Optical Navigation-Related Factors Interfering With The Accuracy of Robot-Assisted Surgery

Wei Tian (tianwei2019@yeah.net)
Beijing Jishuitan Hospital
Zhan Shi
Beijing Jishuitan Hospital
Zuchang Li
Beijing Jishuitan Hospital
Mingxing Fan
Beijing Jishuitan Hospital
Qilong Wang
Beijing Jishuitan Hospital
Yajun Liu
Beijing Jishuitan Hospital
Bo Liu
Beijing Jishuitan Hospital
Da He
Beijing Jishuitan Hospital
Jingwei Zhao
Beijing Jishuitan Hospital
Zhao Lang
Beijing Jishuitan Hospital
Sai Ma
Beijing Jishuitan Hospital

Research Article

Keywords: planned position, Robot system, optical tracking devices, patient tracker

Posted Date: September 21st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-832508/v1

Abstract

Objective To explore navigation-related factors interfering with accuracy of robot-assisted surgery.

Methods We made a measurement model to test the accuracy of the TianJi Robot system when performing the stimulated screw placement procedure. The three-coordinate machine was used to measure the deviation between the actual position and the planned position. We designed corresponding experiments to explore the effects of different navigation-related factors on the screw placement accuracy. The deviations were measured at different distance (ranging from 1.2 m to 2.2 m) between the navigation optical stereo camera and the tracker and each distance was measured 50 times. The distance between the optical camera and the patient tracker was set at 1.4 m and the deviations were measured at different angles between the camera and the robot tracker, each angle was measured more than 25 times. Data was donated with mean and standard deviation. The line charts were employed to describe the changes of deviations over one clinical factor including distance and angle.

Results Within the available scope of navigation optical system (1.2 m-2.2 m), the deviation increased with the distance (χ^2=479.107, P<0.001). The robotic system accuracy was high and stable (mean deviation 0.332 mm ± 0.067 mm) when the relative angle between the optical camera and the tracker less than 40 degrees.

Conclusions Accuracy of robot system was affected by the relative distance and angle between the optical camera and the tracker. When placing and adjusting the optical tracking devices, surgeons should set the relative distance between the optical camera and the patient tracker as 1.4 m- 1.5 m and the relative angle less than 40 degrees.

Introduction

With the popularization of the concept of “precision medicine”, computer-aided design and manufacturing technology has played an increasing role in spinal surgery[1]. The main objective of the computer aided surgical orthopedic system is to reduce the risk of neurovascular injury through anatomical reconstruction technique, intraoperative real-time navigation technique and bionic robot arm manipulation technique[2].

TianJi Robot is a navigation-guided orthopedic surgical robot with completely independent intellectual property and has been widely used in clinical practice for its high accuracy and wide indications[3, 4]. Tianji Robot system mainly consists of the robot arm system and the optical navigation system (ONS). The 3-D position data of trackers fixed on the patient body surface and on the robot arm was monitored by the passive optical infrared camera in the navigation system. The ONS present an opportunity to monitor the real-time position and orientation of surgical instruments, guiding the robot arm to the accurate surgical path during the screw placement[5].

The passive optical infrared camera, two dynamic references are separate devices in the ONS, thus the relative distance and angle between the camera and references change during robot arm motion. Based on our clinical experience, the procedure may experience additional adjustments in optical navigation device and robot system, the robot arm finally reached the planned position. Navigation-related factors, such as the distance and the angle between the camera and references are thought to influence overall accuracy. However, there were not so many studies reporting such issues.

The goal of this study was to provide surgeons with: i) how such factors interfere with the accuracy of robot-assisted surgery; ii) find a region that improves robot system performance; iii) insight for adjusting optical navigation devices and robot system;

Materials And Methods

The specific robot system used in the study was TianJi Robot system. Briefly, the robot system consisted of an optical tracking navigation system, a robotic arm system and a surgical planning and control software system (robotic workstation). The optical tracking system (NDI, Waterloo, Canada) was made up of an infrared stereo camera and two reference frames (including one patient tracker and one robotic tracker).

