euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024
www.euspen.eu

A comparative study of network sensor and laser tracker in establishing digital twin for robotic manufacturing

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Abstract

This study employs network sensors and laser trackers to track a robot's end-effector and assess the performance of network sensors through comparative experimentation. The establishment of a digital twin for robots using network sensors contributes to enhancing the robot's global accuracy. The novel network sensor, IONA, is capable of providing real-time 6DOF data to the robot, thus assisting in improving the robot's global accuracy. To evaluate the tracking capabilities of the network sensor two sets of experiments with different robot motion modes are designed, with a laser tracker serving as the reference benchmark. These experiments encompass linear and circular motions executed by the robot, each repeated multiple time. The robot's motion speed varies across three orthogonal directions, ranging from 0.5 m/s to 0.01 m/s, encompassing six distinct speed levels. The analysis of the collected experimental data sets indicates that the network sensor exhibits a dynamic tracking accuracy of 0.45 mm when the target motion speed is below 0.5 m/s.

Network sensor, laser tracker, robot, global accuracy, dynamic

1. Introduction

In modern intelligent manufacturing systems, robots play a pivotal role in the automation industry due to their cost-effective efficiency in handling repetitive tasks. Notably, the positional repeatability of mainstream 6-axis robots is exceptionally high, ± 0.05 mm. However, their global accuracy (absolute accuracy) exceeds ± 1.0 mm, which is 20 times less accurate than their repeatability [1]. Various factors contribute to this discrepancy in accuracy, such as the stiffness of robot hardware materials, thermal effects, payload effects, and manufacturing tolerances. In scenarios requiring robot interaction with external devices or multi-robot collaboration, enhancing the robot's global accuracy becomes crucial.

Large-volume metrology technology offers a range of solutions to improve the global accuracy of robots. The measurement systems for robots are diverse, including contact-based coordinate measuring machines (CMM), ball-bars, and non-contact optical sensors such as laser scanners, indoor Global Position System (iGPS) and photoelectric sensors [2]. There are also systems measuring robot velocity, acceleration, force, and torque using inertial sensors and piezoelectric strain gauges. Although these varied measurement systems provide flexible and efficient methods for assessing robots' static errors (pose errors) and dynamic errors (path errors), a distributed network sensor system based on photogrammetry principles can provide 6 degrees of freedom (6DoF) in both static and dynamic measurements in the workplace.

This novel network sensor system can provide real-time 6 DoF positional data (detailed in Section 2.1). According to the manufacturing company's data, the accuracy of this system is 210 µm [3]. However, due to its recent introduction and lack of comprehensive literature reviews evaluating its performance, the measurement accuracy claimed by the manufacturer requires further verification. This paper is designed to experimentally investigate and analyze the dynamic accuracy measurement performance of this network sensor system, comparing it with the performance of a laser tracker under the same experimental conditions.

2. Equipment devices description

The experiment conducted in this paper involves three kinds of equipment: the distributed network sensor IONA produced by Insphere, the Vantage S6 Laser Trackers by FARO, and the UR5e robot from Universal Robots. These three devices are detailed in the following sections.

2.1. Network sensor

This innovative network sensor system, named IONA, is manufactured by Insphere Ltd. It consists of multiple stereo infrared cameras (nodes) arranged around the object to be measured, spherical retro-reflective targets arranged in different configurations called tiles, as shown in Figure 1.

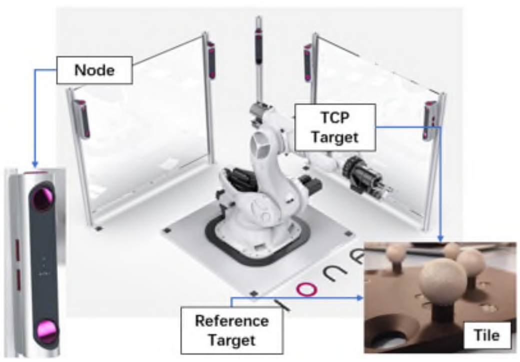


Figure 1. IONA system setup consists of nodes and tiles [4]

In Figure 1, each node of the system is an infrared camera equipped with two wide-angle lenses. These cameras capture images within their field of view and process them accordingly. Due to the retroreflective spheres' high grayscale contrast in the original images, enable the system to determine their positions in 2D images based on stereo imaging principles. Following this, a coordinate transformation process is employed to derive the spheres' 3D coordinates in space [5]. A set of tiles is affixed to the ground or a fixed base where the robot is located, and another set is attached to the robot's end-effector. During high-frequency photography by the cameras, the network sensor system provides real-time coordinates of the Tool Center Point (TCP) relative to the base.

