The use of parallel mechanism micro-CMM in micrometrology

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Abstract*— Over the past two decades there has been a surge in demand for accurate and precise 3D metrology machines to provide measurements in micron scale. This demand is encouraged by the need for quality and process control for the promised technological development of micro electromechanical systems (MEMS). Parallel mechanisms have been the subject of study as positioning machines. Parallel manipulators used as small scale coordinate measuring machine, micro-CMMs, to provide measurements with submicron accuracy for MEMS products with ever decreasing dimensions. This paper highlights some research activities in micro-CMMs. Initially, the advantages of the parallel mechanisms over their serial counterpart CMMs (such as high stiffness, high accuracy, and low inertia), as well as the disadvantages (such as complex forward kinematics, small workspace, complicated structures, and a high cost) are introduced. Then an identification of the major error sources in these structures is presented. Later, the kinematics and the concept of calibration is introduced. Additionally, the main characteristics of the existing methods of calibration and error compensation are discussed. Finally, concluding remarks concerning micro measurements using micro-CMMs are given.

Keywords- micro-CMM; parallel manipulator; micro-measurement.

I. INTRODUCTION

The machining, assembly, inspection and quality controlling of small objects such as MEMS require high positioning accuracy. During the past two decades great attention has been given to micrometrology to fill the gap between the ultrahigh precision measurements of nanometrology and macrometrology [1]. The ratio between measuring range and accuracy is known as the scale factor, see Fig. 1. In precision measurement this ratio is around 10-4. This scale factor can be achieved by conventional measuring methods within the macro and nano scale, while a gap between nano and macro scale measurements exists in the scale interface [2].

II. MICRO METROLOGY AND MICRO-CMMS

Micro machines can provide a very high degree of precision and they consume much less energy than a regular machine. These characteristics make micro machines popular in many industrial fields. Some research on micro coordinate measuring machines (micro-CMM) is discussed in the following paragraph.

Isara (IBS Precision Engineering) is available in the market for ultra-precision measurements; it comprises a moving product table and a metrology frame with thermal shielding on which three laser sources are mounted [3], the working envelope is 100 mm x 100 mm x 40 mm, and it can reach uncertainty of 30 nm. The F25 micro-CMM (Carl Zeiss) is another product, with working envelop of 100 mm x 100 mm x 100 mm, and can provide uncertainty of less than 100 nm [4]. Moreover, the AI-Hexapod of Alio industries has a work envelope of 15 mm to 200 mm with resolution of 5 nm [5]. PI (Physik Instrumente) produced hexapods for high precision linear travel range of up to 100 mm with actuator resolution of up to 5 nm [6]. Further, the National Physical Laboratory (NPL) is currently conducting research on the probe so that measurements accuracy can be improved [7].

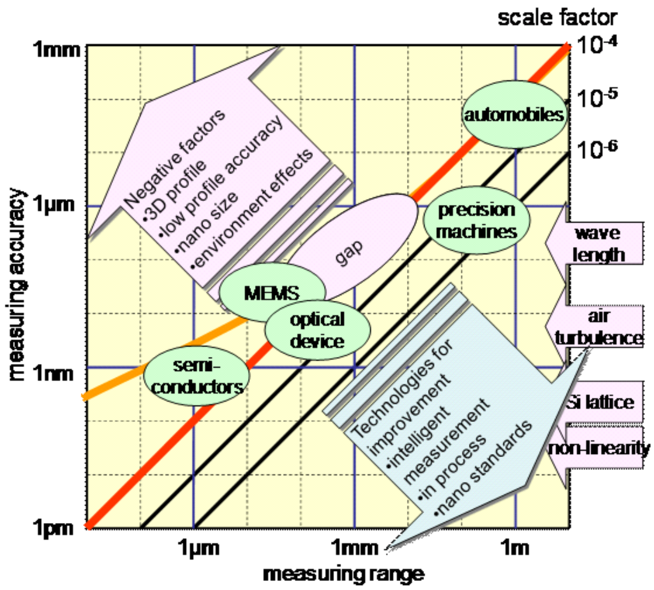

Fig. 1. Scale factor over scale interface [8].

