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Design of a six-DOF motion tracking system based on a Stewart platform and ball-and-socket joints

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Abstract

This paper presents a six degree-of-freedom (DOF) real-time motion tracking system of measuring the position and the orientation for industrial robots in three-dimensional (3D) space. The proposed system is based on a typical Stewart platform design and utilizes six low-cost displacement sensors to monitor the motion of the Stewart platform. The advantage of the proposed system is its simple calibration and easy accessibility; the magnetic ball-and-socket joints used for rotational joints. With special measurement tools, the center of rotation of all twelve joints can be measured in 3D space at a glance. Following more than fifty measurements, the average root mean square (RMS) position accuracy error of the proposed device is less than 0.186 mm and the average of angular accuracy error is less than 0.160 °, making it suitable for monitoring the performance of industrial robot. A commercial robot is also tested by the proposed system to verify its usefulness.

Keywords

Motion tracking; 6D measurement; Stewart platform; Hexapod; Robot accuracy assessment

1. Introduction

Multi degrees-of-freedom (DOF) machines especially industrial robots have been extensively used in various fields for their versatility and programmability [1]. As there are more needs for industrial robots now and more collaborations between humans and robots, it becomes important to evaluate the accuracy and the repeatability of the robots routinely for both quality and safety reasons. In this situation, the accurate measurement of the position and orientation (pose) of the end-effector of robots plays an important role in the performance evaluation.

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There are various approaches to measure one-dimensional (1D) position or some of three-dimensional (3D) positions or orientation; one straightforward device is to touch an object with a probe or sensors [2]. This touch method is simple but involves considerable amount of manual operation resulting in additional errors. One advanced method is a telescoping ballbar [3] measuring the distance between the two balls attached to a target and a reference, but its measurement range is on the order of a few mm [3,4].

Contrary to touch based measurement, non-touch measurement methods are also popularly used; vision-based systems [5] and laser trackers [6]. Vision-based systems calculate 3D position data from single or multiple cameras like MaxSHOT 3D.¹ This approach can provide the accuracy error for less than 1 mm and is convenient to use, but the allocation of multiple cameras is a time-consuming task and the whole system is not easy to move near industrial robots once all cameras are set up. The laser tracker utilizes laser for its measurements providing accuracy error of a few microns level and can measure 3D position, not orientation. However, additional attention is required to make the laser beam on line-of-sight to the retroreflector attached on a target without any breakage.

The measurement methods for full 3D positions and orientation (6D motion) are relatively complex and have their own limitations. Traditional coordinate measurement machines (CMMs [6]) are a well-known solution to measure accurate static positions, but they are too bulky to move around industrial robots, so it is not easy to use them routinely. Another measurement instrument is an enhanced laser tracker from conventional ones [7]. This can measure the orientation of the endeffector with special probes like active target from API¹, but still has the same problems with the conventional laser tracker systems. Another 3D measurement system is multiple camera system with physical markers or reflectors. VICON¹ system can provide accuracy with positional errors on the order of 1 mm or less [8]. Unfortunately, additional care is required for space to locate multiple cameras in 3D space and more than three reflectors attached to a target. Their performance for 6D measurement is enough for industrial robot evaluation, but their cost and the effort for pre-processing are substantial.

An alternative 3D measurement system can be based on inertial sensors or precision motion stages. The common inertial sensors are accelerometer and gyroscope based on micro electro mechanical systems (MEMS) technologies [9]. Due to MEMS technologies, this sensor can provide advantages, like low cost, small form factor, and light weight. However, the generated raw data need to be processed to get accurate 6D positions, which can be another source of error due to drift or noise [10]. The usual application of precision motion stages is for the attachment of sensors or grippers [11,12], like in the case of Atomic Force Microscopes (AFM) [13]. Based on the signal change coming from the attached ends, the current position of the precision motion stage can be utilized to measure the distance.