Robot-assisted surgery workflow

Intraoperative fluoroscopic images were acquired by C-arm (Siemens Medical Solutions, Erlangen, Germany) and transferred to the robotic workstation. 3-D reconstructed images were displayed on the monitor screen, surgeons then planned the entry point and trajectory on the workstation. The robotic arm spontaneously moved to the required position under the guidance of the planning software and the optical tracking system. The three-coordinate measuring machine (Hexagon ROMER 2575, system error 0.028 mm) was used to measure the deviation between the actual position and the planned position (Figure 1).

Deviation measurement:

1. Images of the engineering model (Figure 2) were acquired using a 3-D C-arm.
2. Two spherical ball centers served as entry and exit points of the trajectory respectively.
3. Set the spatial positions of entry point A and exit point B as $X_A(x_a, y_a, z_a)$ $X_B(x_b, y_b, z_b)$.
4. The software system and the optical tracking system guided the robotic arm to the planned path position. The surgeon installed the positioning sleeve within the cannula of the robotic arm, and measured the spatial positions of the central holes P1 (x1, y1, z1), P2 (x2, y2, z2) at both ends of the sleeve. Then on the software, the spatial straight line P1P2 were created and the distances from entry point A and exit point B to line P1P2 were calculated according to the formula below.
5. La and Lb were recorded as the intraoperative deviation at entry point A and exit point B. Set the maximum value as the deviation error.

Formula (the distance from point X_i to the spatial line P1P2):

$$L_i = \sqrt{[(x_1 - x_i) + (x_2 - x_1)t]^2 + [(y_1 - y_i) + (y_2 - y_1)t]^2 + [(z_1 - z_i) + (z_2 - z_1)t]^2}$$

$$t = -\frac{(x_1-x_i)(x_2-x_1)+(y_1-y_i)(y_2-y_1)+(z_1-z_i)(z_2-z_1)}{(x_2-x_1)^2+(y_2-y_1)^2+(z_2-z_1)^2} \quad i = a, b$$

L_i: intraoperative deviation

Experiment set-up

The distance and the relative angle between the stereo camera and tracker both affected the intraoperative deviation error, thus two different series of experiments were performed. The relative angle was the angle between the normal vectors of the tracker plane and the camera plane. The robot workstation automatically calculated values of the relative distance and the relative angle and presented them on the monitor workstation.

Experiment 1. the distance between the stereo camera and tracker

1. To control the relative angle to a fixed value, we set the stereo camera to have the same height as the engineering model (Figure 3). We adjusted the relative angle between the stereo camera and the patient tracker to 0 degree like *face to face*, and selected the relative angle between the robot tracker and the stereo camera as small as possible.
2. Following the workflow of the optical navigation guided robot system, the robotic arm automatically moved to the planned trajectory.
3. We measured and recorded the intraoperative deviation in a certain distance.
4. Different positions were selected: 1.2m, 1.4m, 1.6m, 1.8m, 2.0m and 2.2m (maximum allowable system distance). Given line of site constraints, 1.2m was the minimum practical distance. Beyond 2.2m, either the patient tracker or the robotic arm tracker was invisible to the camera. We repeated 50 times of deviation measurements at each position. Then statistical analysis of the relationship between different distances and image drift errors was made.

Experiment 2. the relative angle between the stereo camera and tracker

Considering the practical clinical environment, we selected 1.4 m as the relative horizontal distance between the stereo camera and tracker. The adjusting rod attached to the stereo camera could change the stereo infrared light direction by moving vertically and horizontally. The relative angle between the stereo camera and tracker was both available on the planning and monitor software. Given the practical range of the optical tracking system, we changed the robotic tracker angle on the control software and measured each robotic arm tracker angle more than 25 times. Thus, we obtained and analyzed the relationship between the deviation error and the robotic tracker angle.

Statistical analysis

All parametric data was expressed as mean ± standard deviation. Preplanned statistical analyses included univariate analysis of variance (ANOVA) assessing covariant of camera distance, the angle between the camera and the robotic arm tracker. Analysis was done in SPSS Version 21.0 (IBM, NY, USA.) and a *p* value of <0.05 was considered statistically significant.

