step size was set to 0.5 mm within a square-step search grid pattern as shown in Figure 3.

6. The bisect-then-search registration and search fiducial detection test method were used for measuring the performance of mobile manipulators.
7. The AGV velocity was limited to 0.25 m/s.
8. AGV motion was programmed with paths and stop points as shown in Figure 2. The America In Motion AGV design and control programs were based on the Kollmorgen NDC8 Controller [12] and included: Layout Designer, Vehicle Application Designer, System Manager, CWay, Systems Application, and Vehicle Diagnostics Tool (VDT). Systems Application design of the control program (transport structure) is shown in Appendix A and the path designs and reflectors are depicted in Figure 2 and in the VDT images shown in Appendix B with VDT files logged and included in the data collected.
9. Robot communication and movement were programmed as described in the Mobile Manipulator Algorithm section. The Universal Robot UR10 robot arm was controlled by an offboard AGV control program developed by NIST and Robotic Research researchers and written in C++ programming language using Visual Studio compiler/text editor. Log files from the robot control program are included in the data collected, as well as the AGV pose when it stops at the RMMA for mobile manipulator measurement.
10. The OTS was setup as described in the Independent Measurement System section. The OTS included 13 cameras where one was set to video. The system was set to detect at 120 Hz and initially calibrated using the manufacturer's method, which classified the calibration as "excellent," as indicated on the controller display. For example, all extraneous reflections were covered and those not covered were masked. The ground plane was then set.
11. To facilitate the data correspondence between the AGV controller, remote robot control, and the OTS, all system clocks must be synchronized to provide accurate time-stamping. The system clocks of the three Windows computers running the OTS, robot controller, and AGV control program were synchronized using a Network Time Protocol (NTP) time server with integrated GPS antenna mounted inside in front of a lab window (see Figure 1). The Omicron time server software display showed that twelve satellites were detected and the time server clock was locked to global positioning system (GPS). The three off-board vehicle computers (OTS, remote robot control, and AGV controller) were configured to synchronize to the time server via a power-over-Ethernet switch. Within 5 minutes prior to each test (before Test 1 and before Test 2), the *w32tm /resync* command was executed on all three computers to send a request to immediately resynchronize the system clock to the configured NTP time server. Baseline tests of system clock precision to NTP using a local time server can have a time offset on the order of tens of ms (see Figure 7).

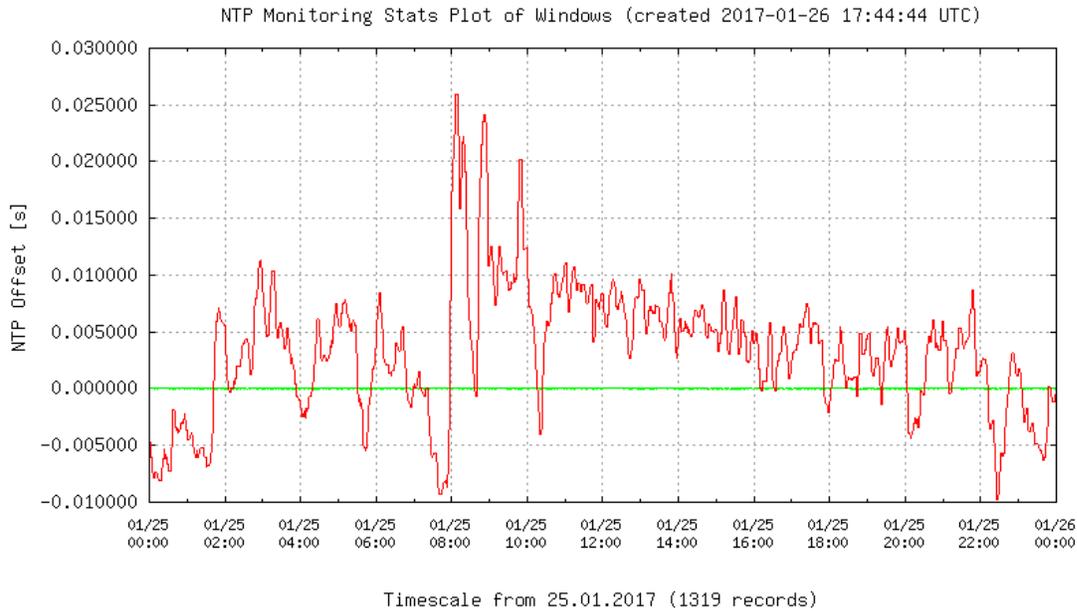


Figure 7 – Screen shot of time offset between a local computer clock and a GPS-locked NTP time server over the course of 24 hours to establish a baseline approximation of the synchronization precision.

12. OTS ground truth markers were set up as shown in Figure 5 and described in the Independent Measurement System section.

### Test Details

13. The AGV was initially located at the home position and the manipulator was located at the stow pose (positioned within the vertical boundaries of the AGV with the laser pointed downward) for each of the two tests.
14. Test 1 was executed:
  1. Tests included the mobile manipulator accessing the RMMA ten times and with the AGV at ten different poses by using the AGV control program shown in Appendix A.
  2. An operator started the VDT recording when the robot was stowed and the AGV was about to move to the next RMMA access pose. Two log files were saved after each recording. AGV paths from the VDT program are shown in Appendix B.
  3. The onboard manipulator was controlled using its control program. Robot control algorithms are shown in Appendix C. Logging automatically began when the robot began moving from the stow position to the RMMA and ended when the robot was again stowed ready for the AGV to move to the next RMMA access pose or the home position.
  4. The OTS recorded the entire test (approximately 30 minutes). An operator started the recording prior to AGV movement from the home position and stopped the recording when the AGV was returning to the home position. Further details about the OTS are shown in Appendix C.
15. Test 2 was executed and followed Test 1 steps 1 through 3 above. Step 4 was changed as follows:

4. The OTS recorded the entire test (approximately 35 minutes). An operator started the recording prior to AGV movement from the home position and stopped the recording when the AGV was returning to the home position.

### Log Files

Log file information for each of the AGV, Manipulator, and OTS are shown: in Appendix D for Test 1, in Appendix E for Test 2, and in Appendix F for Ground Truth.

### Data Collection Anomalies

Four known anomalies, numbered below, occurred in the data collected during the two tests. Instead of retaking data, these anomalies were deemed to be potentially useful to the data user. The events were included in the data set as a unique occurrence, although potentially a situation that might occur in industry.