For measurement of 6D position with affordable cost, some researches utilize a parallel kinematic mechanism with embedded sensors. This is because this parallel kinematic

¹Certain trade names and company products are mentioned in the text or identified in an illustration to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

mechanism has already shown its accuracy by engaging multiple and canceling off noise. Due to this feature, parallel kinematic mechanisms have been used widely in applications like precision motion stages, solar trackers [14,15], etc. For Stewart platform, extensive prior work has been completed regarding the design [16], the modeling of parallel mechanisms [17,18]. Nanua et al. [19] presented a kinematic solution of a Stewart platform with three top joints and six bottom joints. Lawless et al. [20] derived a control model for adaptive velocity-based real-time application. Although much work has been done in application [21], design, manufacturing, and calibration of Stewart platforms and parallel mechanisms, there is little work on the design of parallel mechanisms for motion tracking and measurement. Shi et al. [22] developed a method for kinematic calibration of a hexapod nanopositioner. Olarra et al. [23] proposed an experimental-based evaluation for a Stewart platform, which includes a derived kinematic model and its calibration. Oiwa and Ikuma [24] presented a calibration method for a six DOF parallel manipulator with a redundant passive chain. For measurement based on Stewart platform, Schiele et al. [25] measured the position of a robot end-effector using a 6 DOF parallel kinematic mechanism (called hexapod [26,27] or Stewart platform), which consists of an end-effector, a fixed base, and six telescoping legs between them. Nubiola and Bonev [7] built a six DOF parallel measurement system with the hexapod and the hexapod with six telescoping ball bars is also utilized in coordinate measurement machines (CMM) [6].

In this paper, a motion tracking system is proposed for affordable 6D measurement for industrial robots. For affordability, low-cost displacement sensors are utilized. To improve the measurement accuracy, the Stewart platform design and magnetic ball-and-socket joints are utilized. The fabricated system is calibrated with a commercial laser radar system and then measured the 6D motion of industrial robots to verify its portability and affordability. The design of the proposed device, the corresponding software to get the 6D measurement, and experiments are as followed.

2. Design of the motion tracking system

The main design objective of the proposed 6D motion tracking system is to utilize low cost linear displacement measurement sensors and multiply their capability to a 6D position and orientation measurement sensor by utilizing a parallel kinematic mechanism, which is a Stewart platform [19] with magnetic ball-and-socket joints. The proposed system is designed with six sensors attached on the struts of the Stewart platform and the magnetic ball-and-socket joints are used for the bottom six joints and top six joints making the calibration process simpler and more accurate. A commercial laser radar system (LR) like Nikon MV-200¹ can measure the 3D coordinates of the center of a tooling ball, with the measurement uncertainty of ± 0.100 mm. This is accomplished by scanning its surface and finding the spot where a maximum intensity of the reflected laser light is measured. This instrument is utilized in this study to measure the 3D coordinates of the center of the stainless-steel balls used in the magnetic ball-and-socket joints, which is identical to the center of the joint rotation. With this feature, the proposed system is designed to make all the joints visible from a single point of view. Thus, the measurement of the 3D coordinates of the centers of rotation of the twelve joints are measurable from a single point of view. Thus, additional registration among multiple measurements is avoidable, so the calibration of the sensors and

the measurement of the geometric features (kinematic model) of the proposed system are straightforward and simple to use. Details are given in the following sections.

2.1. Mechanical design

Fig. 1(a) shows the fully assembled 6D motion tracking system. This design follows the typical Stewart platform and is composed of a top plate, a bottom plate and six struts between them. The top plate is a flat plate serving as the interface to the external applications such as industrial or collaborative robots. The bottom plate is firmly fixed to the ground. The six struts connect the top plate with the bottom plate and allows the 6D motion of the top plate relative to a fixed bottom plate, as a typical Stewart platform does.

Fig. 1(b) shows the schematic design; the strut consists of a sliding mechanism and two joints. The sliding mechanism allows one DOF linear motion and the joints allows three DOF rotation. When the top plate is in motion with respect to the bottom plate, the linear slider allows the length change of each strut for 6D motion and the two joints allow rotational motions. The details about each component are described in the following section.

2.2. The strut with a linear slide potentiometer

The strut used in the proposed system is shown in Fig. 2(a) consisting of a linear slider, a linear slide potentiometer, and two joint sockets. The two sockets are located at both ends and used as a component of a magnetic ball-and-socket joint. Each socket has a neodymium magnet to hold a stainless-steel ball shown in Fig. 1(a). Fig. 2(b) is the strut without the two joint sockets and Fig. 2(c) and Fig. 2(d) show its 3D design. The linear slider is composed of a sliding rod, a linear bearing and a case made of aluminum as shown in Fig. 2(d). The linear slider allows the change of the strut length, as described before and the corresponding length change is measured by the linear potentiometer connected to the slider through the lever in Fig. 2(d). The two sockets and a blue housing for the slide potentiometer are made with 3D printed Polylactic Acid (PLA).