Results

Experiment 1

Univariable effect of the distance on deviation in ONS was summarized in Table 1. There was an increase in deviation error with increasing distance between the stereo camera and tracker (p<0.001) in Figure 4. Not only the mean error of the maximum distance of 2.2m was larger than other distances, but also the standard deviation error was obviously larger, which showed that the ONS accuracy is unstable and the image drift error was obvious at the maximum distance.

Table 1. analysis for the effect of the distance on deviation in ONS

Distance (m)	Mean error (mm)	Standard error (mm)	Min. error (mm)	Max. error (mm)	*p* value
1.2	0.423	0.020	0.384	0.461	
1.4	0.528	0.039	0.402	0.550	
1.6	0.729	0.026	0.699	0.811	
1.8	0.832	0.066	0.705	0.903	
2.0	0.885	0.022	0.816	0.923	
2.2	1.147	0.105	0.895	1.497	
					<0.001

* ANOVA used for more than two groups.

Experiment 2

In Figure 5, with the increase of the relative robotic tracker angle, the mean deviation error in the central area position has no obvious fluctuation, but has a slow ascending to 0.4 mm with the relative robotic tracker angle ranging from 40 to 50 degrees and a fast ascending at the boundary.

Discussion

Most studies focused on the size screws breaching the pedicle wall on postoperative CT images to access the accuracy and deviation of orthopedic robot system[6–9], but the position of a pedicle screw depends on not only the accuracy of the navigation-based surgical robot system, but also many other factors, including the screws skidding during the insertions into the pedicles. This study investigated the accuracy and deviation of ONS in a controlled laboratory environment with several variables. The variables studied were chosen for the clinical relevance, as they may be affected by the operating room set-up and intraoperative procedure: the distance between the stereo camera and tracker, the relative angle between the stereo camera and tracker, the spatial position of the camera and tracker.

In this study, we designed the clinical deviation as the distance between the actual position and the planned position. Under the influence of several variables, the actual position of the robotic arm is not able to coincide with the image position mapped by optical tracking devices. For that reason, we propose a new concept called “image drift”. The bigger the image drift is, the more difficult it is for the robotic arm to reach the planned surgical path position, and as a result, the accuracy of screw implantation will be affected accordingly.

There was an increase in deviation error with increasing distance between the stereo camera and tracker. At the maximum distance of 2.2 m, the ONS system accuracy is unstable and the image drift error is obvious at this largest distance. This finding is consistent with that of Gundle (2017) who reported that both accuracy and precision were negatively affected at increased distances between the navigation system camera and the grid[10]. The literature of the NDI Polaris optical tracking system proved that the distance error at each grid point generally increased with the distance from the camera[9]. A possible explanation for this might be the optical characteristics, in addition to the number of reflecting spheres on the patient tracker and the spatial arrangement among the reflecting spheres.

Another important finding was that the clinical deviation is negatively affected by the relative angle between the stereo camera and the robot tracker. We noticed that when the relative angle exceeded 50 degrees statistical abnormal points appeared (corresponding mean error > 1mm), which represented the image drift error is obvious under this condition. This result may be explained by the fact that with the increasing relative robotic tracker angle, multi reflection and interference of rays generated by certain retroreflective spheres on the robot arm tracker resulted in the occurrence of the image drift and inaccurate intraoperative accuracy.

Orthopedic surgical robots have recently improved the accuracy of the pedicle screw placement by decreasing the deviation caused by the inaccurate identification of these anatomic landmarks and the instability of free-hand screw placement [6]. As a major component of Tianji Robot, the optical navigation system has the characteristics of high accuracy and stability. However, there are some opportunities for error to occur in the optical navigation system. Previous studies have shown that the relative location relationship between the optical tracking camera and the tracker, including distance and angle, is an influencing factor[10, 11]. However, there is no corresponding detailed data to confirm and explain the accuracy and deviation of the optical navigation-based surgical robot system.

The results of this study suggest minimizing the distance from a surgical robot system's camera to the surgical site to improve its accuracy. Should a certain space be reserved for the anesthesiologist to operate, the horizontal relative distance between the stereo camera and the surgical site is 1.4m. The clinical accuracy of the ONS in this study may become worse when either the patient tracker or the robotic tracker is on the boundary and the relative angle between the stereo camera and the robot tracker exceeds 40 degrees. The ideal operating room set-up and intraoperative procedure need attentions. The relative robotic tracker angle is advised to be as small as possible (face to face) and the position of two trackers to be near the central area during the operation, so as to provide an accurate and stable area of ONS.