Micro machines have attracted a renewed interest in introducing and developing new types of parallel kinematics machines [9]. Unlike the open-chain structure of the serial mechanisms, parallel manipulators consist of several links

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connected in parallel to create a closed-chain structure. Generally parallel manipulators consist of a moving platform and a fixed base, connected by several legs. Fig. 2 shows 3-DOF 3-UPU translation parallel robot which has been proposed in 1996 by Prof. Lung-Wen Tsai [10].

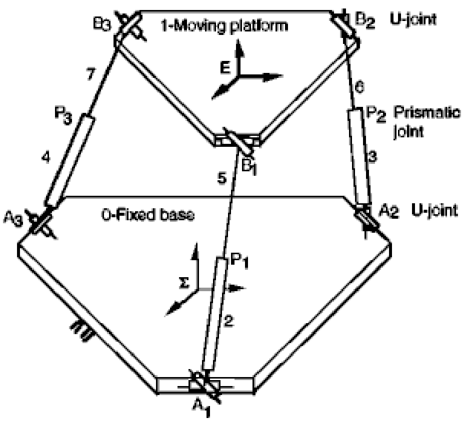

Fig. 1: Tsai's translation parallel manipulator (courtesy of Prof. Lung-Wen Tsai)

Parallel Kinematic Manipulators (PKM) were extensively studied as micro positioning and machining structures [11–13]. For instance, Liu [14] has developed a micro 3-PRS parallel manipulator, Harashima [15] has introduced an integrated micromotion systems, a micro parts assembly system, Zubir [16] presents a high-precision micro gripper that was designed by Bang [17]. Moreover, Gilsinn [18] worked on developing a scanning, tunnelling microscope using macro-micro motion system.

III. PARALLEL VS. SERIAL CMMS

The major advantages of parallel mechanisms as compared to their serial counterparts can be summarised as:

Firstly, higher accuracy, since its moving components are more strongly related and errors are not cumulative and amplified. Secondly, they have higher structural rigidity than the serial CMMs, since the end-effector is simultaneously carried by several legs in parallel. Lastly, they carry lighter moving mass, as the location of all the actuators and motors are in the base close to the end effector, allowing it to function at a higher speed and with greater precision [19]. Therefore, parallel robots are suitable for applications in which high speed, high positioning accuracy, and a rapid dynamic response are required.

Another advantage of the PKM is the solution of the inverse kinematics equations is easier. However, the problems concerning kinematics and dynamics of parallel robots are as a rule more complicated than those of serial one.

The main disadvantage of parallel CMMs is the limited workspace [20–22], and the difficulty of their motion control due to singularity problems [19,23]. Many researchers studied the singularity problem and workspace analysis of some planar parallel mechanisms [24,25].

As PKM are used for more difficult tasks, control requirements increase in complexity to meet these demands. The implementation for PKMs often differs from their serial counterparts, and the dual relationship between serial and parallel manipulators often means one technique which is simple to implement on serial manipulators is difficult for PKMs (and vice versa). Because parallel manipulators result in a loss of full constraint at singular configurations, any control applied to a parallel manipulator must avoid such configurations. The manipulator is usually limited to a subset of the usable workspace since the required actuator torques will approach infinity as the manipulator approaches a singular configuration. Thus, some method must be in place to ensure that the manipulators avoid those configurations.

In PKMs deformations caused by gravitation forces has very significant effect due to the non-constant stiffness of the structure within the workspace. In contrast, for serial kinematics machines the deformation can be considered constant in the entire workspace and therefore it can easily be automatically compensated in the calibration.

IV. ERROR SOURCES

The positioning accuracy of parallel mechanisms is usually limited by many errors, some authors identified the errors affecting the precision of parallel mechanisms as follows [19,26–28,19]: manufacturing errors, assembly errors, errors resulting from distortion by force and heat, control system errors and actuators errors, calibration, and even mathematical models. These errors should be divided into two main sources, static errors for those not dependent on the dynamics and process forces, and dynamic errors for errors due to the movement and measuring method [29].