Theoretically, a single camera can determine the coordinates; however, the distributed network's advantage lies in avoiding line-of-sight issues and providing multiple data sets for the same measurement, thereby achieving redundancy. This redundancy is further optimized in data processing, ensuring the final position data is within an acceptable precision tolerance. According to the product technical manual, the accuracy (1σ) of this metrology system is 210 µm and the measurement frequency is 10 Hz [3]. However, this often represents the manufacturer's measurement in ideal conditions. In practical use, uncertainties in this system arise from factors such as the ambient temperature of the environment, background light intensity, reflectivity of the measured object's material, the speed of the target's movement, and the number of sensors involved.

2.2. Laser tracker

The laser tracker is a high-precision 3D metrology system that integrates advanced technologies such as laser interferometry and angular measurement, primarily used in the field of large-volume spatial coordinate metrology. In robotic metrology, it is often considered one of the most reliable metrology methods. Its working principle involves the precise metrology of 3D coordinates through encoder-based angle measurement and laser time-of-flight distance measurement. In the experiment, the FARO Vantage S6 Laser Tracker was utilized, which boasts a single-point angular accuracy (2σ) of 20 µm + 5 µm/m and a distance angular accuracy (2σ) of 16 µm + 0.8 µm/m, operating at a frequency of 50 Hz [6].

2.3. Robot

In the experiment, the 6-axis UR5e robot from Universal Robots was employed to generate dynamic trajectories. This robot facilitates the easy production of trajectories and adjustment of motion speeds. It has a maximum payload of 5 kg, a reach distance of 850 mm, and a maximum tool speed of 1 m/s. The robot's pose repeatability is 0.03 mm [7].

3. Equipment setup

3.1. Equipment layout

The arrangement of the three instruments used in the experiment is depicted in Figure 2. The UR5e robot is mounted on a stable table and positioned in a corner. The network sensor (IONA) is set up in a C-formation around the robot, approximately 1.5 meters away, ensuring that each node's field of view is centered on the robot's end-effector. A set of tiles, serving as the target, is affixed to the table and remains stationary, establishing the base coordinate system reference for the network sensor. Another set of tiles is placed on the robot's end-effector to track its trajectory. The laser tracker is mounted on a tripod approximately 3.5 meters away from the robot. A 1.5-inch spherical mirror reflector (SMR) of the laser tracker is magnetically attached to the robot's end-effector.

The robot performs linear and circular motions in the three directions of the illustrated coordinate system. For each movement, both the network sensor and the laser tracker record the robot's trajectory. The obtained measurement results are compared to verify the dynamic tracking performance of the network sensor.

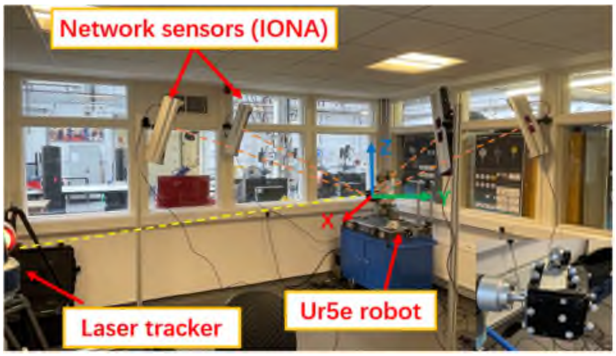


Figure 2. Experiment layout in the laboratory and the end-effector of the robot with tiles and SMR

3.2. Experiment procedure

As shown in Figure 3, the robot was programmed to perform linear reciprocating motions in three mutually orthogonal directions and circular motions on three orthogonal planes. It results in a total of six different movement trajectories, labeled as Trajectories 1-6. The robot conducted experiments at different speeds under these 6 trajectories, with 6 speed gradients ranging from 0.01 m/s to 0.5 m/s, as detailed in Table 1. This gradient of speeds was designed based on the range of tool speeds commonly used in real-world robotic applications.