Limitations of this experiment

As a lab-based model, a limitation of this study is its lack of direct clinical correlation. Clinical factors, such as the strong pressure procedure of the surgeon, drilling, etc., soft tissue compression and the change of the organization structure may also cause image drift during the operation[12]. In future, based on this lab-based result, we will carry out relevant cadaveric research to access the influence of clinical factors on image drift. A strength of this study is that we accessed the clinical accuracy in ONS variables largely within the control of the operating surgeon, or else feasible by changes in the navigation system software.

Conclusions

The clinical accuracy of the ONS is negatively affected by the increasing distance between the stereo camera and tracker, the relative angle between the stereo camera and the robotic tracker (> 40 degrees).

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

The publication fee is supported by Beijing Natural Science Foundation (Grant Number L192048).

Authors' contributions

WT conceived the study. ZS collected the data, performed the data analysis and drafted the first version of the manuscript. ZCL and MXF constructed finite element modeling. QLW and JWZ analyzed the data, and wrote the first draft of the manuscript. YJL and ZL provided the critical comments to design the study. HD and LB provided additional advice. SM contributed to the literature review. All authors read and approved the final manuscript.

Acknowledgements

Not applicable.

Authors' information

Wei Tian, MD, FRCSEd (Ortho)*, Zhan Shi, MD*, Zuchang Li, MD, Mingxing Fan, MD, Qilong Wang, MD, Yajun Liu, MD, Bo Liu, MD, Da He, MD, Sai Ma, MD, Jingwei Zhao, MD, Zhang Lao, MD, Beijing Jishuitan Hospital, Beijing, China

Address for correspondence

Wei Tian, MD, FRCSEd (Ortho), Department of Spine Surgery, Beijing Jishuitan Hospital, No. 31, Xinjiekou East St, Xicheng District, Beijing, China, 100035 Email: tianwei2019@yeah.net

Disclosure: *Wei Tian and Zhan Shi contributed equally to this project and manuscript preparation.

