COMPARISON OF REGISTRATION METHODS FOR MOBILE MANIPULATORS

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Mobile manipulators can be effective, efficient, and flexible for automation on the factory floor but will need safety and performance standards for wide adoption. This paper looks at a specific area of performance standards [1] for docking and workpiece registration, with the intent of evaluating how quickly, repeatably, and accurately a mobile manipulator end effector can be aligned with a known physical target to facilitate peg-in-hole insertion tasks. To evaluate mobile manipulator docking, we conducted experiments with an automated guided vehicle (AGV)-mounted arm in a laboratory space equipped with an extensive optical tracking system and a standardized test piece (artifact) simulating an industrial assembly. We experimented with different strategies and sensors for registration and report on these approaches.

1. Introduction

Mobile manipulators (i.e., robot arms onboard mobile robotic bases) hold promise in industrial applications* for flexible and reconfigurable automation and are now being marketed at industrial material handling exhibitions as useful tools [2, 3]. Typical applications currently being considered for mobile manipulators are: i) unloading trucks [4], ii) bagged-goods (e.g., dog food bags) handling, iii) conveyer loading/unloading, iv) picking canned and boxed goods from shelves in supermarkets, and v) delivering, placing, and manipulating semiconductor wafer pods within wafer fabrication facilities [5]. The first four applications have looser constraints on the mobile manipulator pose (position and orientation) and do not require precise alignment with the workspace. Vision is integrated into these

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systems to position a vacuum gripper to pick up the box, bag, or metal can in the manipulator's workspace. However, the last application, wafer pod manipulation, and other assembly-type operations, (e.g., peg-in-hole), require much tighter tolerances on positioning from the mobile manipulator.

The National Institute of Standards and Technology (NIST) Robotic Systems for Smart Manufacturing Program [6] is currently researching, among other topics, both automatic guided vehicle (AGV)/mobile manipulator performance and vision performance standards [7]. The program develops and deploys advances in measurement science by improving performances of robotic systems to achieve dynamic production for assembly-centric manufacturing.

Assembly operations performed by a mobile manipulator require accurate registration to the workpiece. Registration refers to the process of measuring and mapping the feedback from one system (e.g., mobile manipulator) to the model of another (e.g., artifact), correcting for differences in resolution, scale, direction, and timing. [8] 'Calibration' is instrument (e.g., camera) adjustment or output correlation of the instrument readings with its known accuracy. These two terms are sometimes interchanged in the literature. Various registration methods have been researched, including:

- Quick Reference (QR) codes [9] combined with calibrated vision [10] - tracking error: under 20 mm, maximum errors: 45 mm at the largest camera-target distance.
- QR codes for mobile robot registration and end effector error [11] - maximum positional repeatability: 1.1 mm (one point) to 4.0 mm (multiple points).
- High-precision calibration - average errors based on the Tsai hand-eye calibration combined with a high-speed calibration - average errors: ± 0.1 mm and ± 0.1° - based on a combination of laser triangulation and image processing [12].
- Constrained manipulator endpoint to a single contact point while executing manipulator motion where manipulator joint angles are read to develop a calibration model [13].
- Touch probing using peg-in-hole and particle filter solutions [14, 15].

This paper describes three alternative methods for registering mobile manipulators to a workpiece. The first builds upon [11] from Aalborg University where QR codes were used in combination with vision processing. The second and third use 'fine' and 'bisect' search methods using a laser retroreflector to determine fiducial location with respect to the mobile manipulator. Experiments and experimental results are then described for each of these calibration alternatives.

2. Registration Methods

Registration of a mobile manipulator with a workpiece can be performed using a number of techniques, as briefly described in the introduction. If the accuracy requirements of the task are low, then simple navigation of the base to the desired pose may be adequate. However, we assume the manipulator accuracy requirements are greater than the base's accuracy and more information is required for a suitable transformation between the manipulator and workpiece coordinate systems. The following subsections describe three non-contact methods tested at NIST for registering a mobile manipulator to a workpiece - detection of QR codes using vision and two search methods using a laser retroreflector and reflective fiducials. Future research may combine the registration methods by using a laser spot detection method as described in [17 and 18].

2.1. *Visual Fiducials*

Visual fiducial systems allow for six degrees-of-freedom (6DOF) positional tracking of fiducial targets, or tags. Since these systems are well-developed, and can be implemented with open source software, inexpensive cameras, and virtually free printed targets, they have a number of advantages for use in robotics research and testing procedures for industrial robot evaluation and validation.