1. During both tests, the VDT data file inconsistently collected data when the vehicle stopped and the robot was asked to perform a task. Although the robot controller logged data both when the vehicle stopped and when the robot began registration with the RMMA, there is still a gap in that data. Figure 8 shows a sample of the VDT data with this gap shown as an error. The gap/error occurs when the AGV controller communicates to the robot controller that it has stopped and to relinquish control until receiving a “continue AGV control” handshake where once again, the AGV can continue motion control. During this communication, the AGV is decelerating and coming to a steady state stop, which can vary in time depending on the floor surface undulation or the AGV system itself.

```

usedrefl 1488989853.4250 5.4703 6.3 10.830 11.218 11
state 1488989853.4248 6.2953 7.6549 1.5732 1 100
laser 1488989853.3899 4.137 4.9 0 0
laser 1488989853.4137 5.039 4.8 0 0
laser 1488989853.4250 5.470 6.3 0 0
laser 1488989853.4359 5.888 11.7 2 119
laser 1488989853.4401 6.048 14.5 3 105
set 1488989853.4248 0 0.0169 0 0.0281 0 0.0283
enc 1488989853.4846 0 0.0171 0 0.0283 0 0.0286
usedrefl 1488989853.4771 1.1658 4.9 1.813 8.916 4
state 1488989853.4846 6.2953 7.6550 1.5731 1 100
laser 1488989853.4459 6.266 14.2 2 106
laser 1488989853.4501 0.146 15.3 3 111
laser 1488989853.4584 0.457 10.2 2 122
laser 1488989853.4651 0.713 6.9 1 127
laser 1488989853.4771 1.166 4.9 0 0
navserver 2.7.0 (type 'help &lt;return&gt;' for help)
protocol 1 2
protocol 2 2
error protocol not supported
error illegal subscribe argument wlanstat
error illegal subscribe argument wlanecan
enc 1488990057.9047 0 0.0171 0 0.0283 0 0.0286
state 1488990057.9047 6.2943 7.6551 1.5736 1 100
set 1488990057.9047 0 0.0169 0 0.0281 0 0.0283
enc 1488990057.9645 0 0.0171 0 0.0283 0 0.0286
state 1488990057.9645 6.2943 7.6551 1.5736 1 100
set 1488990057.9645 0 0.0169 0 0.0281 0 0.0283
enc 1488990058.0245 0 0.0171 0 0.0283 0 0.0286
state 1488990058.0245 6.2943 7.6551 1.5736 1 100
set 1488990058.0245 0 0.0169 0 0.0281 0 0.0283
enc 1488990058.0847 0 0.0171 0 0.0283 0 0.0286
state 1488990058.0847 6.2943 7.6551 1.5736 1 100
set 1488990058.0847 0 0.0169 0 0.0281 0 0.0283
enc 1488990058.1445 0 0.0171 0 0.0283 0 0.0286
state 1488990058.1445 6.2943 7.6551 1.5736 1 100
set 1488990058.1445 0 0.0169 0 0.0281 0 0.0283
enc 1488990058.2049 0 0.0171 0 0.0283 0 0.0286
state 1488990058.2049 6.2943 7.6551 1.5736 1 100

```

Figure 8 – Gap (blue highlight) in data from the AGV VDT program when the vehicle was at a stop location waiting for the robot to communicate to the AGV that it can again continue motion control.

2. During Test 1, while the AGV was accessing the seventh pose, the safety laser protecting obstacles near the forks detected a safety cone within its rotation path and caused an emergency stop. The test was continued upon an AGV reset.
3. During Test 1, while returning to the home position, the AGV veered off-path by more than the approximate 76 mm (3 in) safety standard allowance and emergency stopped itself. The event was also recorded with both the OTS and the VDT.
4. During Test 2, while the AGV was returning to the home position, it again veered off-path by more than the approximate 76 mm (3 in) safety standard allowance and emergency stopped itself. The event was also recorded with both the OTS and the VDT.

## Data Correspondence Between Log Files

### Example Robot controller data log file

When the AGV stops and the robot controller begins logging data, the log file is produced and corresponds to the time when the robot begins moving from the stow position to the first bisect reflector (i.e., marker -1). For example, in the file: “data\_2017-03-08\_11.21.21\_circle.csv”, start would be at time “8.959”. See Figure 9.

time	iter	marker	init_x	init_y	init_z	init_xrot	init_yrot	init_zrot	ok	time	steps	x	y	z	xrot	yrot	zrot	
8.959	0	-1	-6.85455	-768.837	328	180	0	90	1	27.8485	44	-17.681	-768.592	327.909	-179.999	-0.00476	89.996	
39.209	0	-2	-1.99696	-464.079	328	180	0	90	1	27.8012	44	-13.9864	-466.554	328.024	179.997	0.008815	89.9986	
67.972	0	0	-168.222	-615.709	328	180	0	90	78.187	1	8.80808	33	-167.274	-614.26	328.089	-180	0.012592	89.9948
78.19	0	1	137.503	-617.988	328.089	-180	0.012592	89.9948	113.058	1	33.2612	117	137.482	-620.425	327.953	-179.996	0.004393	89.9754
113.061	1	0	-167.265	-614.26	328.089	-180	0.012592	89.9948	114.665	1	0.000112	1	-167.318	-614.275	328.143	-179.999	0.021486	90.0102
114.667	1	1	-93.7501	-747.756	328.089	-180	0.012592	89.9948	119.067	1	3.20751	15	-93.1962	-746.887	328.142	179.999	0.026547	89.981
119.07	1	2	58.6187	-750.839	328.089	-180	0.012592	89.9948	120.269	1	0.000113	1	58.7203	-750.847	328.135	179.996	0.021242	89.9801
120.271	1	3	137.473	-620.425	328.089	-180	0.012592	89.9948	121.471	1	0.000101	1	137.48	-620.319	327.967	-179.991	-0.00579	89.9919
121.473	1	4	63.9577	-486.928	328.089	-180	0.012592	89.9948	122.674	1	0.000103	1	63.9949	-486.926	328.141	179.999	0.019586	89.9888
122.677	1	5	-88.4112	-483.846	328.089	-180	0.012592	89.9948	123.878	1	0.000203	1	-88.4738	-483.81	328.037	-180	-0.00159	90.0013

Figure 9 – Example log file and highlighted timestamped data line that corresponds with the AGV and OTS log files.

### Example AGV data log file

The AGV logs data from the Vehicle Diagnostics Application (VDA) with timestamping shown in Unix epoch format (i.e., the number of seconds that have elapsed since 00:00:00 Coordinated Universal Time (UTC), January 1, 1970, not counting leap seconds in local time). Within the VDA file: “8Mar2017-1123test.bz2”, data covers time from the 1120 (home to pose 1) test through 1123 (pose 1 to pose 2) test. Within the 8Mar2017-1123test.bz2 file, timestamp “set 1488990089.9447” corresponds to the robot data log file: “data\_2017-03-08\_11.21.21”, data point “8.959”. The log data line corresponding to this timestamp shows:

set 1488990089.9447 0 0.0285 0 0.0182 0 0.0182

This time is when the robot initially moves from the stow position to the first bisect reflector; i.e., marker -1. Note that between “set 1488990140.2395” and “set 1488990210.4846”, there is a gap in the data during this time so no correspondence can occur here across the robot log file and the AGV log file.

### Example Optical Tracking System data log file

Within log file: “Take 2017-03-08 11.20.45 AM\_truncated”, the timestamped data point: “44.95833” corresponds to the nearest timestamp to the above robot data and AGV data. See Figure 10.

5399	44.925	0.001055	-0.00147	0.001541	-1	-0.88665	1.95831	2.80056	0.000216	-1.02862	1.958421	2.746074
5400	44.93333	0.001059	-0.00145	0.001567	-1	-0.88664	1.958324	2.800544	0.000216	-1.0286	1.958442	2.746052
5401	44.94167	0.000861	-0.00143	0.001554	-1	-0.88659	1.958315	2.800521	0.000234	-1.02855	1.958451	2.746024
5402	44.95	0.00084	-0.00145	0.001587	-1	-0.88656	1.958323	2.800524	0.000238	-1.02852	1.95847	2.746034
5403	44.95833	0.000687	-0.0015	0.00159	-1	-0.88654	1.958299	2.800545	0.000247	-1.0285	1.958464	2.746066
5404	44.96667	0.000644	-0.00145	0.001613	-1	-0.88651	1.958284	2.800565	0.000252	-1.02847	1.958461	2.746073
5405	44.975	0.00144	-0.0016	0.001298	-1	-0.88637	1.958372	2.800542	0.00019	-1.02835	1.958372	2.746094
5406	44.98333	0.001533	-0.00163	0.001313	-1	-0.88633	1.958376	2.800533	0.000192	-1.02831	1.95837	2.746092

Take 2017-03-08 11.20.45 AM\_Tru

Ready

Figure 10 – Example log file and highlighted timestamped data line that corresponds to the AGV and robot log files.