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Figures

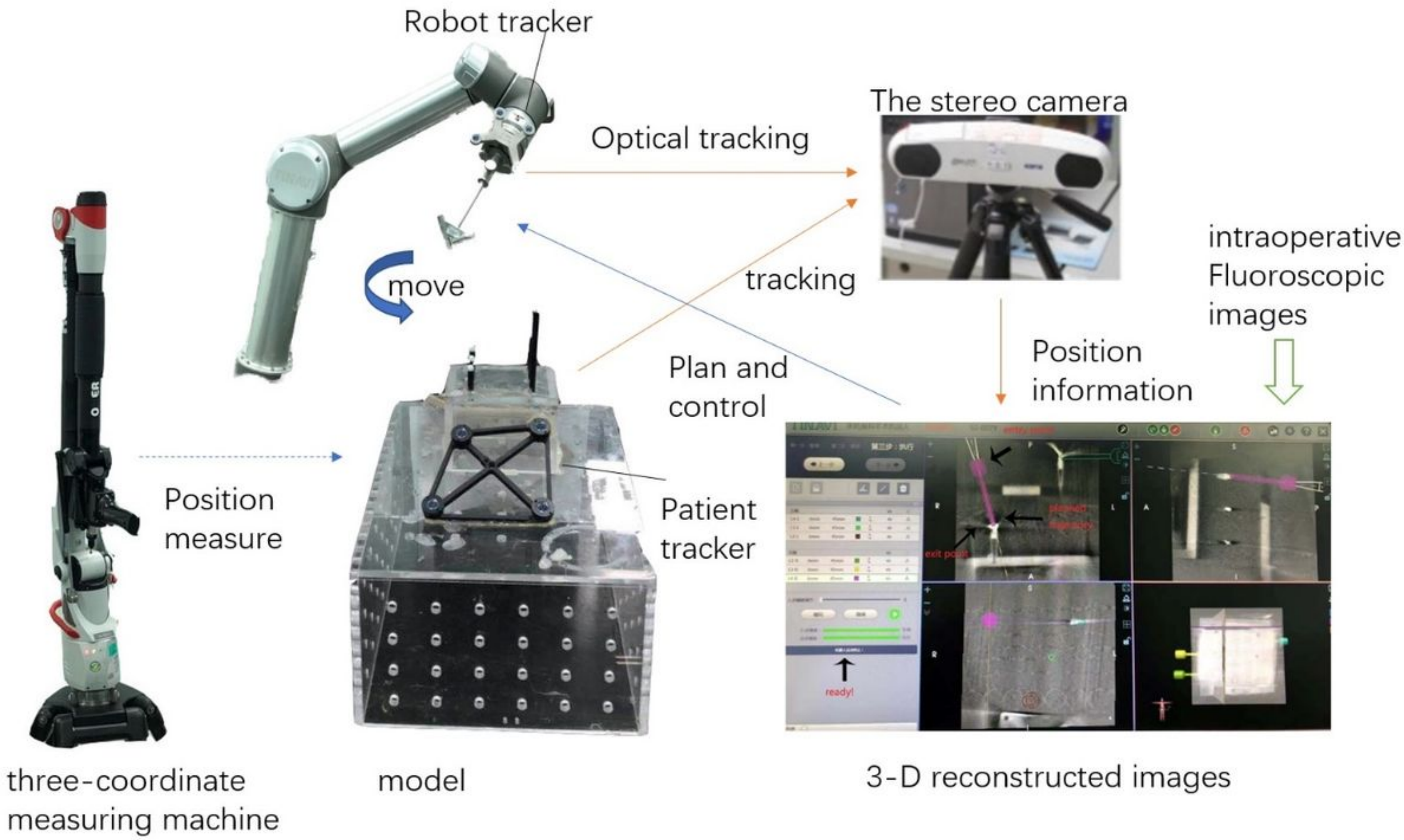

Figure 1

main components and steps in TianJi Robot system.