2.3. The top and the bottom plates and their assembly

The top and the bottom plates are designed and built as shown in Fig. 3(a) and (b), respectively. The top plate is composed of three arms and six stainless-steel balls; three arms hold the six balls in 3D space and are designed not to hide the balls from a commercial laser radar system described before. The stainless-steel balls will be attached to the magnetic socket on the top of the strut to form a magnetic ball-and-socket joint. The bottom plate is similar with the top plate, and has a few mounting holes to hold it firmly on the ground.

With the two plates and the six struts, the proposed 6D motion tracking system can be assembled as shown in Fig. 3(c). By carefully selecting the viewing point, the whole twelve balls in the joints can be visible. A commercial laser radar system will be placed at this viewing position to measure the 3D space position coordinates of all twelve ball centers without moving the proposed hexapod system. With the assembled system, all six potentiometers are electrically connected to their power supply and their output is monitored by a computer data acquisition system. Once the six streams of potentiometer data are

obtained from the struts in real-time, the position and orientation of the top plate will be calculated by a computer program, which is described in the following section.

3. Theoretical analysis

Once the length data from the hexapod six struts are obtained, the 6D motion of its top plate can be calculated based on its kinematic model. A Stewart platform design in Fig. 1(b) is utilized to describe the proposed system. In the home position, the six joints for the top plate and the six joints for the bottom plate are aligned with their respective planes. For convenience, the following parameters are defined to describe the geometry of the kinematic model, as shown in Fig. 1(b). The length of each strut $i \in \{1, 2, \dots, 6\}$ is denoted as L_i and is denoted as the distance between the Cartesian centers of the two balls and socket joints, A_i and B_i , respectively, located at the end of the strut. At the platform's home position, we denote the positions of the six center points on the top platform and the six on the bottom stages as A_i^0 , and by B_i^0 , respectively. L_i^0 is the initial length of the strut i . These values were measured with a commercial laser radar system and are discussed in the following section.

When the stage is at the home position, the strut length will be equal to the distance between the two centers of the universal joints on the strut, as described below:

$$(A_i^0 - B_i^0)^T (A_i^0 - B_i^0) - (L_i^0)^2 = 0, \quad (1)$$

where, L_i^0 is the length of the strut i . For the inverse kinematics, the position of the moving platform in the proposed motion tracking system is considered as the input, while the output is a set of six dependent variables. Based on the different designs, we try to obtain the values of the variables, given the displacement of the top platform $[T] = [Rv]$. Here $[R]$ is the 3×3 rotation matrix and v is the translational vector. Given that the rigid top platform moves from the original position to the new position by the transformation matrix $[T]$, the positions of the top three spherical targets at the new position can be derived as:

$$A_i = [T]A_i^0 = [R]A_i^0 + v, i = 1, \dots, 6 \quad (2)$$

where A_i^0 are constants given in Table 2. The constraint equations of the kinematic model are obtained by equating the distance between the joints on the base and the joints on the platform to the strut length L , i.e.,

$$(A_i - B_i^0)^T (A_i - B_i^0) - L_i^2 = 0, i = 1, \dots, 6 \quad (3)$$

where $L_i = L_i^0 + \delta_i$, and δ_i is the change in length of strut i . By solving Eq. (3) for L_i , we can obtain δ_i , when the top platform is in a new position.

Contrary to the inverse kinematics, the implementation of the forward kinematics is not straightforward and its numerical processing takes too much time for real-time operation. Since the proposed system has to monitor the continuous motion in real time, it is desirable to find a stable, and fast, forward kinematics algorithm. The forward kinematics selected in this paper is based on the Newton-Euler approach [28,29]. This approach is able to get the motion and the orientation of the top plate, even if there is some moderate noise in the strut length measurements. This approach is implemented based on a design optimization approach by minimizing an error object function J_{obj} , where J_{obj} is defined based on Eq. (3) and is described below:

$$J_{obj} = \sum_{i=1}^6 ((A_i - B_i^0)^T (A_i - B_i^0) - L_i^2)^2 \quad (4)$$

The term J_{obj} indicates the summation of the difference between the real and calculated lengths from the inverse kinematics, so this approach is designed to find the parameters which can minimize the J_{obj} . This approach is described as follows:

1. Initialize the six parameters of the 6D motion of the top platform. The initial value of each parameter is set equal to the value of each parameter at its home position.
2. The strut length is calculated through the inverse kinematics based on the six parameters described in step 1 or obtained in step 6.
3. Six real strut lengths are obtained by converting the stream of the data from the slide potentiometers.
4. The objective function in Eq. (4) is calculated based on the data from step 3.
5. When the objective function reaches its minimum within the user-defined tolerance, the optimization process is terminated and proceed to step 7. If not, proceed to step 6.
6. A numerical sensitivity analysis is performed to get the gradient function, then a new set of the undetermined six DOF parameters will be selected and re-iterate steps 4 to 5.
7. Proceed to step 3, unless the user stops the process.