### Time Correspondence across data files

A Time Correspondence program was developed to correlate the time stamps when the robot, AGV, and OTS all logged data at approximately the same start-activity time, including the time when a file was produced and the time when a reflector was detected. An example of the program output is shown in Figure 10. The output includes data files from the Robot, AGV, and OTS and uses the three associated Unix timestamps when the laser retroreflector (i.e., EOAT) registers with the -1 marker (i.e., first bisect reflector). The program then shows the start time of the OTS program file and the time to generate the robot log file. It then provides an estimated offset time from the robot to the OTS files to provide a check to the data user on where to locate this data point and correlate times. The program translated the file’s local timestamps from the OTS (OTS Time column) and robot (Robot Time column) into UTC and finally Unix timestamp epoch, which is the number of seconds since January 1, 1970.

Each measurement in the robot file has a relative offset from file creation; this offset was added to provide the values for the column “Robot Start Time” in Figure 11. The difference between the column Robot Start Time (s) and OTS Time is computed to provide a relative OTS Offset (s) estimate. The estimate is then compared to the row in the OTS data with the closest time-stamp *before* the OTS estimated offset to determine the OTS data point corresponding to the robot and AGV measurements. Similarly, the corresponding robot time is shown for the AGV. Appendix G shows the time correspondence across all data files using this format.

Robot Time (s)	Marker	OTS Time	Robot Start Time	OTS Offset (s)	AGV Set (s)
1488990081	-1	1488990045	1488990089.959	44.959	1488990089.9447

Figure 11 – Example time correspondence across the robot, OTS, and AGV files output from the Time Correspondence program.

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# Appendices

## Appendix A - AGV transport structure

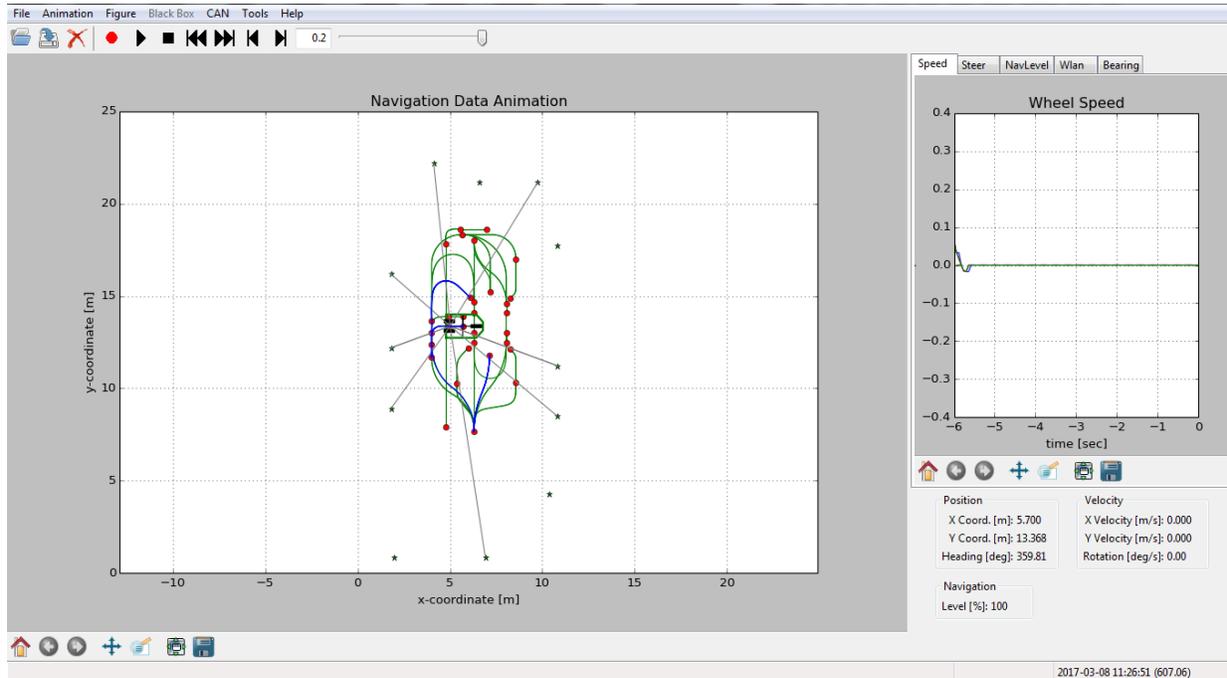
Figure A-1 shows the transport structure to control the AGV through tests 1 and 2.

Row	Label	Instruction	Condition	Label Destination	Label Error	Point 1	Operation 1	[Attrib.]		Remark
1		P_set	-			&COUNT	0			
2		P_set	-			&TO	123			
3		P_set	-			&target	0			
4	start	CmvPnt	-			320	0			home position
5		CmvPnt	-			326	0			circle location
6		P_set	-			&target	2			signal that we have arrived at a target and have data
7	wait1	P_==	FALSE	wait1		target	0			wait here till robot changes target to 0
8		CmvPnt	-			346	0			square location
9		P_set	-			&target	1			signal that we have arrived at a target and have data
10	wait2	P_==	FALSE	wait2		target	0			wait here till robot changes target to 0
11		CmvPnt	-			368	0			circle location
12		P_set	-			&target	2			signal that we have arrived at a target and have data
13	wait3	P_==	FALSE	wait3		target	0			wait here till robot changes target to 0
14		CmvPnt	-			333	0			square location
15		P_set	-			&target	1			signal that we have arrived at a target and have data
16	wait4	P_==	FALSE	wait4		target	0			wait here till robot changes target to 0
17		CmvPnt	-			382	0			circle location
18		P_set	-			&target	2			signal that we have arrived at a target and have data
19	wait5	P_==	FALSE	wait5		target	0			wait here till robot changes target to 0
20		CmvPnt	-			328	0			square location
21		P_set	-			&target	1			signal that we have arrived at a target and have data
22	wait6	P_==	FALSE	wait6		target	0			wait here till robot changes target to 0
23		CmvPnt	-			344	0			circle location
24		P_set	-			&target	2			signal that we have arrived at a target and have data
25	wait7	P_==	FALSE	wait7		target	0			wait here till robot changes target to 0
26		CmvPnt	-			390	0			square location
27		P_set	-			&target	1			signal that we have arrived at a target and have data
28	wait8	P_==	FALSE	wait8		target	0			wait here till robot changes target to 0
29		CmvPnt	-			374	0			circle location
30		P_set	-			&target	2			signal that we have arrived at a target and have data
31	wait9	P_==	FALSE	wait9		target	0			wait here till robot changes target to 0
32		CmvPnt	-			370	0			square location
33		P_set	-			&target	1			signal that we have arrived at a target and have data
34	wait10	P_==	FALSE	wait10		target	0			wait here till robot changes target to 0
35		CmvPnt	-			320	0			home position
36		P_+	-			&COUNT	1			increment count and loop back to start
37		Nop	Always	end						
38	end	CmvPnt	-			320	0			

