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A Six-Dimensional Motion Measurement Device with Micrometer-Accuracy ⋆

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Abstract: This paper presents a novel six-dimensional Motion Measurement Device (MMD). The MMD consists mainly of an upper plate, a lower plate, and six ball bars. Each ball bar has two high precision balls at its ends and uses a linear optical scale as the displacement sensor. The six ball bars connect the two plates to form the parallel measuring kinematics of a Stewart platform. The MMD can be mounted on the main spindle of a multi-axis CNC machine tool or the end-effector of a robotic manipulator. When the dynamical system is driven by the motion controller, the MMD simultaneously measures the lengths of the ball bars and obtains the actual pose of the tool. The MMD can be used for six-dimensional pose measurement in kinematic calibration. It also enables closed-loop position/orientation control for the end-effector of a robotic manipulator.

Keywords: Motion measurement device, Six-dimensional pose measurement, Stewart platform, Ball bar, Micrometer-accuracy

1. INTRODUCTION

Robotic manipulators have been applied in several industrial applications. However, its positioning accuracy is significantly degraded by the structural flexibility, gear backlash, and joint friction which cannot be captured from the encoders installed at each joints. Therefore, it is essential to directly measure the position and orientation of the end-effector such that the possibility of closed-loop control is given. Methods to measure six-dimensional motion include using a traditional coordinate measurement machine (CMM) [Hammond (1999)], an enhanced 3D laser tracker [Kamali et al. (2016)], and a visual-based stereo camera system [Li et al. (2016)]. These approaches are either tedious to setup or incapable of providing micrometer-accuracy measurements in real-time. To address this unmet need, we develop a six-dimensional motion measurement device (MMD) based on the Stewart platform mechanism [Stewart (1965); Fichter (1986)].

The Stewart platform is well known for its parallel kinematics and six-dimensional driving capability. It consists of an upper plate, a lower plate, and six servo controlled legs. The joints on the upper and the lower plate are ball joints and U-joints, respectively. Through driving the six legs to given lengths, the upper plate moves to a desired pose relative to the lower plate. Much work of the Stewart platform in terms of modeling [Clinton et al. (1997)], kinematics [Liu et al. (1993)], construction [Cleary and Arai (1991)], calibration [Oiwa and Ikuma (2014)], and dynamic control [Kumar et al. (2015)] has been done in the past five decades. However, it is very challenging to construct a Stewart platform with micrometer-accuracy due to its complexity of kinematic structure and sensitivity to mechanical and thermal errors.

The idea of this research is to develop a high accuracy six-dimensional MMD based on the parallel kinematics of the Stewart platform. Similar idea has been found in a recent publication [Kim et al. (2019)], but the measuring error was reported more than 0.1 mm, which is not yet acceptable for industrial applications. On the contrary, our MMD exhibits the accuracy of position measurement in the level of ± 1 μm after calibrating the geometric and thermal errors. With the high-accuracy and real-time pose measurement provided from the MMD, fast and accurate servo control of robotic manipulators becomes implementable.

2. THE MMD AND ITS PRINCIPLE OF MEASUREMENT

The developed MMD is shown in Fig. 1, which consists of an upper plate, a lower plate, and six ball bars. Each ball bar has two high precision balls at its ends and uses linear optical scale (TONiC Readhead / RELM20 INVAR linear scale, Renishaw Co.) as displacement sensor. Different from the traditional Stewart platform, the two plates of the MMD connect with the ball bars via magnetic ball joints. This arrangement avoids mechanical errors in the U-joint and contributes to the supreme accuracy of the MMD. To measure the motion of a machine, the upper plate is mounted on the tool holder and the lower plate is fixed on the work table. Then install the six ball bars connecting the two plates to form the parallel measuring kinematics (see Fig. 1b). The open kinematic chain of the machine between the tool and the workpiece is thus closed by the six ball bars of the MMD.

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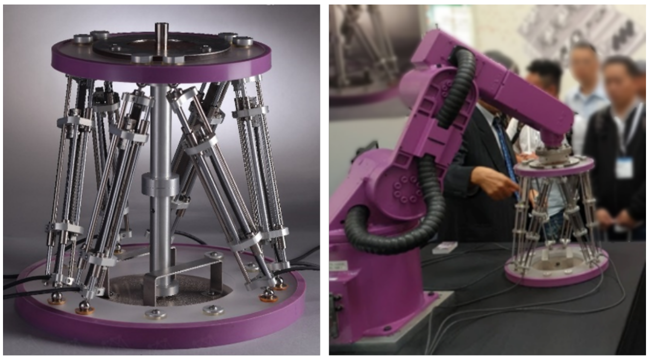


(a) (b)

Fig. 1. The developed motion measurement device. (a) Based on the Stewart platform, the MMD is capable of performing six-dimensional motion measurement in real-time; (b) The application of the MMD in measuring the pose of the end effector of the robotic manipulator.