The implementation of the kinematic software is composed of three processes described in Fig. 4(a): a data acquisition process, a forward kinematics process, and a 3D visualization process. The data acquisition process should handle six streams of data from the six potentiometers in real-time simultaneously through a multi-channel National Instruments¹ DAQ card. The forward kinematics process is implemented based on the process above with the quasi-Newton approach from the Microsoft Solver Foundation 3.1¹ [30]. Experimental results show that the forward kinematics process takes (0.1 to 0.11) second for one 6D motion pose calculation (between (9 and 10) Hz). Based on the calculated position data, the 3D visualization process displays the top plate pose in 3D space using the 3D graphic library

OpenGL [31] and OpenTK [32] libraries for more intuitive understanding. All three processes are implemented with the C#¹ programming language, National Instruments DAQ library¹, and .NET framework¹ for tight collaboration among the three main processes.

Fig. 4(b) is a capture of the 6D measurement system and the corresponding results on a display in real-time. All the systems are installed on the top of a cart and the other components like power supplies and the computer are placed under the cart. Since all the systems are on a cart, this can move easily around any robot or objects to perform pose measurements. Once the proposed system is assembled, the proposed motion tracking system is experimentally calibrated and evaluated in the following section.

4. Experimental testing of the proposed system

4.1. Localization of the twelve joints

For good operating accuracy, it is necessary to get the accurate geometric dimensions for all components in the proposed system, especially the 3D space coordinates of the center of rotation of the six joints on the top plate and the six joints on the bottom plate. The accurate measurement of the coordinates of the center of rotation of the twelve joints will influence the movement accuracy of the proposed system. For this measurement, a commercial laser radar system (LR)[33], shown in Fig. 5(a) is utilized. The LR was developed to directly measure traditional tooling balls, trihedral or even reflective tape. The LR scans the surface of a ball spirally and finds the highest intensity reflection point. The highest intensity reflection indicates that at that point the laser beam is normal to the surface and is on the line passing through the center of the ball. Since the radius of the ball is already well known, the 3D position coordinates of the center of the ball can be calculated from this highest intensity reflection point. Instead of tooling balls, the LR measures the balls in the magnetic ball and socket joints shown in the inset of Fig. 5(b) in this study, where the red spot is the reflection of the laser beam emitted from the LR looking for the maximum reflection spot. In this case, the center of the ball in the magnetic ball and socket joint coincides with the center of the rotation of the joint. This method is a direct measurement of the ball center of rotation, so this can avoid additional processes coming from indirect methods. In addition to this, all the top six joints and the bottom six joints are extruded from their centers with slender beams. This skinny shape can reduce its hidden area and make them all visible from certain points of view. Hidden joints should be measured by rotating the object or by using a mirror. The only calibration processing left is a coordinate transformation of all the joints from the LR coordinate system to the proposed system. With this LR and the proposed system shown in Fig. 5(a), all twelve joints are measured, and the corresponding results are listed in Table 1. This measurement is done without any rotation nor any mirror, so no registration or translations are needed. All dimensions in Table 1 have a few mm level difference from its original CAD design, which comes from assembly and discrepancies in 3D printing. The top plate is about 170 mm above the bottom plate and the six joints on the top plate are located at the perimeter of a circle with a radius of 120 mm. The six joints on the bottom plate are located on the perimeter of a circle with a radius of 150 mm.