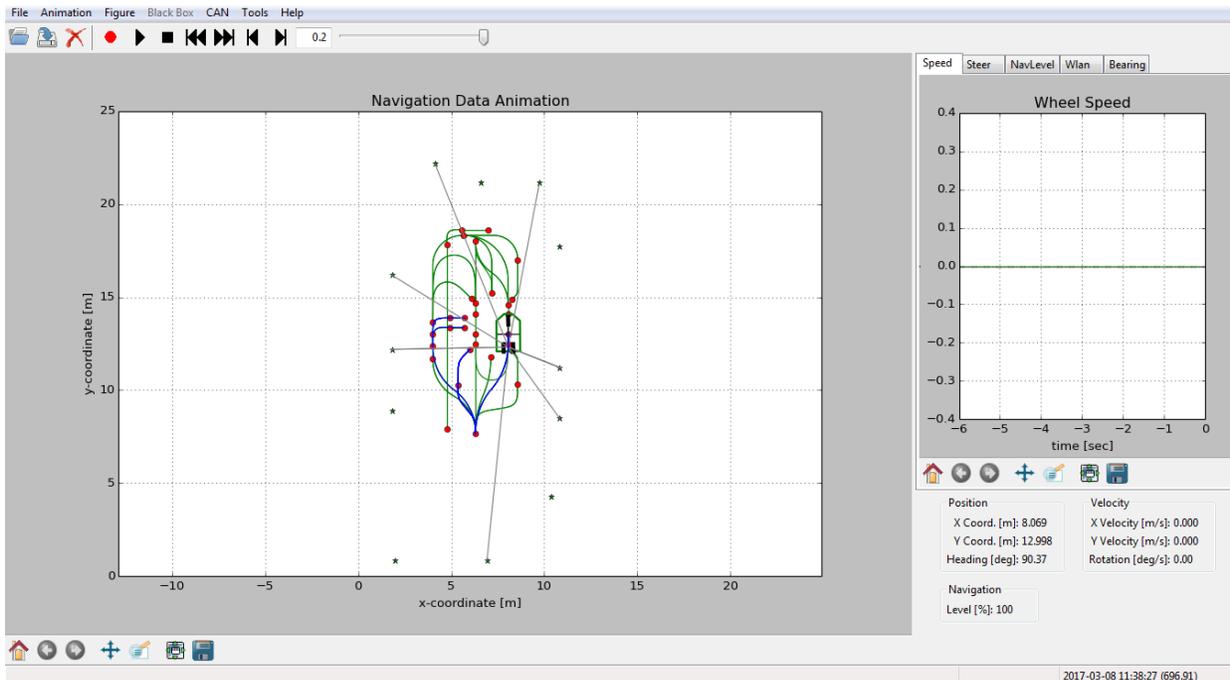
Figure A-1 – Transport structure program used to control the AGV during tests.

## Appendix B - AGV paths from the Vehicle Diagnostics Tool

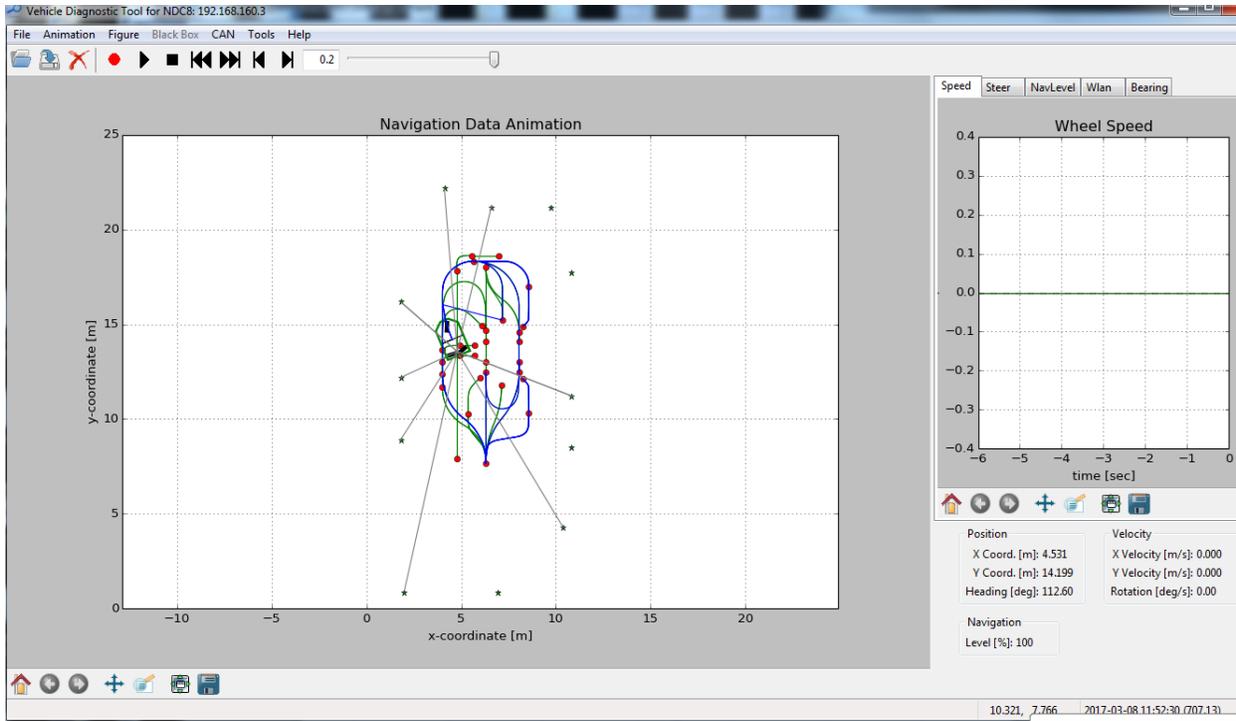
Figures B-1 a, b, and c show screenshots from the AGV Diagnostics Tool application during test 2 (test 1 included similar information). The images show the programmed points (red), planned paths (green), actual paths driven (blue), facility reflectors (gray dots), and navigation sensor detection of reflectors (gray lines) at consecutive points in time during Test 2.



a



b



C

Figure B-1 a, b, c - Snapshots of the Vehicle Diagnostics Tool showing the programmed points (red), planned paths (green), actual paths driven (blue), facility reflectors (gray dots), and navigation sensor detection of reflectors (gray lines) at consecutive points in time during Test 2.

## Appendix C - Optical Tracking System information

Numerous optical tracking systems (OTS), including motion capture systems, have been developed in research centers and commercialized [9]. These OTS systems are proving useful as ground truth measurement systems to assess the performance of robots, autonomous ground vehicles, and assembly tasks in smart manufacturing. In order to be used as ground truth, the accuracy of the OTS must be at least ten times better than a given system under test. The twelve-camera OTS system which has submillimeter uncertainty in our setting [10] serves as ground truth for evaluating the performance of an automatic guided vehicle (AGV) with an onboard robot arm (mobile manipulator) and for evaluating the performance of robotic workstation assembly tasks (see Figure C-1).

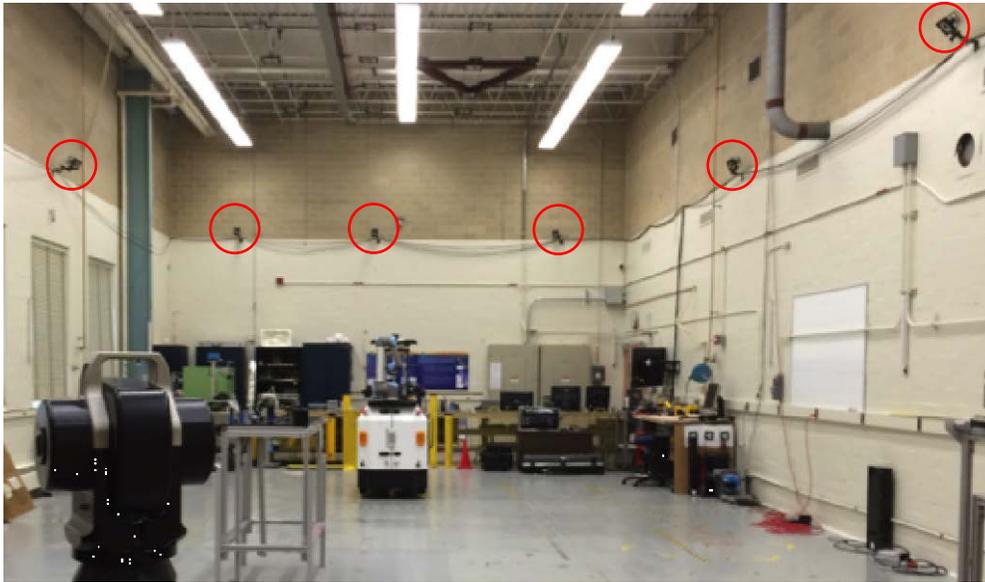


Figure C- 1 The lab is equipped with twelve (six are shown and circled in red) optical tracking system cameras. The data is collected over an area of approximately 13000 mm x 6000 mm while the optical tracking system tracked the mobile manipulator motion. The laser tracker on the left was not used for this data collection.