The MMD performs both forward and backward kinematic transformation in processing the measured data. The kinematic parameters for the transformation are the positions of the ball joints on the upper plate and the lower plate, and the lengths of the six ball bars. The forward kinematic transformation calculates the pose of the upper plate coordinate system from the measured lengths of the ball bars. The inverse kinematic transformation calculates the lengths of the ball bars from the given pose of the upper plate.

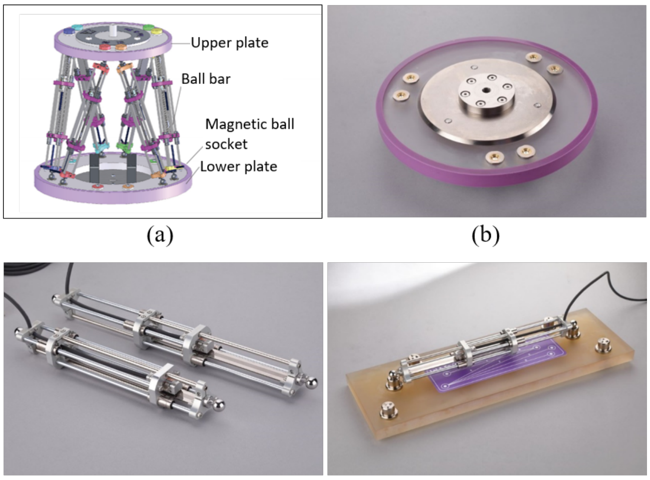
The MMD is a passive measuring device and does not have any actuation unit. The relative motion between the upper and the lower plate is the result of tool driving. The MMD measures the lengths of the ball bars, performs the forward kinematic transformation, and obtains the pose of the upper plate relative to the lower plate in real-time. The pose of the tool relative to the workpiece is then derived. The real-time obtained tool pose contains the effects of system dynamics, geometric errors, and thermal errors of every single element in the kinematic chain of the machine.

3. THE MMD CONSTRUCTION AND ERROR COMPENSATION

3.1 The upper and the lower plate

The MMD is to perform inspections or measurements on the shop floor, where no temperature control is expected. Therefore, the MMD itself must keep its accuracy in the allowable temperature range. This requirement can be achieved by the selection of low coefficient of thermal expansion (CTE) material for the MMD components and the use of effective methods for the thermal errors compensation.

The upper plate and the lower plate of the MMD in Fig. 2b have two-layer design: position layer and load-bearing layer. To ensure that the positions of the ball joints are thermally stable, the ball sockets are inserted into the position layer made of ceramic glass with a CTE less than 0.5 ppm. The height of the socket is minimized to avoid bending moment exerting on the ball socket. The use of near-zero CTE material such as ZERODUR for the two plates is even better, but much more expensive. The ceramic glass position layer is supported by a load-bearing layer which is made of INVAR alloy. Its CTE is about 2 ppm. All internal and external mounting forces and moments are acted on the INVAR layer and should not transmit to the position layer.



(a) (b)

(c) (d)

Fig. 2. The components of the MMD. (a) The construction of the MMD; (b) The upper plate; (c) The ball bar; (d) The reference plate.

The accuracy of the MMD is determined by the accuracy of its kinematic parameters. Hence, the position of each ball joint on the upper plate and the lower plate must be measured exactly, for example by using a coordinates measuring machine (CMM) with ultra-high accuracy.

3.2 The ball bars

The ball bar shown in Fig. 2c consists of a readhead assembly (left) and a scale assembly (right). Each assembly uses three parallel rods to form a spatial structure, which maximizes the flexural rigidity of the ball bar and enables high stiffness against bending moment. Among the three rods, two are guiding rods and the third is a tension rod. All rods are made of INVAR alloy with a CTE of 2 ppm. Each assembly has two linear guides with circulating balls to guide the other assembly. The ball bar uses an optical scale for the displacement measurement. The CTE of the scale is 0.7 ppm. The resolution is 50 nm.

To eliminate possible geometric errors caused by the ball-socket joint, the balls at the ends of the ball bar are of the grade 3 or better. According to the Standard ABMA/ANSI/ISO-3290 Grade Specifications, the sphericity of a grade 3 ball is less than 0.076 μm and the surface roughness is less than 0.01 μm. Therefore, the run-out error of the ball-socket joint is expected to be lower than 0.1 μm.

3.3 Geometric error compensation of the ball bars

The ball bar is bound with geometric errors. The stiffness of the ball bar is limited and its weight may cause a deflection. The optical scale is also not ideal. It has linearity errors because it measures the deflected length of the ball bar. It is important that the displacement sensor of the ball bar is measuring the actual distance between the two balls, not the deflected length.