4.2. Characterization of the slide potentiometers

Once the geometric dimensions of all joints are obtained, the potentiometer attached to each strut needs calibration and performance evaluation. The calibration is the process to establish the relationship between the electric output from the potentiometer and strut lengths. For this calibration, the strut in Fig. 2(a) is installed with two balls in its two-magnetic ball and socket joints, and the distance between the two balls is measured by the same LR used in the previous section. By comparing the distance between the two balls with the electric output signal acquired from the potentiometer for several different lengths, the relationship is established and between the electric output from the potentiometer and the distance and the strut length L_{strut} can be expressed as:

$$L_{strut}(\text{mm}) = C(\text{mm}/V) \cdot V(V) + L_i(\text{mm}) \quad (5)$$

Where, V is the output from the potentiometer in V unit and the main parameters C and L_i are listed in Table 2. Once all the potentiometers are calibrated, the calibrated potentiometers are verified at several different lengths by comparing the calculated distance from Eq. (5) with the distance measured by the LR. With more than ten measurements, the test shows that the maximum distance error is less than 0.076 mm, and the average error is 0.01 mm, and its standard deviation is 0.041 mm.

4.3. Performance evaluation

The accuracy of the proposed 6D motion tracking system was evaluated after the previous calibration. The top plate is randomly placed in 3D space for more than ten different poses and those are measured by both the hexapod kinematic model software of the proposed system and the commercial laser radar system. By comparing the calculated 6D motion with the direct measurement from the commercial laser radar system, the accuracy of the proposed system is evaluated numerically. The corresponding results are plotted in Fig. 6(a) for translational motion measurements and Fig. 6(b) for rotational motion measurements, respectively. The test motions of the coordinate system in Fig. 6(a) is based on the coordinate system of Fig. 1(b).

From translational motion measurements, the horizontal axis in Fig. 6(a) shows that the proposed system can perform horizontal motions ranging from -18 mm to 31 mm and vertical motions of up to 23 mm. The corresponding errors with respect to the commercial laser radar system measurements are plotted on the vertical axis in Fig. 6(a). This error tends to increase with larger motions. Their average error values and their standard deviations are listed in Table 3. The average translational error is less than 0.186 mm with the standard deviation less than 0.441 mm. The error along Z-axis is relatively smaller than the other directions, which is common at Stewart platform design.

For the rotational motion measurement, the horizontal axis in Fig. 6(b) shows the proposed system can measure the rotational motions up to 31° . The corresponding errors plotted in the vertical axis in Fig. 6(b) shows that there are no strong relationships between the rotational angles and its measurement error, but some random fluctuations. Their average error and its

standard deviation are listed in Table 3. The average rotational error is less than 0.160° with the standard deviation less than 0.528° .

The maximum measurable range of the proposed system is approximately 90 mm along the X-axis, 90 mm along the Y-axis, and 40 mm along the Z-axis, respectively. This range is based on the motion range of the struts engaged in the system and will be discussed later for the trajectory issue. Each top plate pose (position and orientation) measurement takes approximately 70 ms to 100 ms, so the data sample rate is 12 to 10 samples per second. Since all the data comes from analog potentiometers, this measurement speed depends on the data acquisition card and the computer processing time for the kinematic calculation. Thus, this measurement speed can be faster with a better computer and data acquisition hardware.

4.4. Test with a commercial industrial robot

After the calibration and self-tests described in the previous section, the proposed 6D motion tracking system is tested with one commercial industrial robot to verify its effectiveness. For this purpose, a seven DOF collaborative robot is tested. Since all the components of the proposed metrology system are on a cart, it can easily be moved in front of the robot. The end of the left arm plate of the robot is mechanically linked to the top moving plate of the proposed 6D motion tracking system as shown in Fig. 7(a). With this set-up, the robot is commanded to make a 50 mm movement along a straight line, which is repeated five times with two options: (1) The first option is a single 50 mm move command which is shown in Fig. 7(b) and another command back to its original position. (2) The second one is the same commands with four via-point, which is a series of five 10 mm move commands for a total of 50 mm and a series of five 10 mm move commands in the opposite direction to return to the original position, shown in Fig. 7(c).

The objective of this test is to show the usability of the proposed system, not to evaluate the performance of the commercial robot, so the motions from the commercial robot are simply monitored with the proposed system to check if there are any noticeable differences with the motion metrology system. With the set-up described above, the proposed 6D motion tracking system measured the position and orientation of the top plate attached to the robot arm.

The motions measured by the proposed system are plotted in 3D in Fig. 8(a); the blue line corresponds to movement of a single 50 mm movement and the red line for a series of five 10 mm movements. Fig. 8(b,c,d) show a portion of the X , Y and Z components of Fig. 8(a). From these figures, the proposed metrology system can track the motion of the robot arm well and has the capability to show the difference between them. The main difference of the two optional moves is that the second option move takes a longer period of time to execute because of the extra commands used for this option. The first option can generate motion faster than the second option, but the second option tends to keep a better track.