The OTS tracking system will save the Take files (TAK), Project files (TTP), and Calibration (CAL) [11]. The information in TAK files is described in [11]. The TAK file name includes the time that the file was created (e.g., Take 2017-03-08 12.48.17 PM.csv). Each TAK file contains the frame number, relative time stamp, rigid body name and pose (i.e., position and orientation), pose error, and each marker pose with marker quality. TAK files are then exported into .csv files and for this data set are shown in Appendices D and E.

## Appendix D - Test 1 data files and file information

The three systems (AGV, manipulator, and OTS) have associated data collected during Test 1 where the test includes one large OTS data log.

### AGV VDT - .bz2 files

VDT files are named by the operator and .bz2 (.bz2) suffixed files listed in Figure D-1 are labeled with (from left to right) the file data and time, the file close date, the file type, and the file size, respectively, across columns (see Appendices D and E). Information shown within these files is described in the NDC8 controller documents [12] for the VDT program. Within the file are text lines, which, among other line-leaders, shows 'set', 'laser', 'state', and 'usedrefl'. Epoch time immediately follows these line-leaders. The remaining information provided in this file contains status information of the vehicle. The user should consult NDC for further description.

 8Mar2017-1123test.bz2	3/8/2017 11:24 AM	BZ2 File	315 KB
 8Mar2017-1126test.bz2	3/8/2017 11:27 AM	BZ2 File	296 KB
 8Mar2017-1128test.bz2	3/8/2017 11:29 AM	BZ2 File	297 KB
 8Mar2017-1135test.bz2	3/8/2017 11:36 AM	BZ2 File	239 KB
 8Mar2017-1137test.bz2	3/8/2017 11:38 AM	BZ2 File	242 KB
 8Mar2017-1140test.bz2	3/8/2017 11:42 AM	BZ2 File	292 KB
 8Mar2017-1143test.bz2	3/8/2017 11:45 AM	BZ2 File	416 KB
 8Mar2017-1147test.bz2	3/8/2017 11:48 AM	BZ2 File	406 KB
 8Mar2017-1149test.bz2	3/8/2017 11:51 AM	BZ2 File	476 KB
 8Mar2017-1152test.bz2	3/8/2017 11:52 AM	BZ2 File	489 KB

Figure D-1 - List of BZ2 file types that include timestamp and laser navigation sensor data.

### AGV - .csv files

Figure D-2 shows a list of comma separated value files with (from left to right) .csv suffixes named by the operator and adding to the vehicle internet protocol address with \_file data and time, followed by the file close date, the file type, and the file size, respectively, across columns (see Appendices D and E). Information shown within these files is described in the NDC8 controller documents [12] for the VDT program. Within the file are headers on columns as shown in Figure D-3. The headers refer to the AGV X, Y, and angle with respect to 0° as shown in Figure 2. The NavLevel column refers to the navigation confidence level, 100 being the highest. The user should consult NDC for further description.

	192.168.160_position8Mar2017-1123.csv	3/8/2017 11:25 AM	Microsoft Excel Comma Separated Values File	115 KB
	192.168.160_position8Mar2017-1126.csv	3/8/2017 11:27 AM	Microsoft Excel Comma Separated Values File	89 KB
	192.168.160_position8Mar2017-1128.csv	3/8/2017 11:29 AM	Microsoft Excel Comma Separated Values File	84 KB
	192.168.160_position8Mar2017-1135.csv	3/8/2017 11:36 AM	Microsoft Excel Comma Separated Values File	52 KB
	192.168.160_position8Mar2017-1137.csv	3/8/2017 11:38 AM	Microsoft Excel Comma Separated Values File	53 KB
	192.168.160_position8Mar2017-1140.csv	3/8/2017 11:43 AM	Microsoft Excel Comma Separated Values File	73 KB
	192.168.160_position8Mar2017-1143.csv	3/8/2017 11:45 AM	Microsoft Excel Comma Separated Values File	112 KB
	192.168.160_position8Mar2017-1147.csv	3/8/2017 11:48 AM	Microsoft Excel Comma Separated Values File	110 KB
	192.168.160_position8Mar2017-1149.csv	3/8/2017 11:52 AM	Microsoft Excel Comma Separated Values File	132 KB
	192.168.160_position8Mar2017-1152.csv	3/8/2017 11:53 AM	Microsoft Excel Comma Separated Values File	138 KB

Figure D-2 - List of comma separated value files that include AGV position and orientation.

X[mm]	Y[mm]	Angle[deg]	NavLevel
6302	7655	89.88	100

Figure D-3 – Snapshot of AGV .csv file header and data.

### Robot log files

Robot log files, suffixed with .dat, are listed in Figure D-4 and are automatically created and named by the robot control program with file creation date/time and pattern measured. The following columns show the date/time when the file was automatically closed, the file type, and the file size. An example of the log file data within a .dat log file is shown in Figure D-5 with further explanation where needed.

	log_2017-03-08_11.21.21_circle.dat	3/8/2017 10:23 AM	DAT File	9 KB
	log_2017-03-08_11.24.34_square.dat	3/8/2017 10:25 AM	DAT File	4 KB
	log_2017-03-08_11.26.46_circle.dat	3/8/2017 10:28 AM	DAT File	9 KB
	log_2017-03-08_11.29.14_square.dat	3/8/2017 10:34 AM	DAT File	34 KB
	log_2017-03-08_11.35.59_circle.dat	3/8/2017 10:37 AM	DAT File	5 KB
	log_2017-03-08_11.38.22_square.dat	3/8/2017 10:40 AM	DAT File	10 KB
	log_2017-03-08_11.42.01_circle.dat	3/8/2017 10:43 AM	DAT File	5 KB
	log_2017-03-08_11.45.10_square.dat	3/8/2017 10:47 AM	DAT File	8 KB
	log_2017-03-08_11.47.59_circle.dat	3/8/2017 10:49 AM	DAT File	6 KB
	log_2017-03-08_11.51.29_square.dat	3/8/2017 10:51 AM	DAT File	1 KB

Figure D-4 - List of robot log DAT files for Test 1.

Log File Information	Explanation of Data Entry
Averaging 10 positions	Averaging multiple AGV position values to get a more stable value.
Sample spread: 1.6mm 1mm 0.0515662deg	Range of AGV position values (x, y, and angle) averaged to get reported AGV pose value
Vehicle position = 7155.56 11808.9 90.1583	AGV pose (X, Y, angle)
Starting circle	Pattern of fiducials
Pausing 0.1 seconds.	Pause to allow arm to settle after moving to initial position