To eliminate the geometric errors of a ball bar, a reference plate of near-zero CTE (<0.01 ppm) is included in our system. There are seven three-point supported magnetic ball sockets on the reference plate (Fig. 2d), and seven reference distances predefined by couples of the ball sockets. Before the real-time measurement using the MMD, each ball bar must be initialized first. To do this, the ball bar is placed on the reference plate for seven times with different reference distances. Each reference distance and the corresponding reading of the ball bar build a calibration point. After the initialization, seven calibration points are obtained and the relationship between the reading of the ball bar and its exact center distance is described by a linear least squares fitting function, also known as the center distance function (CDF).

In addition, the initialization of the ball bars is conducted under the ambient temperature. The thermal errors of the ball bar at the moment of initialization is included automatically in the CDF function. That means, the CDF function also compensates for the initial thermal error of the ball bar.

3.4 Thermal error compensation of the ball bars

When implementing the MMD with micrometer-accuracy, time-varying thermal errors become a critical factor that limits the accuracy of the ball bars' measurements. Fig. 3(a) shows the measured thermal errors of eight ball bars. Eight ball bars are placed on eight reference plates of CTE 0.5 ppm at time zero. Their lengths are 320 mm. The readhead is warmed up for 30 minutes. The room temperature remains practically unchanged. Then the readings of the ball bars are reset and the air conditioner is switched on for 5 hours. In the period between 30 and 330 minutes, the thermal errors are resulted from the change of room temperature from 30 to 24 degree Celsius. After the air conditioner is switched off, the room temperature raises slowly to 29 degree Celsius. The experimental results show that the thermal errors of the ball bars are around 5 μm.

To compensate for the ball bar's thermal errors, the MMD uses an extra ball bar and assigns it as reference ball bar. The six ball bars connecting the two plates are labeled as working ball bars. During the real-time motion measurement, the reference ball bar is placed on the reference plate of near-zero CTE. Since the CTE of the reference plate is near-zero, the reference distance remains constant regardless of the changing ambient temperature. A change of readings of the reference ball bar is the thermal effects on the reference ball bar. The real-time measured thermal errors are then used for the compensation of thermal errors of all working ball bars.

Fig. 3(b) shows the effectiveness of the thermal errors compensation with the reference ball bar. After the compensation, the thermal errors of the working ball bars reduce from 5 μm to ± 0.4 μm. It is clear that minor differences exist between the thermal errors of each ball bar. A reasonable decision is to select the ball bar having the mean thermal error as the reference ball bar.

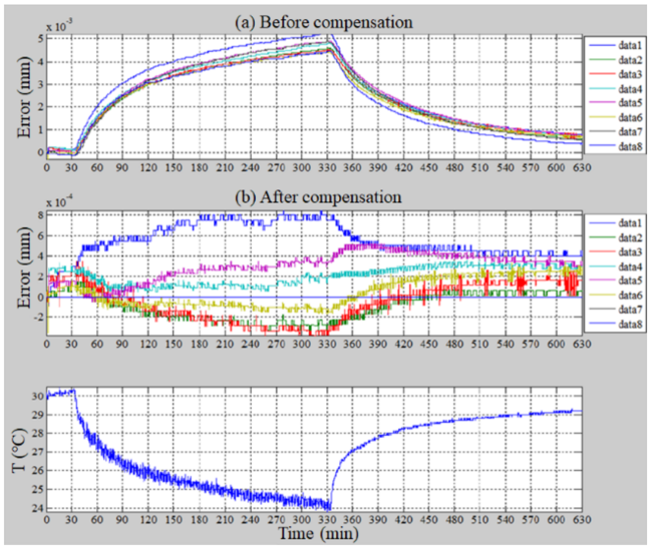


Fig. 3. Measured and compensated thermal errors of the ball bars.

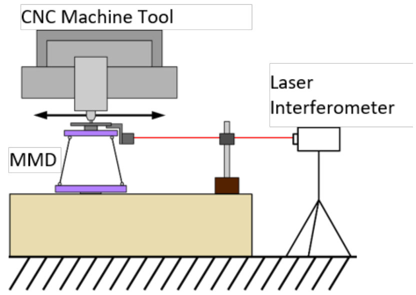


Fig. 4. The experimental setup for evaluating the accuracy of the MMD.