5. Conclusions

A 6D motion tracking system is proposed and designed. The fabricated system is also utilized to evaluate the performance of a commercial robot. The proposed system is relatively low-cost and easy to move, so this can evaluate the performance of industrial robots periodically without any significant effort.

For these purposes, the proposed 6D motion tracking system is designed based on the features below:

1. a six DOF motion platform is designed based on a well-known Stewart platform mechanism,
2. low-cost slide potentiometers are attached to the struts of the proposed system to monitor the 6D motion,
3. a magnetic ball-and-socket joint is utilized at twelve joints of the proposed system, which is preferred for simple calibration and quick maintenance, and
4. the kinematics software is designed based on the quasi-Newton approach to calculate the position and orientation data of the top plate.

The performance of the proposed system is evaluated by comparing with a commercial laser radar system showing that the average error of the proposed motion tracking system translational motion error is less than 0.186 mm and the rotational motion error less than 0.160 °. Considering the performance of the industrial robots, these values make the proposed system suitable for monitoring the industrial robots. In addition, the real-time continuous motion of a commercial robot is also monitored by the proposed system without any significant effort. This test shows that the proposed system can be a low-cost alternative to existing solutions to evaluate the performance of commercial robots routinely.

The performance of the proposed tracking system can be improved by replacing the linear slide potentiometers with μm level accuracy sensors, like linear variable differential transformer (LVDT) displacement sensors or linear encoders. If the displacement sensor is replaced by a force sensor, this system can be converted to a six DOF force/torque sensor as well.

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(a)

(b)

Fig. 1.

The proposed 6D motion tracking system: (a) a fabricated system; (b) schematic drawing.

Fig. 2.

The strut with a slide potentiometer: (a) the strut with the two joint sockets; (b) the strut without the two sockets; (c) the 3D CAD of the strut; and (d) the cross-sectional view of (c). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

Fig. 3.
 The assembled 6D motion tracking system: (a) the top plate; (b) the bottom plate attached on ground; (c) The assembled proposed hexapod system.

(a)

(b)

Fig. 4.

The kinematic software: (a) three main processes; (b) demonstration of the kinematic software operating on real time to determine the top plate position and orientation (pose).

Fig. 5. The proposed 6D motion tracking system being calibrated by a commercial laser radar system: (a) A commercial laser radar system is monitoring the proposed system; and (b) the data captured by the software (inset: a laser spot searching for the center of the ball).

Fig. 6.

Measurement errors: (a) The translational motion errors along X , Y , and Z axis; (b) The rotational motion errors along X , Y , and Z axis.

Fig. 7.

Measurement setup with a commercial robot arm: (a) The mechanical set-up; (b) a single 50 mm move command for 50 mm movement; and (c) a series of five 10mm move commands for a total of 50 mm movement.

Fig. 8. Measurement of the position of the robot arm end plate; (a) Motion in 3D plot; (b) the X component of (a); (c) the Y component of (a); and (d) the Z component of (a). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

Table 1

3D position of the Cartesian centers of the twelve joints at home position.

Joints	X(mm)	Y(mm)	Z(mm)
A_1^0	71.306	-91.749	170.245
A_2^0	85.271	86.425	168.754
A_3^0	47.697	112.550	168.504
A_4^0	-112.872	35.253	170.064
A_5^0	-117.102	-10.626	169.958
A_6^0	30.104	-112.134	170.087
B_1^0	129.535	-30.208	1.429
B_2^0	133.036	9.187	0.590
B_3^0	-38.529	127.062	-2.222
B_4^0	-74.371	110.277	-2.277
B_5^0	-91.067	-96.795	0.836
B_6^0	-58.606	-119.523	1.644

Table 2

Calibration parameters for the six slide potentiometers.

Strut	Conversion coefficient (C in mm/V)	The default length (L_i in mm)
1	17.572	151.05
2	18.186	150.98
3	17.935	155.85
4	17.368	148.79
5	17.816	152.98
6	17.159	155.92

Table 3

Error measurements of the motion tracking system.

Motion errors		Average	Standard deviation
Translation	X	0.056 mm	0.263 mm
	Y	−0.177 mm	0.348 mm
	Z	0.016 mm	0.062 mm
Rotation	X	−0.068 °	0.253 °
	Y	0.139 °	0.359 °
	Z	−0.040 °	0.086 °