Bisecting point...	Beginning bisect 1 of 2
x dim = 44.5	Length of chord in x direction
y dim = 43.4194	Length of chord in y direction
Pausing 0.1 seconds.	Pause to allow arm to settle after move to center of reflector
point moved from -6.93095 -768.802 to -17.681 -768.592	Initial position estimate and bisected center
distance = 10.752	Distance between initial position estimate and bisected center
Pausing 0.1 seconds.	Pause to let arm settle
Bisecting point...	Beginning bisect 2 of 2
x dim = 43	Length of chord in x direction
y dim = 42.0312	Length of chord in y direction
Pausing 0.1 seconds.	Pause to let arm settle
point moved from -1.98639 -464.069 to -13.9864 -466.554	Initial estimate of position and bisected center
distance = 12.2545	Distance between initial estimate and bisected center
running 2 iterations	Number of pattern iterations
Starting iteration 0	
65.2586 Moving to position[0] : [-168.222, -615.709, 328, 180, 0, 90]	
at position[0].	First fiducial position
66.6558 at [-168.263, -615.776, 328.089, -180, 0.014069, 90.0037]	
Running spiral search...	Didn't immediately detect fiducial, running search
66.6573 Running spiral search	These are the positions commanded as the search progresses. Each should be a 0.5 mm move.
66.6574 at [-167.763, -615.776, 328.089, -180, 0.014069, 90.0037]	EOAT [x, y, z, roll, pitch, yaw]
66.761 at [-168.263, -615.276, 328.089, -180, 0.014069, 90.0037]	
66.864 at [-168.763, -615.776, 328.089, -180, 0.014069, 90.0037]	
67.857 at [-168.263, -616.276, 328.089, -180, 0.014069, 90.0037]	
68.51 at [-167.263, -616.276, 328.089, -180, 0.014069, 90.0037]	
69.0611 at [-167.263, -615.276, 328.089, -180, 0.014069, 90.0037]	
69.6631 at [-167.763, -614.776, 328.089, -180, 0.014069, 90.0037]	
70.2571 at [-168.763, -614.776, 328.089, -180, 0.014069, 90.0037]	

70.8591 at [-169.263, -615.276, 328.089, -180, 0.014069, 90.0037]	
71.4611 at [-169.263, -616.276, 328.089, -180, 0.014069, 90.0037]	
72.0622 at [-168.763, -616.776, 328.089, -180, 0.014069, 90.0037]	
72.6652 at [-167.763, -616.776, 328.089, -180, 0.014069, 90.0037]	
73.2662 at [-166.763, -616.776, 328.089, -180, 0.014069, 90.0037]	
73.8682 at [-166.763, -615.776, 328.089, -180, 0.014069, 90.0037]	
74.2692 at [-166.763, -614.776, 328.089, -180, 0.014069, 90.0037]	
74.8713 at [-167.263, -614.276, 328.089, -180, 0.014069, 90.0037]	
75.4725 Search stopped successfully at offset [0.947901, 1.4491] after 8.80808 seconds and 33 steps.	
Completed iteration 0	
75.4751 Moving to position[1] : [137.503, -617.988, 328.089, -180, 0.0125922, 89.9948]	Move to second fiducial : EOAT [x, y, z, roll, pitch, yaw]
at position[1].	
77.0722 at [137.491, -617.909, 327.947, -179.995, 0.00257236, 89.9823]	(Repeat from above.)
Running spiral search...	
77.0734 Running spiral search	
77.0734 at [137.991, -617.909, 327.947, -179.995, 0.00257236, 89.9823]	
77.1764 at [137.491, -617.409, 327.947, -179.995, 0.00257236, 89.9823]	
77.8734 at [136.991, -617.909, 327.947, -179.995, 0.00257236, 89.9823]	

Figure D-5 – Robot .dat file example showing column labels and data.

Robot log files, suffixed with .csv, are listed in Figure D-6 and are automatically created and named by the robot control program with file creation date/time and pattern measured. The following columns show the date/time when the file was automatically closed, the file type, and the file size. An example of the log file data within a .csv log file is shown in Figure D-7a, b, c.

 data_2017-03-08_11.21.21_circle.csv	3/13/2017 12:05 PM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.24.34_square.csv	3/8/2017 10:25 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.26.46_circle.csv	3/8/2017 10:28 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.29.14_square.csv	3/8/2017 10:34 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.35.59_circle.csv	3/8/2017 10:37 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.38.22_square.csv	3/8/2017 10:40 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.42.01_circle.csv	3/8/2017 10:43 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.45.10_square.csv	3/8/2017 10:47 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.47.59_circle.csv	3/8/2017 10:49 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_11.51.29_square.csv	3/8/2017 10:51 AM	Microsoft Excel C...	1 KB

Figure D-6 - List of comma separated value robot log files for Test 1.

time	iter	marker	init_x	init_y	init_z	init_xrot	init_yrot	init_zrot	ok	time	steps	x	y	z	xrot	yrot	zrot	
8.959	0	-1	-6.85455	-768.837	328	180	0	90	1	27.8485	44	-17.681	-768.592	327.909	-179.999	-0.00476	89.996	
39.209	0	-2	-1.99696	-464.079	328	180	0	90	1	27.8012	44	-13.9864	-466.554	328.024	179.997	0.008815	89.9986	
67.972	0	0	-168.222	-615.709	328	180	0	90	78.187	1	8.80808	33	-167.274	-614.26	328.089	-180	0.012592	89.9948
78.19	0	1	137.503	-617.988	328.089	-180	0.012592	89.9948	113.058	1	33.2612	117	137.482	-620.425	327.953	-179.996	0.004393	89.9754
113.061	1	0	-167.265	-614.26	328.089	-180	0.012592	89.9948	114.665	1	0.000112	1	-167.318	-614.275	328.143	-179.999	0.021486	90.0102
114.667	1	1	-93.7501	-747.756	328.089	-180	0.012592	89.9948	119.067	1	3.20751	15	-93.1962	-746.887	328.142	179.999	0.026547	89.981
119.07	1	2	58.6187	-750.839	328.089	-180	0.012592	89.9948	120.269	1	0.000113	1	58.7203	-750.847	328.135	179.996	0.021242	89.9801
120.271	1	3	137.473	-620.425	328.089	-180	0.012592	89.9948	121.471	1	0.000101	1	137.48	-620.319	327.967	-179.991	-0.00579	89.9919
121.473	1	4	63.9577	-486.928	328.089	-180	0.012592	89.9948	122.674	1	0.000103	1	63.9949	-486.926	328.141	179.999	0.019586	89.9888
122.677	1	5	-88.4112	-483.846	328.089	-180	0.012592	89.9948	123.878	1	0.000203	1	-88.4738	-483.81	328.037	-180	-0.00159	90.0013

a

time	iter	marker	init_x	init_y	init_z	init_xrot	init_yrot	init_zrot	ok
8.959	0	-1	-6.85455	-768.837	328	180	0	90	1
39.209	0	-2	-1.99696	-464.079	328	180	0	90	1
67.972	0	0	-168.222	-615.709	328	180	0	90	78.187
78.19	0	1	137.503	-617.988	328.089	-180	0.012592	89.9948	113.058
113.061	1	0	-167.265	-614.26	328.089	-180	0.012592	89.9948	114.665
114.667	1	1	-93.7501	-747.756	328.089	-180	0.012592	89.9948	119.067
119.07	1	2	58.6187	-750.839	328.089	-180	0.012592	89.9948	120.269
120.271	1	3	137.473	-620.425	328.089	-180	0.012592	89.9948	121.471
121.473	1	4	63.9577	-486.928	328.089	-180	0.012592	89.9948	122.674
122.677	1	5	-88.4112	-483.846	328.089	-180	0.012592	89.9948	123.878

b

time	steps	x	y	z	xrot	yrot	zrot	
27.8485	44	-17.681	-768.592	327.909	-179.999	-0.00476	89.996	
27.8012	44	-13.9864	-466.554	328.024	179.997	0.008815	89.9986	
1	8.80808	33	-167.274	-614.26	328.089	-180	0.012592	89.9948
1	33.2612	117	137.482	-620.425	327.953	-179.996	0.004393	89.9754
1	0.000112	1	-167.318	-614.275	328.143	-179.999	0.021486	90.0102
1	3.20751	15	-93.1962	-746.887	328.142	179.999	0.026547	89.981
1	0.000113	1	58.7203	-750.847	328.135	179.996	0.021242	89.9801
1	0.000101	1	137.48	-620.319	327.967	-179.991	-0.00579	89.9919
1	0.000103	1	63.9949	-486.926	328.141	179.999	0.019586	89.9888
1	0.000203	1	-88.4738	-483.81	328.037	-180	-0.00159	90.0013

c

Figure D-7 - Robot .csv file example showing a) full data as shown in the file and larger b) left and c) right sides of the full data shown for readability.

