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Introducing a new design of 3dof parallel micro-manipulator

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Abstract
In this work, new design of parallel micro-manipulator is introduced, the machine is intended to be used with high precision and high accuracy measurement of part dimensions in micron scale. The mechanism of the machine is passed on 3 degrees of freedom (3DOF) parallel manipulator, where the end effector of this machine carries touch probe. The major advantage of this design is eliminating the effect of Abbé error, and it is intended to achieve submicron accuracy for a work envelope of at least (100x100x100) mm. In this paper, the design and structure of the machine is presented, its coordinate system was developed and the mathematical measuring model to explicitly define the coordinate of the probe in x, y and z directions have been derived.

Keywords: Parallel manipulator, Kinematic modelling, Abbé error, precision measurement.

1. Introduction

The technology of micrometrology measurement has received much attention in research during the past two decades to fill the gap between the ultrahigh precise measurements of nanometrology and macrometrology [1]. However, here is still a gap for measurement systems that can measure in 3D over a distance of up to 100 mm to an accuracy of submicron but not quite at nanometre level. This limitation is due to either lack of accuracy or probing system [2].

Parallel CMMs have become a hot topic of research as micro positioning and machining structures [3], [4]. The main disadvantage of parallel CMMs is the limited workspace [5], [6], and the difficulty of their motion control due to singularity problems [7], [8].

With this paper the authors believe that at least some of the problems can be overcome with the proposed machine, such as workspace limitation, effect of angular errors and singularity problems. Therefore it is anticipated that these systems will come closer or even achieve the goal of a true micro-CMM.

2. Description of the machine design & Structure

The proposed machine consists of a moving tetrahedron frame with fixed angles between its legs, and the main vertex pointing downwards. The legs of this frame are carried by three runner blocks where they can slide freely. The runner blocks are connected to the actuated prismatic joints with spherical joints. Moreover, laser distance sensors are installed on the edges of the moving frame in order to acquire accurate measurement of the length of the legs. The movement of the prismatic joints are controlled by three linear motors. 3D view and top view of the machine are shown in Figure 1.

The arrangement of this machine provide movement in 3 degree of freedom (3-DOF), translation in z direction, rotation around x axis, and rotation around y axis. In other 3-DOF manipulators, like Oiwa's design [9], the workspace is very small because of the limitation of using rotational joints. this arrangement provides significant advantage by using spherical joints. The use of spherical joints ensures that larger workspace is achieved. Any point within the workspace can be reached by controlling the 3 linear actuators.

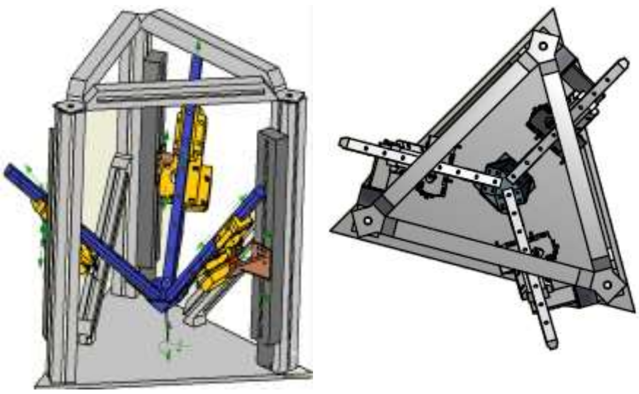

Figure 1. machine in 3D view (left), and top view (right).

This design is also singularity free within the whole workspace, which is beneficial to the motion control. Error due to joints is minimized by the reduced number of joints and connections, compared to other parallel manipulators. The design considers theoretically eliminating Abbé error, this is done by having the axes of measurement pointing towards the probe tip.

3. Coordinate system

The coordinate system is shown in Figure 2. The origin O(0,0,0) is placed at the centre of the base. The prismatic joints intersect with the base at points a, b and c, x-axis equally divides the angle at point a, and the z-axis is perpendicular to the base plane (a,b,c).

l_i : the distance between pivot point of the ball joint pi and the probe tip po

β_i : the angle between the tetrahedron legs, $\beta_a = \beta_b = \beta_c = 68^o$

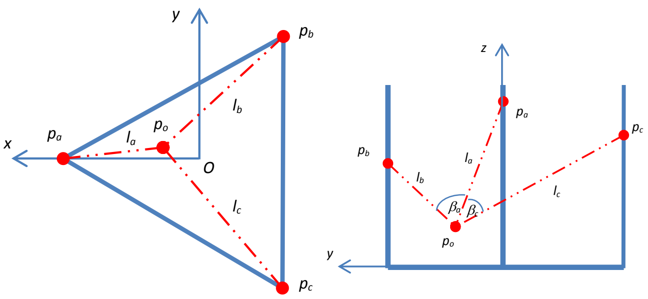

Figure 2. The coordinate system: top view *xy* plane (left), and front view *yz* plane (right).

