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Dynamic Metrology Performance Measurement of a Six Degrees-of-Freedom Tracking System Used in Smart Manufacturing

Citation

ABSTRACT
Multi-camera motion capture systems are commercially available and typically are used in the entertainment industry to track human motions for video gaming and movies. These 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 motion capture system must be at least ten times better than a given system under test. This chapter creates an innovate artifact and test method to measure the accuracy of a given motion capture system. These measurements will then be used to assess the performance of the motion capture system and validate that it can be used as ground truth. The motion capture system will then serve 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 that utilize robot arms and hands.
Keywords
dynamic, performance measurement, robot, tracking system

Introduction

Numerous optical tracking systems, including motion capture systems, have been developed in research centers and commercialized. Over the past several years, these systems have gained enormous market share [1] in the entertainment industry, neuroscience, biomechanics, flight and medical training, and in simulations [2–8]. As a result, there have been several advances in improving the accuracy of such human motion caption systems as documented in two surveys. The first [2] analyzes research up to the year 2000; the second [3] analyzes research from 2000 to 2006 and the overview of a history of motion capture systems in 2013 [4]. These surveys cite more than 350 articles with topics such as novel methodologies for automatic initialization, reliable tracking and pose estimation in natural scenes, and movement recognition.

Tracking systems also have been used in the field of robotics [5–10]. Specific applications have included programming by demonstration, imitation, tele-operation, activity or context recognition, and humanoid designs. This chapter presents yet another use for these systems in robotics: to provide ground truth for assessing the performance of robot and robot vehicle motion. Specifically, this chapter focuses on a test method to validate the accuracy of a tracking system within the work volume of a given robotic system under test by using a novel metrology bar artifact. This method will ensure that the tracking system is capable of providing the necessary measurement uncertainty to be used as ground truth by guaranteeing the tracking system is at least an order of magnitude better than the expected performance of the given robotic system under test.

As the field of robotics advances and expands to new application spaces, such as assembly, performance measures are needed to fully understand robot capabilities. Tracking systems that can provide ground truth measurement for dynamic robots are critical for supporting robot performance evaluation. The National Institute of Standards and Technology (NIST) conducts research on the safety and performance of robot arms and hands, automatic guided vehicles (AGVs), and integrated systems such as those comprised of arm, hand, and perception components, as well as collaborating robots, in support of standards development. The International Organization for Standards (ISO) 9283:1998 [11] and the American National Standards Institute/Robotic Industries Association (ANSI/RIA) 15.05 [12] are available standards used to assess the performance of an industrial robotic arm as an individual unit. The recently formed ASTM Committee F45 on Driverless Automatic Industrial Vehicles [13] will be used to assess the performance of AGVs.

It is predicted that future smart manufacturing systems will include robot arms performing high-tolerance assembly tasks, AGVs making fine adjustment of docking
positions, and complex coordination of mobile manipulators (i.e., robot arms mounted on mobile bases) that offer the combination of high mobility and manipulability. For example, an ideal utilization of the kinematic redundancy in the mobile manipulator is to perform assembly tasks on a moving vehicle body \[6,7,14\]. It is also predicted that next-generation robot systems will be more flexible with multiple degree-of-freedom “robotic hands” and will provide levels of versatility and control closer to that of a human. This flexibility will enable much more rapid retasking, making robotics a viable alternative to support small- and medium-sized manufacturers. As such, ground truth measurement systems that can capture system-level robot performance will aid researchers in evaluating robot designs, developments, capabilities, and standard task (pose and motion) performance.

This chapter discusses a test method for six degree-of-freedom (6DOF) tracking systems and a new design for relative pose, error/uncertainty artifacts used to compare systems under test. Experiments using the artifacts in two test spaces (i.e., a robot arm space and a larger space used for AGV testing) and using two different tracking systems are then discussed. Data analysis and results follow.

**Test Method for Tracking Systems**

We present a test method to validate tracking system measurement errors/uncertainties (standard deviation). Currently, a method from the manufacturer provides unknown system uncertainties within the operational space of a robotic work volume. One of the goals of the method is to provide assurance that measurements made by the tracking system are at least an order of magnitude better than the expected performance of a given robotic system under test. If measures do not meet these expectations, then the tracking system must be reconfigured and recalibrated to satisfy the intended benchmarking requirements in order to be used as ground truth.

The test method looks for errors in the fixed configuration of two marker clusters fixed on opposing ends of a metrology bar, called the artifact, in terms of position and angular errors as measured by the tracking system. Two measurement types are performed within the test method. The dynamic measure reports errors as the artifact is moved about the entire measurement space.