In this study, we reviewed fiducial systems commonly labeled as AR, or augmented reality. These systems include: ARTag, April tags, ARToolKit, and ALVAR [19]. We conducted experiments using the "A software Library for creating Virtual and Augmented Reality" or ALVAR version because of its integration with Robot Operating System (ROS). Integration with ROS allowed the use of ROS preprocessing, visualization, and message-passing facilities. Like the other systems, ALVAR uses rectangular black and white targets with a black outer square for location, and an internal matrix of squares that codes the identity of the target. Other fiducial targets used include standard camera calibration targets (i.e., checkerboards), QR codes, and application-specific targets.

ALVAR and similar systems have advantages in flexibility and cost over other 6DOF tracking systems that may require more expensive and extensive installations. We need to understand robustness, working range and orientations, accuracy, and response time for ALVAR use in testing procedures and standards. These needs do not have universal solutions since the system performance depends on implementation details. Robustness depends on occlusion and camera details; working range depends on target size, camera resolution, and camera focal length; response time depends on camera frame rate, resolution, and computer processing unit speed; and ultimate accuracy depends on all these factors, including target motion speed relative to frame rate.

2.2. *Fine and Bisect Search Methods*

A 'fine search' method was described in [18 and 20] as it evolved; it is included in this paper to focus on the registration aspect. The method uses a laser retroreflector detector carried by the manipulator to detect reflective fiducials attached to the reconfigurable mobile manipulator apparatus (RMMA). The RMMA is a metal plate with fiducial mount points at precise locations. The fiducial is a collimated reflector on a base that attaches to the RMMA.

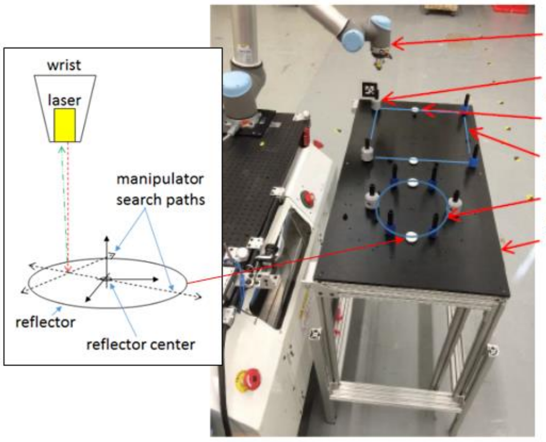
A computer aided design model of paths and docking points was used by a vehicle control program to move the AGV from one docking pose to another near the RMMA. The vehicle control program positioned the vehicle at various orientations with respect to the RMMA and the manipulator program corrected for vehicle pose allowing it to register with pre-taught targets using fine and 'bisect' search methods described here.

Two pairs of fiducials were positioned at 1) two corners of a 457 mm square pattern of four fiducials and 2) at opposing points along a 305 mm diameter circle pattern of eight fiducials. The fine search originally used a circular search [18] and was tested only on the square pattern. However, it was quickly discovered that fiducial edges were detected causing a potential for the registration to be skewed and increased search steps caused the laser to pass over the fiducial without detecting it.

In [20], a square fine search method was tested. The 'square search' is a sequence of points in a spiral pattern on a square grid. Each step was 0.5 mm, where the smaller step size and the use of 1 mm and 2 mm fiducials minimized previous issues. Figure 1 (a) shows a graphic of the square search method and Figure 1 (b) shows the RMMA (black table). The gray housings each include a camera iris that is used to change the fiducial detection diameter. This method works relatively well for aligning the mobile manipulator with the workpiece. However, errors in the mobile base pose measurement can cause a lengthy initial registration search.

For the bisect method, the detection of two, relatively large (42 mm diameter) reflectors was performed before the fine search method. All reflectors were the same type micro-reflector. After detecting the large reflector, a bisecting search pattern determined the center of the reflector with 0.5 mm steps along relative X- and Y- axes to the manipulator base.

The reflector diameters were large enough that no initial search was required to locate them, despite the measured maximum 13.3 mm error in the mobile base pose. Figure 1 (a) shows a concept drawing of the bisect method and Figure 1 (b) shows the mobile manipulator positioned next to the RMMA, the RMMA square



a b

Figure 1 (a) Bisection search concept, (b) the mobile manipulator positioned next to the RMMA, the RMMA square and circle patterns, and the large reflectors within each pattern.

and circle patterns, and the large reflectors within each pattern. Once the center of the large reflector was located, the manipulator began a fine search of the 2 mm fiducials using the square search method.