A. Static errors

A high static accuracy is a basic requirement for any micromeasuring machine. Obviously the actual geometry of any machine does not match exactly its design. These differences may cause small positional changes of the probe.The machine then must be properly calibrated to identify its geometric parameters. Any manufacturing and assembly errors of the machine components, especially the joints, will introduce kinematic errors [30]. Sensor errors are caused by angular errors of the actuator (Abbey’s effect) and bending load caused by the weight of the actuator itself [31]. The kinematic errors can be drastically reduced by proper manufacturing and assembly of the machine parts and sensors. Previous studies showed the influence of joint manufacturing and assembly on the positioning error [19,32]. Moreover, Huang et al. [33] studied the assembly errors and used manual adjustable mechanisms to control assembly errors. The elastic deformations of the machine structure due to the flexibility of machine components could lead to gravitational errors, a numerical control unit can be used to compensation for the gravitation errors [34]. Moreover, thermal errors should be considered as another source that significantly affects the accuracy due to the thermal deformations and expansion of the legs [34]. Thermal errors can be reduced by compensating for the resulting thermal deformation of the components using a very complex thermal model [35].

Tsai [36], Raghavan [37], Abderrahim and Whittaker [38] have studied the limitations of various modelling methods.

B. Dynamic errors

These types of errors are dependent on configuration of the machine. Dynamic errors occur only during operating the machine and depend on the velocity, the acceleration and the forces applied on the end effector. The main sources are friction, wear and backlash occurring in the joints and actuators and deflection in the legs. Additionally, elastic deformations of the machine kinematics through process forces or inertial forces and natural vibrations of the machine can be another sources of dynamic errors.

Static errors are claimed to have the most significant effect on the machine accuracy [35]. Nevertheless, in high precision micro-CMMs the positional error of dynamic sources must be considered. Pierre [39] showed that the operation and the performance of the sensors significantly affect the precision of the manipulator. Hassan analysed the tolerance of the joints [40].

The performance of micro-CMMs in terms of accuracy and precision is influenced by numerous error parameters that require effective error modelling methods [32,41]. Moreover, the error models are of great importance in order to evaluate the machine and understand the effect of the different parameters. Forward solution for error analysis was also covered [42–44].

V. KINEMATIC MODELLING

Parallel mechanism modelling is usually divided in literature into two divisions namely kinematic or geometric models and the dynamic model [45].

The position kinematic model mathematically describes the relations between joint coordinates and the probe position and orientation. The change in the probe's pose is defined with respect to the reference coordinate system. While the dynamic model provides a relation between the probe's acceleration, velocity, coordinates and the influence of forces such as inertia, gravity, torque and non-geometric effects such as friction and backlash.

In serial mechanisms; one given joint position vector corresponds to only one end-effector pose. The kinematics problem is not difficult to solve. in contrast, in parallel mechanisms the solution is not unique, one set of joint coordinates may have different end-effector poses.

In 1986 Fichter [46] determined the equations to obtain the leg lengths, directions and moments of the legs and derived these equations for the Stewart platform. Later in 1990, Merlet [47] developed the Jacobian matrix, derived the dynamic equations and determined the workspace of general parallel manipulators. In general, the first step in solving the initial position is to create the forward and inverse position kinematic model by setting the non-linear equations that relate the manipulator variables and the probe pose, then in the next step the non-linear equation system can be solved using analytical or numerical methods or even graphical methods in simple mechanisms.

The position kinematic model can be solved by direct or inverse kinematics, depending on the input and output variables.

A direct position kinematic model (DPKM) is used to calculate the pose of the probe, given the values for the mechanism.

An inverse position kinematic model (IPKM) is used to calculate the mechanism's variables for a pose of the probe,

A differential kinematic model is usually used to determine singular configurations or to control the mechanism.

A direct differential kinematic model (DDKM) is used to obtain the velocity of the end-effector, given the joint velocities.

Inverse position kinematic model (IDKM) is used to obtain the joint velocities, given the velocity of the end-effector.

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Several studies have focused on solving the inverse kinematics of PKM either geometrically [48], analytically [48,49] or applying the Denavit-Hartenberg (D-H) model [50], the use of analytical methods is complex, given that the chains share the same unknown factors; therefore, the solutions are usually found using numerical algorithms. In rather simple systems geometric methods can be used. Rao [51] proposed the use of a hybrid optimization method starting with a combination of genetic and the simplex algorithm. However, for 2-DOF system applying an analytical solution can be more efficient.