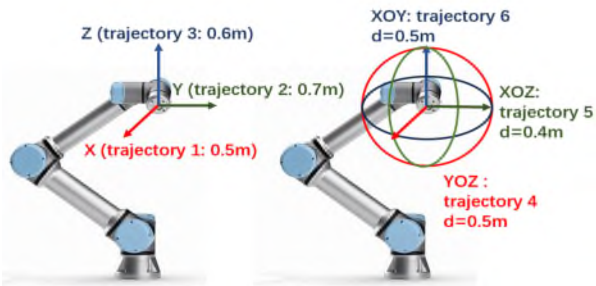


Figure 3. The robot's six motion trajectories and travel distances: Trajectories 1-3 are linear reciprocating movements in three directions, and Trajectories 4-6 are circular movements on three planes.

Table 1 Speed gradients of the trajectories

	Speed gradients from 0.01 m/s to 0.5 m/s					
Speed [m/s]	0.01	0.1	0.2	0.3	0.4	0.5

Due to the limitations of the robot's working space and its maximum reachable range, the sizes of the 6 trajectories are illustrated in Figure 3. For each of the six trajectories, the robot executed movements at six different speeds, yielding a total of 36 sets of experimental data. To minimize randomness in the experiments, the robot performed four reciprocating runs at each speed for every trajectory.

4. Results and discussion

To analyze the results, it is not feasible to directly compare the recorded results of two different metrology methods for the same robotic trajectory. In the network sensor system, the