This test method was implemented in two NIST robot testbeds, each retrofitted with a passive marker optical tracking system for ground truth measures. The first implementation is for an AGV with an onboard robot arm (mobile manipulator) to develop performance measures for AGVs and mobile manipulation. Safety and performance test method developments are frequently reported to the AGV industry and are used as reference to propose revisions to the ANSI/Industrial Truck Standards Development Foundation B56.5 AGV safety standard \[15\] and the ASTM Committee F45 AGV performance standard. The second is for a tabletop robotic work cell being used to develop performance measures for perception, grasping, and assembly.
Two metrology bars, 620 mm and 320 mm in length, were used, each having five reflective markers attached to prongs on each end (see Fig. 1). The metrology bars were used to measure the tracking system measurement uncertainties within the vehicle lab and robotic work cell, respectively. The metrology bar markers on each end form two perpendicular planes to the bar that define the bar length. The bar length was shortened for the robotic work cell in an attempt to maximize metrology bar movement. Carbon fiber bars were chosen based on a combination of cost and reduction of the effects of thermal expansion on the position uncertainty. The latter is defined by using the standard metrics that were developed in ASTM E2919, Standard Test Method for Evaluating the Performance of Systems that Measure Static, Six Degrees of Freedom (6DOF) Pose [16].

Actual positions and motions were only approximated because the metrology bar was randomly held and moved by a person throughout the test spaces. For the vehicle lab/static case experiments, the 620-mm metrology bar initially was placed in the center of the space, approximately 1.5 m above the floor. For the vehicle lab/dynamic case experiments, the bar was carried by a researcher at a height of approximately 2.5 m above the floor (i.e., overhead) and walked in a raster scan pattern throughout the space to maximize coverage. Note that the approximate height of the AGV navigation sensor is 2.1 m above the floor. Similarly, for the robotic work cell/static case experiments, the 320-mm bar was placed approximately 0.2 m above a table. For the robotic work cell/dynamic case experiments, the bar was moved by a researcher throughout the volume created by the camera field of views and was reachable by a robot arm to be mounted within the space. Velocities of bar

![FIG. 1](image) NIST metrology bars, (a) 620 mm long and (b) 320 mm long, used to measure static and dynamic ground truth system uncertainty. The bars are sitting on a holder that is on the NIST reconfigurable mobile manipulator apparatus.
motion also were not measured and are approximated at a slow walk, perhaps 0.5 m/s, for the vehicle lab and between 0.5 m/s and 1 m/s for the robotic work cell. Future measurements of the vehicle lab will include programmed vehicle movement of the metrology bar throughout the space.

Measurement of a Tracking System

This section describes a test method that provides a set of statistically based performance metrics and test procedures to quantitatively compute the performance of a given 6DOF optical tracking measurement system. Specifically, the test method looks for variations in the measurements from an optical tracking system of two marker sets rigidly attached to opposing ends of a metrology bar as shown in Fig. 1. These variations are then decomposed into uncertainties (position and angle errors) as outlined here. Two measurement types, static and dynamic, are performed within this test method. The static measurement reports system errors as the artifact is statically placed in different locations within the entire workspace, and the dynamic measurement reports system errors as the artifact is moved about the entire workspace. The resulting system errors are used to calculate measurement statistics outlined as follows.

**POSITION AND ANGLE ERRORS/UNCERTAINTY**

The position and angle errors are defined in the following way: For each instance of time $t$, the optical tracking system outputs the left object pose and the right object pose of the metrology artifact. The pose error is then defined as the difference between the left object pose and the right object pose at time $t$ and represented as the homogeneous matrix:

$$
\hat{H}(t) = \begin{bmatrix} \hat{R}(t) & \hat{T}(t) \\ 0 & 1 \end{bmatrix}
$$

where $\hat{R}(t)$ is a 3 by 3 rotation matrix representing the orientation of the object at time $t$ and $\hat{T}(t)$ is a 3 by 1 translation vector representing the position of the object at time $t$. The ground truth of the relative pose is assumed to be known and measured by a coordinate measuring machine and represented as the homogeneous matrix:

$$
H(t) = \begin{bmatrix} R(t) & T(t) \\ 0 & 1 \end{bmatrix}
$$

where $R(t)$ is the 3 by 3 rotation matrix representing the known orientation of the relative pose and $T(t)$ is the 3 by 1 translation vector representing the known position of the relative pose. The ground truth relative pose is measured by a coordinate measurement machine.