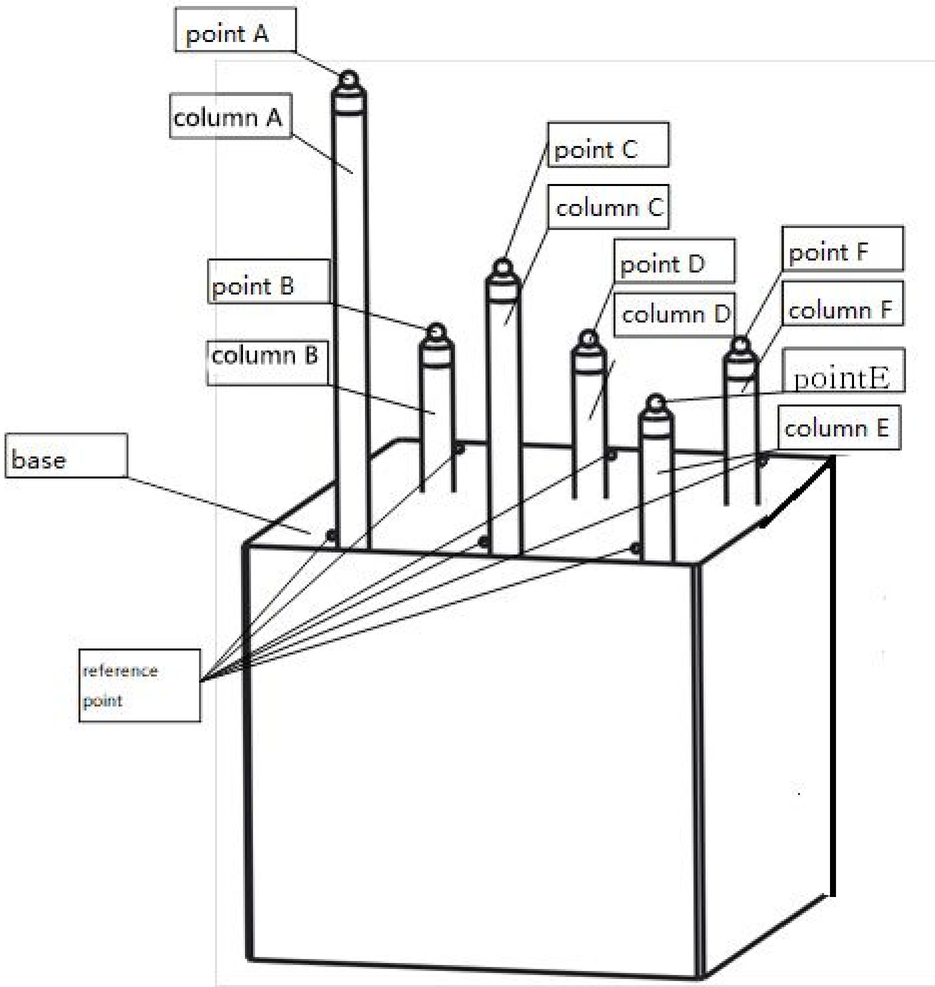

Figure 2

Structure chart of the engineering model. The engineering model was composed of the base, columns, spherical balls and reference points. The base and columns were made of non-visualized materials in medical imaging, while the test points and reference points were clearly visualized martials. The test points were the spherical centers of stainless-steel spherical balls which were placed on the columns.

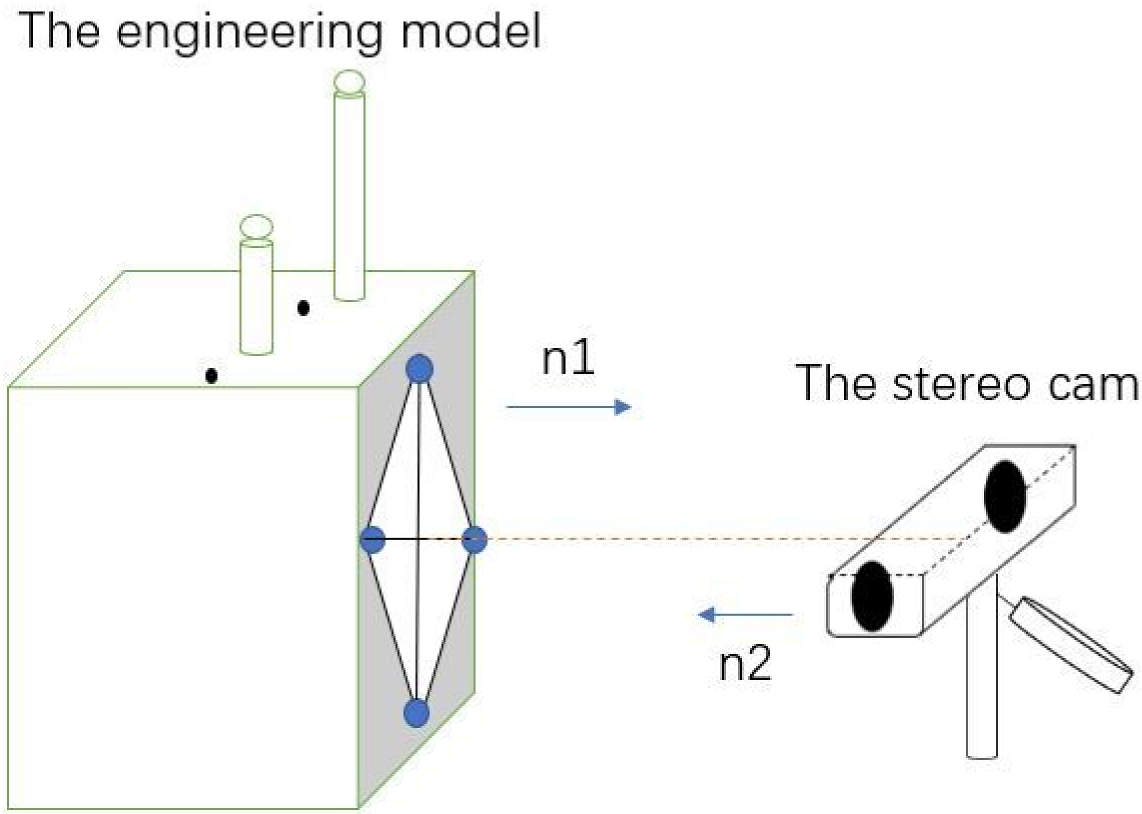

Figure 3

the drawing showed the placement of the engineering model and the stereo camera. n1, n2 corresponded to the normal vector of the tracker plane and tracker, respectively.