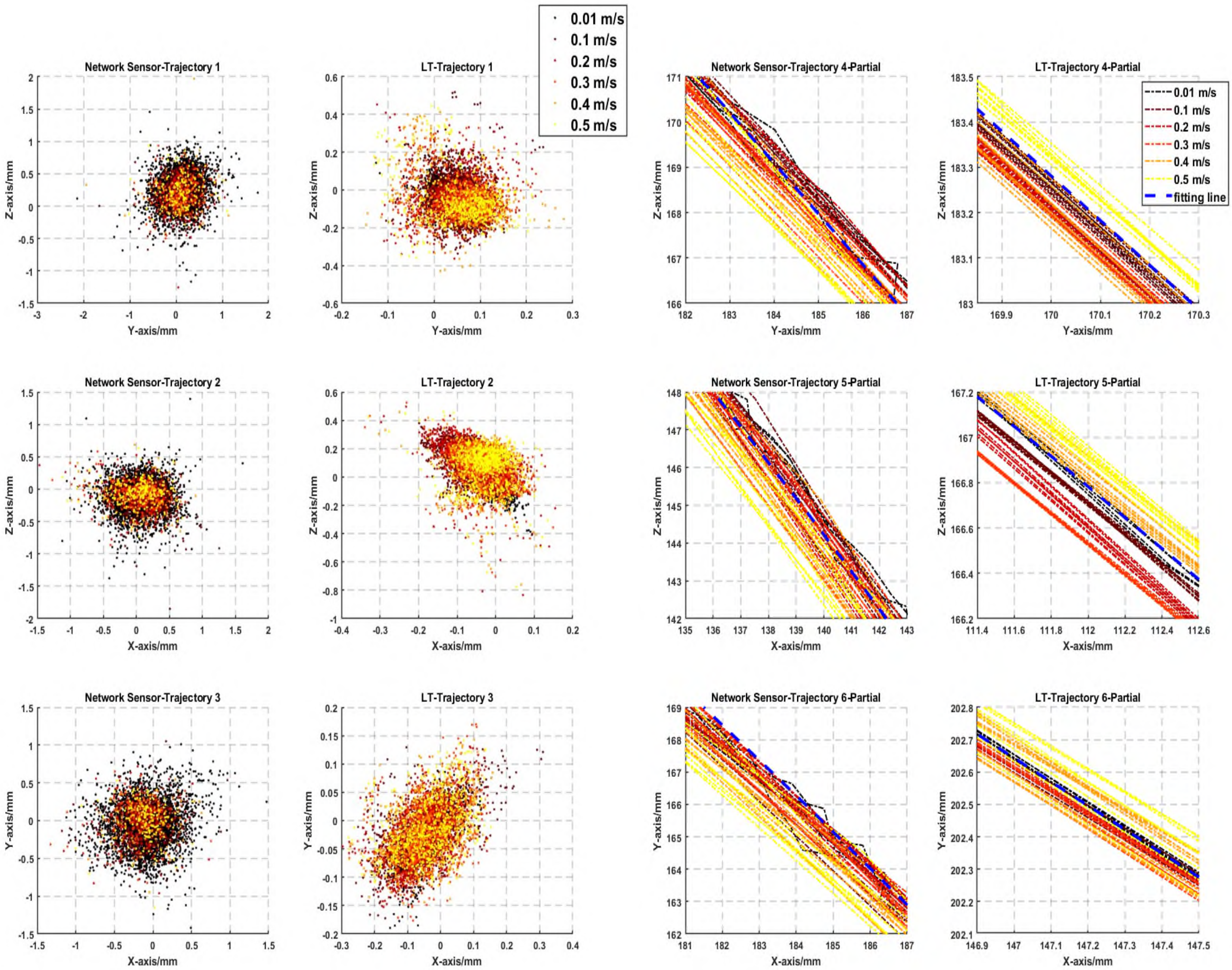


Figure 4. The 2-left columns shown the measurement of Trajectories 1-3 from both the network sensor and laser tracker, projected onto a 2D plane. The origin of each graph is positioned at the location of the fitted line. The 2-right columns display a magnified view of the measurement of Trajectories 4-6 from both the network sensor and laser tracker, projected onto the plane of the fitted circle. This includes a legend for the robot's speed variations and the fitting line.

robot's TCP coordinates are set in the software based on the tiles at the robot's end-effector, and the reference coordinates are set based on the tiles on the table. In contrast, for the laser tracker system, the reference coordinates are based on the tracker's base, and the robot's TCP coordinates are determined using the SMR. To compare the dynamic tracking performance of these two metrology systems, this paper adopts the method of reference line generation proposed by Wang et al [8].

4.1. Reference Line generation

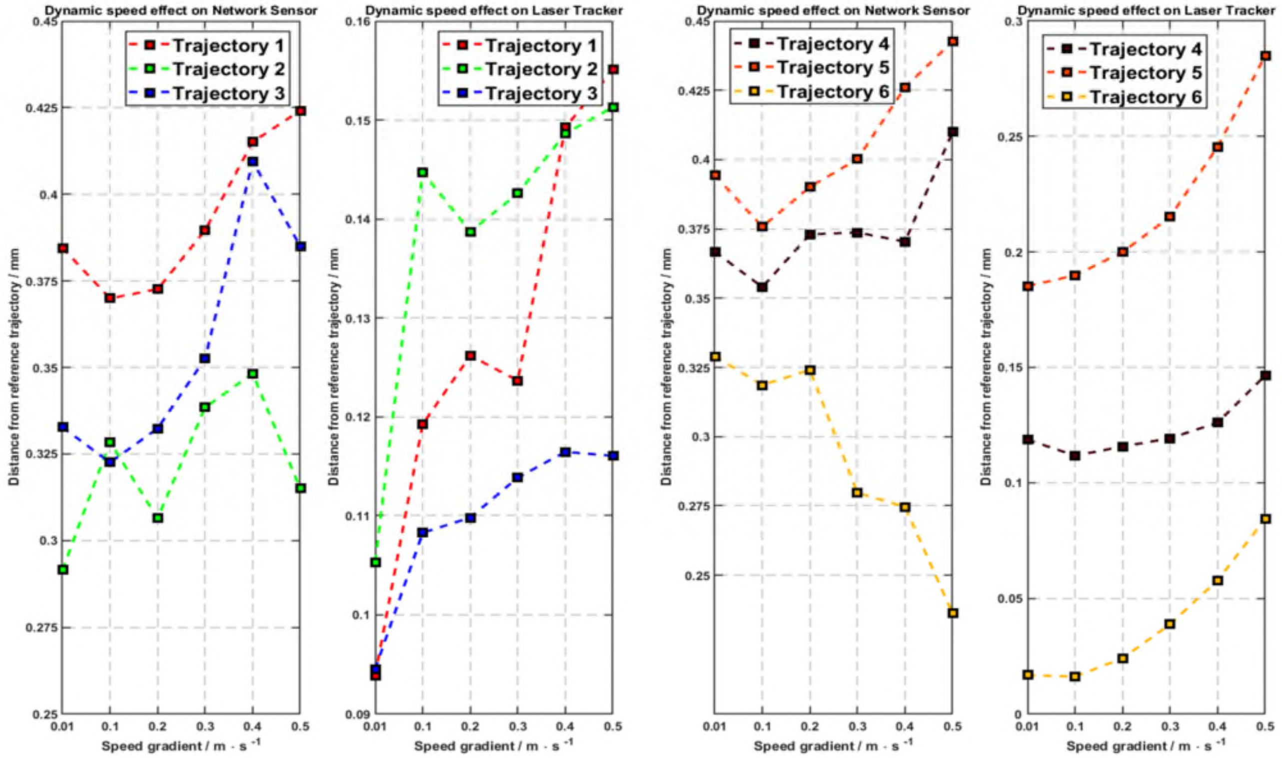
To compare the results of the two metrology systems, the fitting was generated using the data from the six trajectories where the robot's motion speed was lowest (0.01 m/s). The fitted results are considered the actual motion trajectory of the robot in that direction and are used as the reference for comparison. For linear motions, six sets of 0.01 m/s data from both metrology systems can be used to fit six reference lines. Similarly, for circular motion, six reference circles can be fitted. The fitting for linear motion is done using linear least squares. Fitting a spatial circle for circular motion is a relatively complex task, and there are various algorithms for fitting a circle to discrete points in space. However, since the fitting data in this experiment are obtained at an extremely low speed of the robot and the theoretical circle is known, this paper uses Principal Component Analysis (PCA) to fit the optimal plane, and then projects the point data onto this plane for fitting a planar circle.