The position error, $e_T$, can then be computed as follows:

$$
e_T = \| T \| - \| \hat{T}(t) \| = \text{Length of } T - \text{Length of } \hat{T}
$$
The rotation error matrix can be computed as follows:

$$\Delta R = R^{-1} \ast \dot{R}(t) = R^T \ast \dot{R}(t)$$  \hspace{1cm} (4)

The angle error of $\Delta R$ can then be computed as [12]:

$$0 \leq e_{\text{RelAngle},t} = \cos^{-1}\left(\frac{\text{trace}(\Delta R(t)) - 1}{2}\right) < \pi$$  \hspace{1cm} (5)

**UNCERTAINTY STATISTICS**

The error statistics from the position error and angle error can be calculated as:

1. Computing the average error:

$$\bar{e} = \frac{\sum_{k=1}^{N} e_k}{N}$$  \hspace{1cm} (6)

2. Computing the standard deviation of the errors:

$$\sigma = \sqrt{\frac{\sum_{k=1}^{N} (e_k - \bar{e})^2}{N - 1}}$$  \hspace{1cm} (7)

3. Computing the maximum of the errors:

$$e_{\text{max}} = \max(e_1, e_2, \ldots, e_N)$$  \hspace{1cm} (8)

Here, $N$ is the number of poses collected.

**Experimental Spaces and Equipment**

**VEHICLE LAB AND VEHICLE**

A relatively large, 9 m by 22 m lab at NIST is used to research the safety and performance of AGVs (see Fig. 2). An AGV approximately 3 m wide by 8 m long by 2 m high and weighing approximately 1137 kg is moved along paths or segments and is positioned at specified points for docking purposes.

Performance measurements were made of vehicle uncertainty (e.g., segment deviation, etc.) when navigating along segments and when stopped at points (e.g., docking repeatability, docking accuracy).

**VEHICLE LAB MOTION CAPTURE SYSTEM**

A multi-camera ground truth (GT) system\(^5\) referred to as “GT1” was set up in the AGV lab. Twelve cameras were mounted to the four lab walls at a height of 4.3 m.

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\(^5\)Disclaimer: 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.
above the floor and used to view the area where the experiments are performed. Cameras have 4.1 megapixel resolution, 120 frames-per-second, and 51° field of view with focus and aperture-opening adjustments. Eighteen markers are grouped into a rigid body, as shown in Fig. 2, and tracked by the GT1 system.

ROBOT TEST SPACE AND ROBOTS
In comparison, a relatively small 2 m by 2 m robot test space (see Fig. 3) at NIST is used to research the safety and performance of collaborative robot arms and advanced, multi-fingered robotic hands. Findings are frequently reported to the industrial robot industry and used as a reference to propose revisions to the RIA 15.06 [17], ISO 10218-1, -2 [11] safety standards subcommittees, and to the robotic hands research community through NIST’s robot hand performance test portal [8].
ROBOT TEST SPACE MOTION CAPTURE SYSTEM
A multi-camera GT system referred to as “GT2” was set up in the robot test lab. Fig. 3 shows the robot test space, the GT2 cameras mounted to a frame above the space, and the 320-mm metrology bar (centered). Eight cameras were mounted to the robot test space frame approximately 1.5 m above the robot base mount surface and view the volume where the robotic experiments are performed. Cameras have 1 megapixel resolution, 120 frames per second, and 4 mm–12 mm zoom with zoom, focus, and aperture-opening adjustments.

Results
We found no published nominal uncertainties for the GT1 tracking system from the manufacturer because they describe the system uncertainty as “sub-millimeter.” The GT2 system manufacturer published the uncertainties as 0.5 mm or more of translation and 0.5° of rotation in a 4 m by 4 m volume using 9-mm diameter markers. The descriptions also do not include procedures for ensuring traceability of measurement uncertainty.

We tested both tracking systems using the NIST developed test method described earlier. We tested the tracking systems in their calibrated states. We provide both the GT1 and GT2 tracking distance and angle uncertainties in the following subsections.

VEHICLE LAB MEASUREMENTS
The GT1 system was first calibrated by mainly adjusting the focus on the cameras in the system. After calibration, the system was measured using the 620-mm metrology bar over an approximate 10 m in width by 8 m in length lab center workspace where most of the AGV testing is performed. The metrology bar was placed at the workspace center. Analysis shows average measurement uncertainty of the static metrology bar length was $\sigma = 0.02$ mm, and for the static angle, it was $\sigma = 0.05°$. In this experiment, $N$ (number of poses) is greater than 30,000 points. The metrology bar was then moved throughout the workspace. The dynamic metrology bar position uncertainty was calculated as $\sigma = 0.26$ mm, and the dynamic angle uncertainty was calculated as $\sigma = 0.20°$. Fig. 4a shows the dynamic bar length uncertainty, and Fig. 4b shows the dynamic angle uncertainty. Each block in the figure graphs uses a natural-neighbor interpolation to obtain the value.