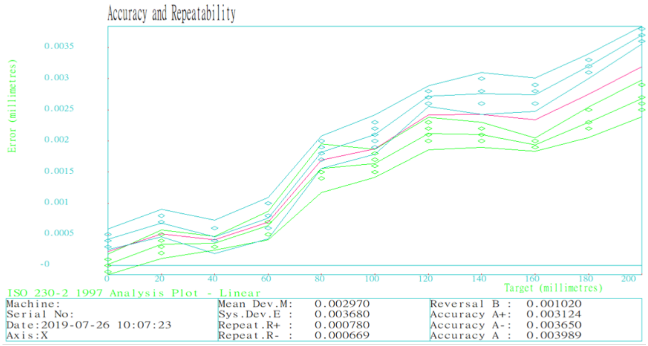
4. EVALUATION OF MMD'S ACCURACY

The kinematic data of the developed MMD are as follows:

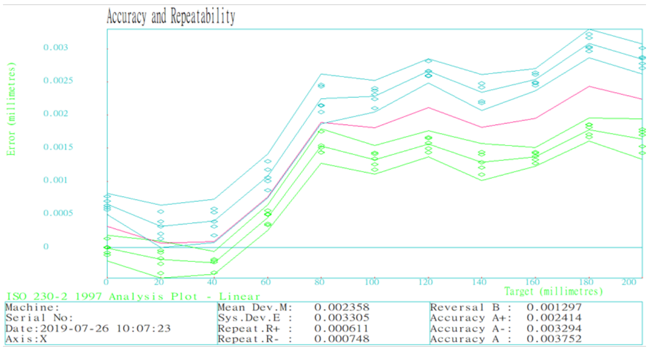
- Circle diameter of the ball joints on the upper/lower plate: 200/280 mm
- Angles for the periodically distributed ball joints: 20/100 degrees
- Measuring range of the ball bar: 250-376 mm

To evaluate its measuring accuracy, the MMD and the laser interferometer (XL80, Renishaw Co.) are setup with a machine tool schematically shown in Fig. 4. The beam reflector is mounted on the upper plate of the MMD. The CNC controller of the machine tool drives the one-dimensional translation along the MMD's X-axis according to the ISO 230-2. The MMD and the laser measure the accuracy and repeatability of positioning errors at the same time. The outputs of the two measuring systems are then compared. Note that it is important to ensure that the measured target of the MMD and that of the laser interferometer are the same. That means, the laser path, the machine's motion direction, and the X-axis of the MMD must be collinear.

Fig. 5a and Fig. 5b show the outputs of the laser interferometer and the MMD, respectively. It can be seen that the two outputs are nearly the same regarding the

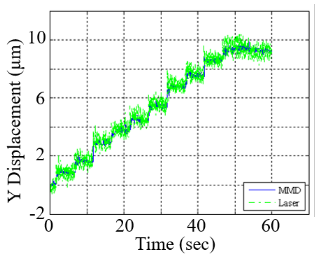


(a)

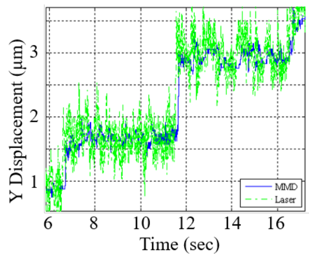


(b)

Fig. 5. The positioning errors of the CNC machine tool. (a) Measured from the laser interferometer; (b) Measured from the MMD.



(a)



(b)

Fig. 6. Comparison of the dynamical motion measurement from the laser interferometer and the MMD. (a) The step motion measured from the laser and MMD, respectively; (b) The zoomed-in section between $t = 6$ to 16 s.

eight statistically evaluated errors, which are listed at the bottom of the figure, including the mean deviation M, the system deviation E, and the reversal B. In the test range of 200 mm, all deviations are less than 1 μm. Specifically, the system deviation E is 0.003680 mm evaluated by the laser interferometer, 0.003305 mm by the MMD. The deviation is 0.000375 mm. Similar results are also obtained in the measurement of positioning errors along the MMD's Y- and Z-axis. Note that the ISO230-2 uses two standard deviations for the evaluation of positioning errors. That means the MMD has the capability of providing high-accuracy position measurements as the laser interferometer does.

We also apply the similar approach to evaluate the MMD's accuracy in measuring the tool orientation. The deviations of the eight statistically evaluated variables in measuring the pitch and roll errors are within 1 arc-second. Finally, the capability of dynamical measurement of MMD is tested. The machine performs consecutive step positioning of 1 μm. The responses are measured by the MMD and the laser interferometer. Fig. 6 shows the results. The step responses measured by the MMD match the laser interferometer's readings. It can be seen that the dynamics of the MMD is also comparable to the laser interferometer.

5. CONCLUSION

A novel MMD is presented in this paper. The developed MMD has genial design and effective compensation methods for geometric and thermal errors to achieve supreme high accuracy. Experimental results have proved the accuracy of the MMD in linear positioning measurements is in the level of ± 1 μm. In the future more investigations in frequency domain will be done to gain more knowledge about the system dynamics of the MMD.

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