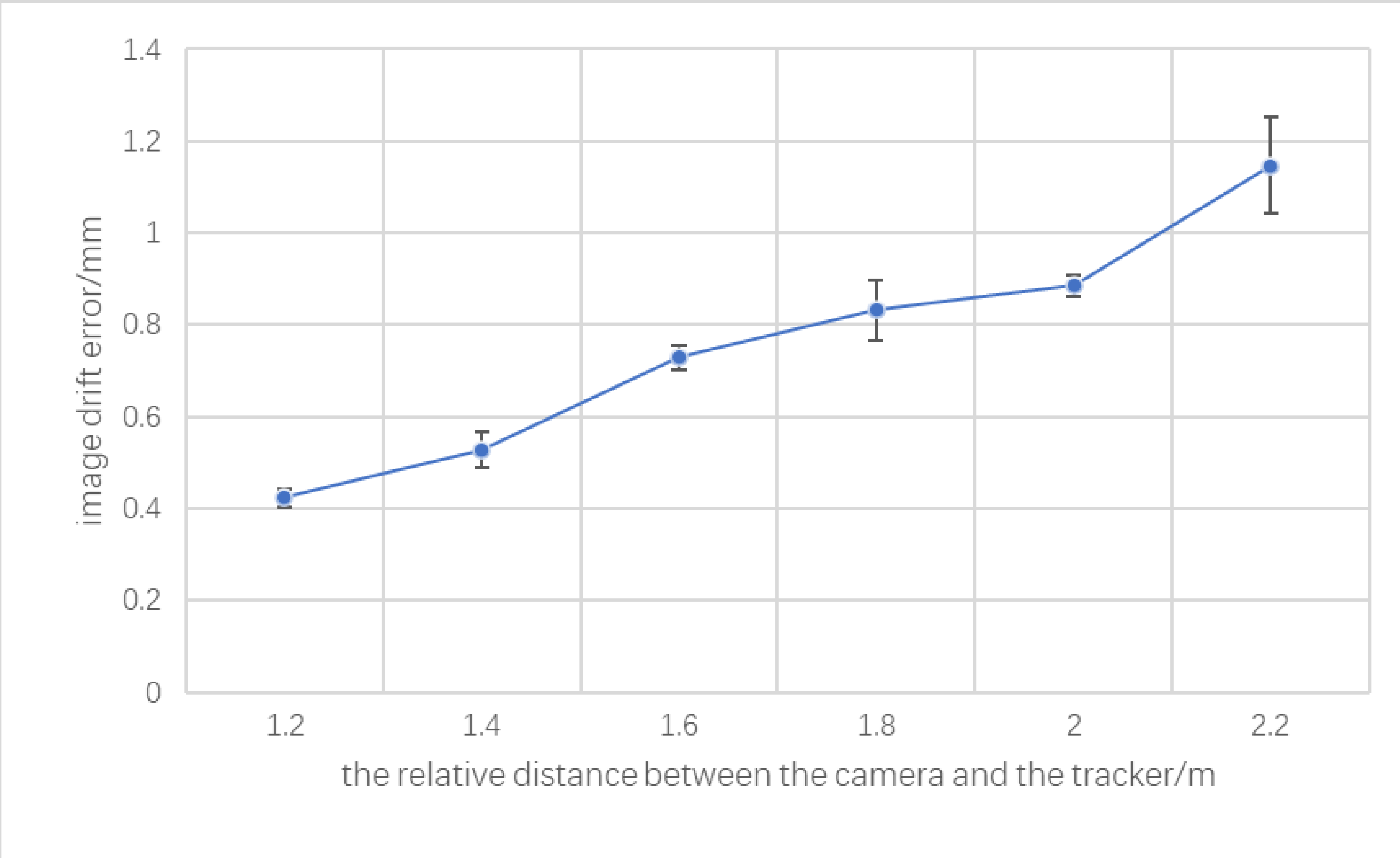

Figure 4

mean deviation error and standard deviation in ONS, by the relative distance measured.