Descriptions of the data entries for each column shown in Figure D-7 are shown in Figure D-8. The example data shown was collected when the robot was measured using the circle pattern.

Log File Header	Explanation of Header
time	Timestamp when data was collected
iter	Iteration of the test: 0 = prior to collecting the circle pattern data; 1 = collecting circle pattern fiducial data
marker	Bisect or fiducial marker: -1 & -2 = left and right, respectively, bisect registration reflectors; 0 & 1 iteration 0 markers = fiducials with variable diameter aperture; 0 through 6 iteration 1 markers = aperture and fixed diameter fiducials
init_x	Initial x robot position
init_y	Initial y robot position
init_z	Initial z robot position
init_xrot	Initial x robot rotation
init_yrot	Initial y robot rotation
init_zrot	Initial z robot rotation
ok	1 = when the search found the target; 0 = the search timed out; Any other number = the time when the search detected the target.
time	Time to complete the iteration. 1 = detection occurred at the robot move to the fiducial (i.e., no further search was required to detect the fiducial)
steps	Number of search moves to detect the edge of the bisect registration reflector or to detect the fiducial
x	Final x robot position
y	Final y robot position
z	Final z robot position
xrot	Final x robot rotation
yrot	Final y robot rotation
zrot	Final z robot rotation

Figure D-8 - Robot .csv log file headers and explanation of headers for each column of data.

### OTS log files

OTS log files are automatically created and labeled by the OTS Tracking program including (from left to right columns in Figure D-9): filename labeled with creation date/time, date/time when the file was processed, file type, and file size.

 Take 2017-03-08 11.20.45 AM\_Truncated 3/8/2017 12:36 PM Microsoft Excel Co... 284,827 KB

Figure D-9 - OTS log file for test 1.

## Appendix E - Test 2 data files

The three systems (AGV, manipulator, and OTS) have associated data collected during Test 2 where the test includes ten data logs - one for each AGV pose.

### AGV VDT - .bz2 files

VDT files are named by the operator and .bz2 (.bz2) suffixed files listed in Figure E-1 are labeled with (from left to right) the file data and time, the file close date, the file type, and the file size, respectively, across columns (see Appendices D and E). Information shown within these files is described in the NDC8 controller documents [12] for the VDT program. Within the file are text lines, which, among other line-leaders, shows 'set', 'laser', 'state', and 'usedrefl'. Epoch time immediately follows these line-leaders. The remaining information provided in this file contains status information of the vehicle. The user should consult NDC for further description.

 8Mar2017-1248test.bz2	3/8/2017 12:49 PM	BZ2 File	120 KB
 8Mar2017-1251test.bz2	3/8/2017 12:52 PM	BZ2 File	193 KB
 8Mar2017-1254test.bz2	3/8/2017 12:54 PM	BZ2 File	245 KB
 8Mar2017-1256test.bz2	3/8/2017 12:57 PM	BZ2 File	293 KB
 8Mar2017-1300test.bz2	3/8/2017 1:02 PM	BZ2 File	279 KB
 8Mar2017-1303test.bz2	3/8/2017 1:05 PM	BZ2 File	261 KB
 8Mar2017-1307test.bz2	3/8/2017 1:08 PM	BZ2 File	270 KB
 8Mar2017-1310test.bz2	3/8/2017 1:11 PM	BZ2 File	371 KB
 8Mar2017-1312test.bz2	3/8/2017 1:13 PM	BZ2 File	362 KB
 8Mar2017-1315test.bz2	3/8/2017 1:18 PM	BZ2 File	486 KB

Figure E-1 - List of BZ2 file types that include timestamp and laser navigation sensor data for test 2.

### AGV - .csv files

Figure E-2 shows a list of comma separated value files with (from left to right) .csv suffixes named by the operator and adding to the vehicle internet protocol address with \_file data and time, followed by the file close date, the file type, and the file size, respectively, across columns (see Appendices D and E). Information shown within these files is described in the NDC8 controller documents [12] for the VDT program. Within the file are headers on columns as shown in Figure E-2. The headers refer to the AGV X, Y, and angle with respect to 0° as shown in Figure 2 b. The NavLevel column refers to the navigation confidence level, 100 being the highest. The user should consult NDC for further description.

 192.168.160_position8Mar2017-1248.csv	3/8/2017 12:49 PM	Microsoft Excel Comma Separated Values File	20 KB
 192.168.160_position8Mar2017-1251.csv	3/8/2017 12:52 PM	Microsoft Excel Comma Separated Values File	44 KB
 192.168.160_position8Mar2017-1254.csv	3/8/2017 12:54 PM	Microsoft Excel Comma Separated Values File	61 KB
 192.168.160_position8Mar2017-1256.csv	3/8/2017 12:57 PM	Microsoft Excel Comma Separated Values File	85 KB
 192.168.160_position8Mar2017-1300.csv	3/8/2017 1:03 PM	Microsoft Excel Comma Separated Values File	72 KB
 192.168.160_position8Mar2017-1303.csv	3/8/2017 1:05 PM	Microsoft Excel Comma Separated Values File	66 KB
 192.168.160_position8Mar2017-1307.csv	3/8/2017 1:08 PM	Microsoft Excel Comma Separated Values File	60 KB
 192.168.160_position8Mar2017-1310.csv	3/8/2017 1:11 PM	Microsoft Excel Comma Separated Values File	92 KB
 192.168.160_position8Mar2017-1312.csv	3/8/2017 1:13 PM	Microsoft Excel Comma Separated Values File	90 KB
 192.168.160_position8Mar2017-1315.csv	3/8/2017 1:18 PM	Microsoft Excel Comma Separated Values File	134 KB

Figure E-2 - List of comma separated value files that include AGV pose for test 2.

### Robot log files

Robot log files are automatically created and labeled by the robot control program with file creation date/time and pattern measured. The second column shows the date/time when the file was automatically closed. Figure E-3 shows a list of DAT robot log files and Figure E-4 shows a list of comma separated value robot log files.

 log_2017-03-08_12.48.26_circle.dat	3/8/2017 11:50 AM	DAT File	9 KB
 log_2017-03-08_12.51.38_square.dat	3/8/2017 11:53 AM	DAT File	5 KB
 log_2017-03-08_12.53.51_circle.dat	3/8/2017 11:55 AM	DAT File	8 KB
 log_2017-03-08_12.56.18_square.dat	3/8/2017 12:01 PM	DAT File	28 KB
 log_2017-03-08_13.02.14_circle.dat	3/8/2017 12:03 PM	DAT File	5 KB
 log_2017-03-08_13.04.31_square.dat	3/8/2017 12:07 PM	DAT File	13 KB
 log_2017-03-08_13.08.06_circle.dat	3/8/2017 12:09 PM	DAT File	4 KB
 log_2017-03-08_13.11.07_square.dat	3/8/2017 12:12 PM	DAT File	6 KB
 log_2017-03-08_13.13.32_circle.dat	3/8/2017 12:14 PM	DAT File	6 KB
 log_2017-03-08_13.16.52_square.dat	3/8/2017 12:17 PM	DAT File	1 KB

Figure E-3 - List of DAT robot log files for test 2.

 data_2017-03-08_12.48.26_circle.csv	3/8/2017 11:50 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_12.51.38_square.csv	3/8/2017 11:53 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_12.53.51_circle.csv	3/8/2017 11:55 AM	Microsoft Excel C...	2 KB
 data_2017-03-08_12.56.18_square.csv	3/8/2017 12:01 PM	Microsoft Excel C...	2 KB
 data_2017-03-08_13.02.14_circle.csv	3/8/2017 12:03 PM	Microsoft Excel C...	2 KB
 data_2017-03-08_13.04.31_square.csv	3/8/2017 12:07 PM	Microsoft Excel C...	2 KB
 data_2017-03-08_13.08.06_circle.csv	3/8/2017 12:09 PM	Microsoft Excel C...	2 KB
 data_2017-03-08_13.11.07_square.csv	3/8/2017 12:12 PM	Microsoft Excel C...	2 KB
 data_2017-03-08_13.13.32_circle.csv	3/8/2017 12:14 PM	Microsoft Excel C...	2 KB
 data_2017-03-08_13.16.52_square.csv	3/8/2017 12:17 PM	Microsoft Excel C...	1 KB

Figure E-4 - List of comma separated value robot log files for test 2.