ROBOT SPACE MEASUREMENTS
In contrast to the GT1 system, the GT2 system used a 320-mm-long metrology bar. Similar to the GT1 system, calibration consisted of adjusting the zoom, focus, and aperture of the cameras in the system.

The metrology bar was placed at the workspace center. Analysis shows average measurement uncertainty over three runs of the static metrology bar length was $\sigma = 0.004$ mm and, for the static angle, $\sigma = 0.006°$. The bar was then moved throughout the entire robot work volume. The dynamic position uncertainty was $\sigma = 0.60$ mm, and the dynamic angle uncertainty was $\sigma = 0.29°$. Fig. 5a shows the
FIG. 4  GTI data captured from the 620-mm metrology bar (a) length and (b) angle within the AGV lab.
FIG. 5  GT2 data captured of the 320-mm metrology bar (a) length and (b) angle within the robot space.

Distance errors (mm) at each point

Angle errors (degrees) at each point
metrology bar length dynamic uncertainty data, and Fig. 5b shows the bar angle dynamic uncertainty data.

Interestingly, we noticed a degradation of uncertainty in the robot space on consecutive dynamic test runs. This behavior is currently being investigated.

MOBILE MANIPULATOR MEASUREMENTS
A recent application for the calibrated GT1 system was to measure mobile manipulator performance of a robot arm installed onboard the AGV as shown in Fig. 6. A NIST reconfigurable mobile manipulator artifact (RMMA) was developed as a possible concept for comparing ground truth technologies such as tracking systems,

FIG. 6 Mobile manipulator being tested using the NIST RMMA.

FIG. 7 Screen captures from the GT1 system showing the AGV, manipulator, and the RMMA rigid bodies formed from markers on each device.
FIG. 8 GT data points relative to the GT system origin (in mm) of (a) the stationary AGV and (b) the RMMA movement over time (in minutes), shown by the varying colors, while the manipulator moves.
laser trackers, and so on. The RMMA is further detailed in Bostelman, Hong, and Cheok [6]. Experiment 1 included placing a mobile manipulator next to the RMMA and then moving the manipulator to various points on the RMMA as shown in Fig. 6. Results showed the average position uncertainty (calibration) between the RMMA and AGV to be $x = 0.07$ mm and $y = 0.02$ mm, both being near the static measurement range of the GT1 system (i.e., $\sigma = 0.02$ mm and $\sigma = 0.05^\circ$).

However, further experiments were performed and suggested surprising results. Experiment 2 measured the uncertainty of the static AGV when the manipulator uses noncontact positioning above the RMMA points. The AGV, RMMA, and manipulator were measured using a single ground truth system, GT1, resulting in motion tracking and relative measurements of the components. Experiment 3 measured the static RMMA movement during the noncontact Experiments 1 and 2. A screenshot of the rigid bodies formed in the GT1 system is shown in Fig. 7, and uncertainty results are shown in Fig. 8.

Experiments 2 and 3 proved that both the AGV and the RMMA were moving even while the AGV was stopped while the manipulator was moving. This occurred despite the fact that the AGV weight was nearly 40 times that of the manipulator, with tests conducted on the ground level with concrete flooring. Results show that position uncertainty spans from approximately $0.15$ mm in $x$ and $0.25$ mm in $y$ for the AGV to $0.5$ mm in $x$ and $0.6$ mm in $y$ for the RMMA. These results showed that the ground truth optical tracking measurement system used in the mobile manipulator experiments was accurate enough to detect motion of a static table (RMMA) and a relatively heavy vehicle due to onboard lightweight manipulator motion. When these uncertainties are combined, maximum uncertainties can be $\sigma = 0.52$ mm in $x$ and $\sigma = 0.65$ mm in $y$, which could induce enough position offset of the manipulator to affect the results of manufacturing operations, such as a relatively high-tolerance assembly operation.

Conclusions

Multi-camera motion capture systems are now commercially available, and their application as ground truth systems for robots and vehicles is on the horizon. This chapter describes a test method and metrics for evaluating and validating tracking system calibration within the operational space of a robotic work volume. The goal of the method is to provide assurance that measurements made by the tracking system are at least an order of magnitude better than the expected performance of the robotic system under test. The test method used is exemplified on two different motion capture systems each in a different size workspace. An example application of one system was used to measure the performance of an AGV with an onboard robot arm (mobile manipulator). Experiments on a mobile manipulator showed that tracking systems in large spaces can even measure small wall, floor, and equipment movements despite their static conditions. This test method and metrics can be used to measure and analyze the performance of any
tracking system that computes the pose of an object while the object is moving. It also helps provide the performance of optical tracking systems to improve optical tracking systems.

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References