In literature many methods have been developed to obtain a mathematical model to solve the direct kinematic of parallel mechanisms. This method determines the roots of one equation, representative of the direct position analysis, in only one unknown. Innocenti et al. [52] solved the direct position analysis and found all the possible closure configurations of a 5-DOF parallel mechanism, in [53] the same authors analysed a 6-DOF fully parallel mechanism. The developed method finds out all the real solutions of the direct position problem of a 6-DOF fully parallel mechanism. Merlet [54] suggested using sensors to solve the direct model and demonstrated that the measurement of the link lengths is not usually sufficient to determine the unique posture of the platform, and that this posture can be obtained by adding sensors to the mechanism. Sensors can be added by locating rotary sensors in the existing passive joints or by adding passive links whose lengths are measured with linear sensors.

In the following a kinematic modelling is presented for a micro-CMM that is been developed by the authors in the labs of the University of Stellenbosch.

The arrangement under study uses spherical joints to connect the three extendable legs to the moving platform and the upper frame. The spherical joints represent three rotational degrees of freedom (3-DOF). In this arrangement the use of spherical joints ensures that a very large workspace is achieved. However, the movement of the platform is restricted to always be parallel to the upper frame. The sacrifice of the rotational movement of the moving platform around the axes is beneficial for solving the kinematics model. Fig. 3 shows a schematic drawing of the micro-CMM machine under study.

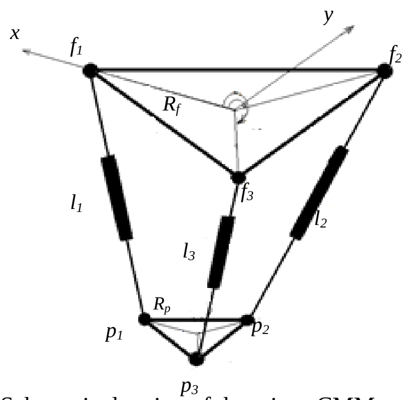

Fig. 3. Schematic drawing of the micro-CMM machine.

The coordinate system is shown in Fig. 4. The origin O_f-(0,0,0) is placed at the centre of the upper frame. The *x*-axis equally divides the angle at point f_1 and the *z*-axis is perpendicular to the frame plane.

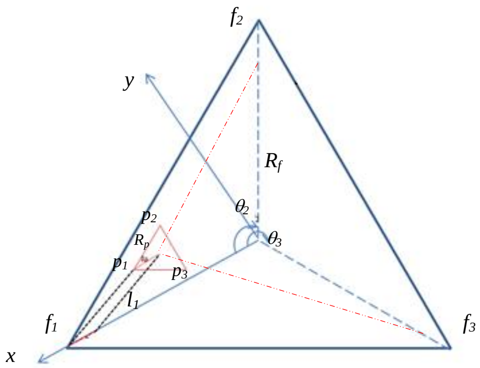

Fig. 4. The coordinate system.

The geometrical parameters are as follows:

R_f : the distance between point f_i and the origin O_f

R_p : the distance between point f_i and the origin O_f

θ_i : the angle point f_i makes with the *x*-axis, $\theta_1 = 0^{\circ}$, $\theta_2 = 120^{\circ}$, $\theta_3 = 240^{\circ}$

l_{min}, l_{max} : the maximum and minimum extensions of the legs.

Because of using spherical joints, the movement of the legs can be expressed by the equation of a sphere. Let's assume that the central point of the moving platform (x,y,z) is the point of intersection of three spheres, and thus, point fi must be shifted towards the point of origin O_f. by $(f_i - p_i)$ where:

$$p_i = [R_p \cos\theta_i \quad R_p \sin\theta_i \quad z]^T \tag{1}$$

$$f_i = [R_f \cos\theta_i \quad R_f \sin\theta_i \quad 0]^T \tag{2}$$

Then the equation of movement of the legs can be written as follows:

$$l_1^2 = \left[x - \left(R_f - R_p\right)\cos\theta_1\right]^2 + \left[y - \left(R_f - R_p\right)\sin\theta_1\right]^2 + [z]^2 \tag{3}$$

$$l_2^2 = \left[x - \left(R_f - R_p\right)\cos\theta_2\right]^2 + \left[y - \left(R_f - R_p\right)\sin\theta_2\right]^2 + [z]^2 \tag{4}$$

$$l_3^2 = \left[x - \left(R_f - R_p\right)\cos\theta_3\right]^2 + \left[y - \left(R_f - R_p\right)\sin\theta_3\right]^2 + [z]^2 \tag{5}$$

Where:

(x,y,z): the probe location

l_1, l_2 and l_3: the leg lengths.