4.2. Results analysis

Due to the difficulty of comparing 3D data, this study converted all data from 3D to 2D. In linear motion, the generated reference line in 4.1 is used as the normal vector of a plane, and all point data obtained from that trajectory are projected onto this plane. As shown on the left side of Figure 4, deviations caused by changes in the robot's speed along the same trajectory are all projected onto the plane. In circular motion, the plane where the fitted reference circle lies is used, and all points obtained at different speeds on that trajectory are projected onto this plane. As seen on the right side of Figure 4, data from spatial circular motion is also visualized in a 2D image.

From the linear motion data, it is evident that when measuring the same trajectory, the network sensor data is significantly more dispersed overall compared to the laser tracker, with a higher number of outliers. Furthermore, the data measured by the laser tracker aligns with the expectation that robot repeatability decreases with increased speed; that is, data points are more concentrated near the origin at lower speeds. However, the network sensor data is more scattered, and the effect of robot speed variation is not well-reflected in its data.

Figure 5. Mean of the distance from the measured coordinate data to the fitting trajectories for network sensor and laser tracker



Additionally, with the increase in robot speed, the number of network sensor data samples rapidly decrease, limited by its measurement frequency of 10Hz.

In the circular motion data, a notable difference between the network sensor and laser tracker recorded trajectories is that the position of the trajectory with the lowest speed for the laser tracker is in the middle. The increase in robot speed results in the trajectory data being evenly distributed on both sides of the fitting line. In contrast, for the network sensor, the low-speed trajectory data is distributed externally, shifting towards the circle's center as the speed increases.

Figure 5 quantitatively displays the average distance of each measurement point from the fitting line under its trajectory relative to increasing speed. As the robot's speed increases, the accuracy of both the network sensor and the laser tracker generally decreases. However, the network sensor shows a paradoxical increase in precision at a speed of 0.5 m/s. This abnormal performance is speculated to be caused by the unsatisfactory measurement frequency of the network sensor under high-speed movement, which leads to insufficient sample collection. Additionally, at a speed of 0.01 m/s, the repeatability of the network sensor's measurements does not significantly improve, suggesting that the system's measurement capability cannot be enhanced by reducing target speed when it is already below a certain threshold.

5. Conclusion

In this work, the dynamic tracking performance of an infrared camera-based network sensor metrology system was validated. Linear and circular motions were set up for the robot, using the measurements from the laser tracker as an experimental control. A method of reference line generation was employed to unify the comparison standards between the two metrology systems. It was concluded that the dynamic measurement accuracy of this network sensor system is between 0.3 - 0.45 mm for target speeds below 0.5 m/s.

This novel network sensor system offers potential for robot metrology and its related applications, as well as the establishment of digital twin systems. Currently, further long-term measurements to verify its accuracy are being conducted, and the development of automated manufacturing systems based on robots and this network sensor is underway.

Acknowledgement

This study was supported by State Key Laboratory of Robotics and Systems (SKLRS-2022-KF-01) and Insphere Ltd (Project: 13727243).

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