### OTS log files

OTS log files are automatically created and labeled by the OTS Tracking program including (from left to right columns in Figure E-5): filename labeled with creation date/time, date/time when the file was processed, file type, and file size.

 Take 2017-03-08 12.48.17 PM	3/8/2017 1:20 PM	Microsoft Excel Co...	14,138 KB
 Take 2017-03-08 12.51.28 PM	3/8/2017 1:20 PM	Microsoft Excel Co...	12,860 KB
 Take 2017-03-08 12.53.40 PM	3/8/2017 1:20 PM	Microsoft Excel Co...	16,117 KB
 Take 2017-03-08 12.56.13 PM	3/8/2017 1:21 PM	Microsoft Excel Co...	38,645 KB
 Take 2017-03-08 13.02.05 PM	3/8/2017 1:22 PM	Microsoft Excel Co...	12,943 KB
 Take 2017-03-08 13.04.25 PM	3/8/2017 1:23 PM	Microsoft Excel Co...	19,205 KB
 Take 2017-03-08 13.07.55 PM	3/8/2017 1:23 PM	Microsoft Excel Co...	11,278 KB
 Take 2017-03-08 13.10.55 PM	3/8/2017 1:24 PM	Microsoft Excel Co...	12,055 KB
 Take 2017-03-08 13.13.22 PM	3/8/2017 1:24 PM	Microsoft Excel Co...	11,921 KB
 Take 2017-03-08 13.16.37 PM	3/8/2017 1:24 PM	Microsoft Excel Co...	5,254 KB

Figure E-5 - List of OTS log files for test 2.

## Appendix F – Ground Truth data files

OTS log files are automatically created and labeled by the OTS Tracking program including (from left to right columns in Figures F-1 and F-2): filename labeled with creation date/time, date/time when the file was processed, file type, and file size.

### *OTS files of the RMMA*

 Take 2017-03-13 10.07.55 AM	3/13/2017 10:41 A...	Microsoft Excel Co...	2,788 KB
 Take 2017-03-13 10.08.43 AM	3/13/2017 10:41 A...	Microsoft Excel Co...	2,757 KB
 Take 2017-03-13 10.09.38 AM	3/13/2017 10:41 A...	Microsoft Excel Co...	2,722 KB

Figure F-1 – List of RMMA ground truth files

### *OTS file of the Static AGV and robot*

 Take 2017-03-15 09.58.32 AM	3/15/2017 9:59 AM	Microsoft Excel Co...	2,908 KB
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Figure F-2 - Static AGV and robot rigid body data capture file, including the robot base.

## Appendix G - Time Correspondence Across All Data Files

Robot File	AGV File	OTS File	Robot Time (s)	Marker	OTS Time	Robot Start Time	OTS Offset (s)	AGV Set (s)
data_2017-03-08_11.21.21_circle.csv	8Mar2017-1123test	Take 2017-03-08 11.20.45 AM.csv	1488990081	-1	1488990045	1488990089.959	44.959	1488990089.9447
data_2017-03-08_11.24.34_square.csv	8Mar2017-1126test	Take 2017-03-08 11.20.45 AM.csv	1488990274	-1	1488990045	1488990282.757	237.757	N/A
data_2017-03-08_11.26.46_circle.csv	8Mar2017-1128test	Take 2017-03-08 11.20.45 AM.csv	1488990406	-1	1488990045	1488990415.196	370.196	N/A
data_2017-03-08_11.29.14_square.csv	8Mar2017-1135test	Take 2017-03-08 11.20.45 AM.csv	1488990554	-1	1488990045	1488990563.099	518.099	1488990089.9447
data_2017-03-08_11.35.59_circle.csv	8Mar2017-1137test	Take 2017-03-08 11.20.45 AM.csv	1488990959	-1	1488990045	1488990968.192	923.192	1488990089.9447
data_2017-03-08_11.38.22_square.csv	8Mar2017-1140test	Take 2017-03-08 11.20.45 AM.csv	1488991102	-1	1488990045	1488991112.502	1067.502	1488990089.9447
data_2017-03-08_11.42.01_circle.csv	8Mar2017-1143test	Take 2017-03-08 11.20.45 AM.csv	1488991321	-1	1488990045	1488991330.411	1285.411	1488990089.9447
data_2017-03-08_11.45.10_square.csv	8Mar2017-1147test	Take 2017-03-08 11.20.45 AM.csv	1488991510	-1	1488990045	1488991519.689	1474.689	1488990089.9447
data_2017-03-08_11.47.59_circle.csv	8Mar2017-1149test	Take 2017-03-08 11.20.45 AM.csv	1488991679	-1	1488990045	1488991690.795	1645.795	1488990089.9447
data_2017-03-08_11.51.29_square.csv	8Mar2017-1152test	Take 2017-03-08 11.20.45 AM.csv	1488991889	-1	1488990045	1488991898.177	1853.177	1488990089.9447
data_2017-03-08_12.48.26_circle.csv	8Mar2017-1248test	Take 2017-03-08 12.48.17 PM.csv	1488995306	-1	1488995297	1488995315.293	18.293	
data_2017-03-08_12.51.38_square.csv	8Mar2017-1251test	Take 2017-03-08 12.51.28 PM.csv	1488995498	-1	1488995488	1488995506.910	18.910	
data_2017-03-08_12.53.51_circle.csv	8Mar2017-1254test	Take 2017-03-08 12.53.40 PM.csv	1488995631	-1	1488995620	1488995639.892	19.892	
data_2017-03-08_12.56.18_square.csv	8Mar2017-1256test	Take 2017-03-08 12.56.13 PM.csv	1488995778	-1	1488995773	1488995786.391	13.391	
data_2017-03-08_13.02.14_circle.csv	8Mar2017-100test	Take 2017-03-08 01.02.05 PM.csv	1488996134	-1	1488996125	1488996143.279	18.279	
data_2017-03-08_13.04.31_square.csv	8Mar2017-103test	Take 2017-03-08 01.04.25 PM.csv	1488996271	-1	1488996265	1488996281.909	16.909	
data_2017-03-08_13.08.06_circle.csv	8Mar2017-107test	Take 2017-03-08 01.07.55 PM.csv	1488996486	-1	1488996475	1488996495.284	20.284	
data_2017-03-08_13.11.07_square.csv	8Mar2017-110test	Take 2017-03-08 01.10.55 PM.csv	1488996667	-1	1488996655	1488996676.326	21.326	
data_2017-03-08_13.13.32_circle.csv	8Mar2017-112test	Take 2017-03-08 01.13.22 PM.csv	1488996812	-1	1488996802	1488996823.912	21.912	
data_2017-03-08_13.16.52_square.csv	8Mar2017-115test	Take 2017-03-08 01.16.37 PM.csv	1488997012	-1	1488996997	1488997021.482	24.482	

Figure G-1 - Time Correspondence Across All Data Files