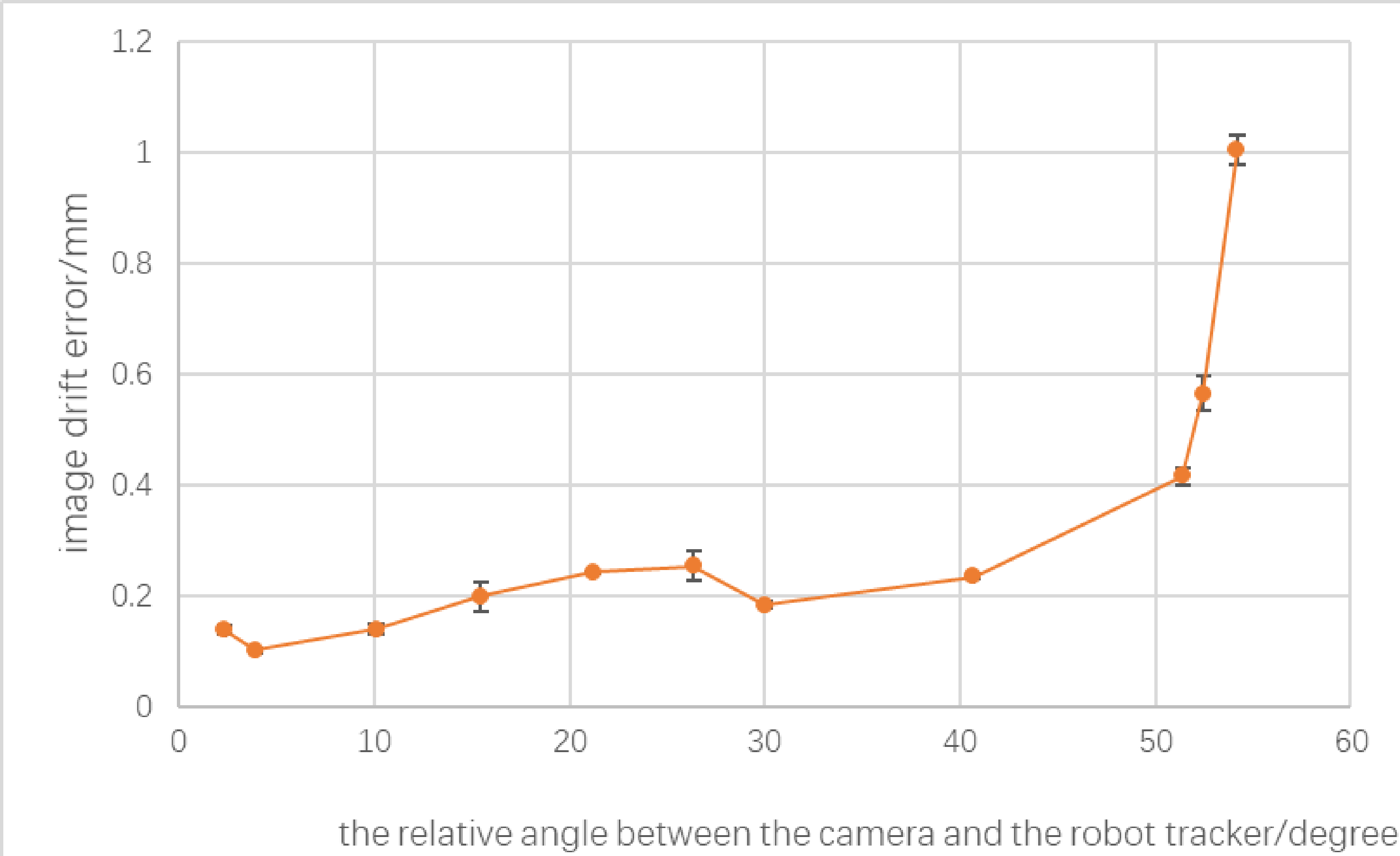

Figure 5

mean deviation error and standard deviation in ONS, by the relative angle measured.