3. Experiments and Results

3.1. *Visual Fiducials*

To evaluate and validate the use of visual fiducial targets, we conducted two sets of experiments using the ALVAR implementation and a 17 mm machine vision camera with a resolution of 1296 pixels x 964 pixels and a fixed 4.5 mm focal length lens.

The first set of experiments looked at the static repeatability of the ALVAR system when the target was moved to static positions by a pan-tilt mechanism. A 200 mm x 200 mm target was mounted on a pan-tilt unit. For the experiments, the pan-tilt was moved systematically throughout its range and allowed to settle before static measurements. The camera viewed the target from a separation distance of 800 mm to 1000 mm as the target was systematically moved to 26 positions of differing tilt and pan. For each position, 306 measurements were taken over 30 s. We calculated the root-mean-square deviation (RMSD) of the measurements to see if ALVAR gave consistent results. Repeatable measurements indicate systemic biases can be corrected by calibration.

We found that the maximum difference from the mean in any one position in any dimension was 0.8 mm (along the Z-axis), and the maximum angular error (in angle axis representation) was 0.18°. Each individual measurement was single shot with no averaging or filtering across measurements. From initial results of sub-millimeter repeatability in position, and fractional angular repeatability, we judge that the basic capabilities of ALVAR are adequate as a subsystem in workpiece registration.

In the second set of visual fiducial experiments, we integrated ALVAR with the systems on an AGV docking with the RMMA. Spacing between the RMMA square and circle patterns was 508 mm. The camera, which was onboard the AGV, repeatedly measured the AGV positioning at the square and circle patterns, and communicated the position to the robot controller.

3.2. *Fine and Bisect Search methods*

The RMMA was set up as shown in Figure 1 (b) for the circle pattern with 1 mm diameter registration fiducials. The circle used 1 mm diameter fiducials and the square used 3 mm diameter fiducials. The 3mm fiducials were hypothesized to achieve faster registration although this was not the case. The AGV control program moved the AGV from a home position away from the RMMA to the first pose pre-determined by the AGV control program. Upon completion of the pattern detection for the first pose, the AGV moved to the second pose, and so forth. Only the first six vehicle poses were completed for the 'fine search' method due to the long registration time. The 3 mm fiducial had the highest average number of search steps at 869 with 1921 maximum steps and 1740 s causing an average search time of 360 s with a maximum of 893 s. The root-mean-square deviation (RMSD) from the mean was 776 steps (403 s).

The 'bisect search' method experiment consisted of locating the mobile manipulator in the same manner as in the fine search method. The RMMA was set up as shown in Figure 1 (b) with the circle and square patterns both using 42 mm diameter registration fiducials. After setup, the experiment was run for all 10 different mobile manipulator poses and repeated five times for a total of 50 poses. The results shown in Table 1 include only the detection of the first 2 mm reflector for each pattern after bisect registration. The bottom of Table 1 shows a summary of all tests averaged over the 50 measurements and includes the average number of steps for the 2 mm reflectors and shows the RMSD from the mean.

Table 1: Mobile manipulator registering to the RMMA using the bisect search method.

AGV Position Number	Pose Angle	Pattern	Average num. of search steps to register	Total bisect + fine search time to register (s)
1	90°	circle	0	86
2	315°	square	6	89
3	0°	circle	0	86
4	0°	square	0	86
5	45°	circle	0	86
6	90°	square	0	86
7	135°	circle	0	86
8	225°	square	0	86
9	270°	circle	0	86
10	270°	square	12	92

Mean Search Steps/Time (s)	1.8 / 0.8	RMSD Search Steps/Time (s)	3.8 / 1.8

4. Conclusions

Experimental results reported for visual fiducials are consistent with the various registration methods from the literature. Under optimal conditions, we estimated repeatability of a visual fiducial at under 1 mm and 0.2° from a single image. From initial results we expect that basic capabilities of ALVAR are adequate as a subsystem in workpiece registration. The second ALVAR experiment provided successful integration with the mobile manipulator. Given other elements in the system, including calibration of camera-to-base, and base-to-arm, and the propagation of error, we would expect total error for the system to be higher.

The fine search method experiments resulted in a high number of search steps and time (average steps: 776, average/maximum time: 360 s/893 s) to register the mobile manipulator. When using the bisect method prior to the fine search, the total bisect plus fine search steps/time was a maximum of 184 steps/86 s or nearly 90% less time than using only the fine search method. Larger bisect search steps, among many other improvements, could be used although would increase the number of registration search steps on the 1 mm or 2 mm fiducials to a potentially unknown amount. Future registration tests will combine the visual fiducial with the search methods to minimize the search time.

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