The probe location can be found by solving eq's (3), (4) and (5). This yields explicit expressions for the *x*, *y* and *z* coordinates of the centre point

$$x = \frac{2l_1^2 + l_2^2 + l_3^2}{4\left(R_f - R_p\right)\left(\cos\theta_1 - \cos\theta_2\right)} - \frac{\left(R_f - R_p\right)\left(\cos\theta_2{}^2 - 1\right)}{2\left(\cos\theta_1 - \cos\theta_2\right)} \tag{6}$$

$$y = \frac{l_2^2 - l_3^2}{2\left(R_f - R_p\right)\left(\sin\theta_2 - \sin\theta_3\right)} - \frac{\left(R_f - R_p\right)\left(\sin\theta_2{}^2 - \sin\theta_3{}^2\right)}{2\left(\sin\theta_2 - \sin\theta_3\right)} \tag{7}$$

$$z = \sqrt{l_2^2 - \left[X + \left(R_f - R_p\right)\cos\theta_2\right]^2 - \left[Y + \left(R_f - R_p\right)\sin\theta_2\right]^2} \tag{8}$$

Previous equations are used to calculate the pose of the probe, given the values for the mechanism parameters. These equations represent the direct position kinematic model (DPKM) of the system

VI. PARALLEL MACHINE CALIBRATION

The calibration could be achieved measuring several mechanism configurations and identifying its respective kinematic parameters. Calibration can be done using model-based approaches and numerical approaches. Hollerbach et al. [55] obtained numerical calibration using the least squares method. Daney [56] used methods based on analysis of intervals to certify the calibration of PKM numerically.

The model-based calibration strategies can be classified into three types: external calibration, constrained calibration and self-calibration.

The self-calibration methods of parallel kinematics generally make use of a number of extra sensors on the passive joints. The number of sensors must exceed the number of degrees of freedom (DOF) of the mechanism. Each pose can be used as a calibration pose. These calibration methods are usually of low cost and can be performed inline. Yang et al [57] used the approach of redundant sensors to calibrate the base and tool by adding one or more sensors on the passive joint in an appropriate way to allow the algorithm to be applied. Singularity based self-calibration method is presented by Last et al. [58]. Parallel mechanisms can be calibrated with this technique only if they have singularities of the second type within their workspace. The advantages of this method are that it does not require any calibration equipment and it gets redundant information from particular characteristics in singular configurations

Constrained calibration methods are based on constraining the mobility during the calibration process, the idea is to keep some geometric parameters constant such as restricting the movement of the moving platform or the motion of any joint, as a result the number of DOF of the mechanism is decreased. The main advantage of these methods is they do not require extra sensors [45].

The calibration methods with external measuring systems is the most frequently used methods. In these methods, the information is obtained using external devices. External calibration can be divided in four categories: (1) calibration with vision as measurement device, (2) the approach of mobility restriction, (3) the approach of redundant leg, and (4) the approach with adapted device of measurement.

Independently of the method chosen, the calibration process is typically carried out using following steps:

The first step is always the development suitable kinematics model to provide a model structure and nominal parameter values.

The second step is data acquisition of the actual position of the moving platform through a set of end-effector locations that relate the input of the model to the output determination.

The next step is the identification of the model parameters based on the collected data by using a numerical method to obtain the optimum values of all the parameters included in the model to minimize the platform position error.

Final step is to identify the error sources and the modelling and implementation of the kinematics compensation models. These methods have been widely studied because of the advantages of these mechanisms.

VII. CONCLUSION

The scope of this paper focuses on the growing need of high accurate and precise measuring machines, specifically the use of PKM in micrometrology. PKMs are known to have useful advantages over their serial counterpart CMMs, these advantages include; high stiffness, high accuracy, and low inertia. Unfortunately, there are some disadvantages of using PKMs such as; complex kinematics, small workspace and complicated structure.

Different types of errors which significantly affect the accuracy are given, static errors are claimed to have the most significant effect. Nevertheless, dynamic errors must be considered for precise measurements. The static errors are caused by manufacturing and assembly errors, non-exact transformation and by the deformations of the machine kinematic through weight forces. Dynamic errors occur only during the operation and depend on the velocity, the acceleration and the forces.

Large amount of research is been carried out concerning developing and introducing new mathematical algorithms, measurement technique and calibration methods to improve PKMs performance. Different reported calibration methods were also presented.

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