4. Development of the kinematic model

Assume that the probe tip (*x*,*y*,*z*) is at the main vertex of the moving tetrahedron, which is the point of intersecting of the three legs. Because of using spherical joints, the equation of movement of the links can be expressed by the following governing equation:

$$l_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \qquad (1)$$

Let the subscript *i* and represent (*a, b, c*) when *i* rotates around *z* axes in clockwise direction, subscripts ip and in refer to the previous and next points, respectively.

From Figure 3 it is clear that values of the *z* coordinate of the moving motors (z_{in} and z_{ip}) can be calculated relative to *z* component of the stationary motor (z_i), where distances dz_{in} and dz_{ip} can be calculated provided that the links l_a, l_b and l_c, as well as angels (β) between them are known.

$$z_{in} = z_i - dz_{in}; \quad z_{ip} = dz_{ip} - z_i \qquad (4)$$

$$dz_{in}^2 = (d_{in})^2 - (b_{in})^2; \qquad dz_{ip}^2 = (d_{ip})^2 - (b_{ip})^2 \qquad (5)$$

$$d_{in}^2 = l_i^2 + l_{in}^2 - 2\, l_i l_{in} \cos(\beta_{in}) \qquad (6)$$

$$d_{ip}^2 = l_{ip}^2 + l_i^2 - 2\, l_{ip} l_i \cos(\beta_{ip})$$

Where *dz* is the height difference between pivot point of the joint on stationary motor and moving joints; d_{in} and d_{ip} are the distance between ith pivot point and the next and previous pivots, respectively; b_{in} and b_{ip} are the distance between pivot points at z_i, respectively; β_{in}, β_{ip} are the angles between leg l_i and legs l_{in} and l_{ip}, respectively.

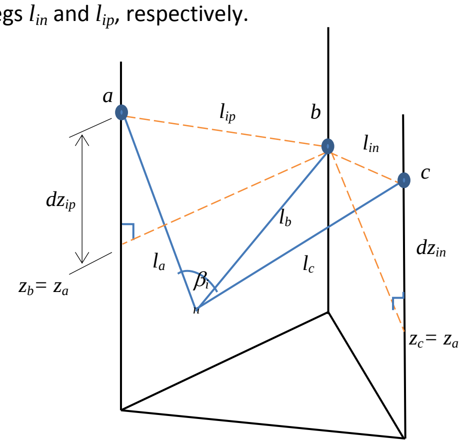

Figure 3. Schematic drawing of the machine. Point *b* is stationary.

At the start of the operation *z* is assumed to be equal to zero, or alternatively, the stationary point will have $z = -z_i$, and $z_i = 0$.

The coordinate of the probe location can be found by solving eq's (1), and replacing the values of zin and zip from eq (4). This yields explicit expressions for the *x*, *y* and *z* coordinates of the centre point of the probe as follows:

$$y = \frac{-v \pm \sqrt{v^2 - 4uw}}{2u} \qquad (7)$$

$$z = F + D\,y \qquad (8)$$

$$x = A + B\,y \qquad (9)$$

Where:

$$A = \frac{\left(\frac{c_{in} - c_i}{2\,z_{in}} - \frac{c_i - c_{ip}}{2\,z_{ip}}\right)}{\left(\frac{x_i - x_{ip}}{z_{ip}} - \frac{x_{in} - x_i}{z_{in}}\right)}; \qquad B = \frac{\left(\frac{y_i - y_{in}}{z_{ip}} - \frac{y_{ip} - y_i}{z_{in}}\right)}{\left(\frac{x_i - x_{ip}}{z_{ip}} - \frac{x_{in} - x_i}{z_{in}}\right)};$$

$$c_i = l_i^2 - x_i^2 - y_i^2 - z_i^2; \qquad D = \frac{y_{in} - y_i}{z_{in}} - B\,\frac{x_{in} - x_i}{z_{in}};$$

$$F = A\,\frac{x_{in} - x_i}{z_{in}} - \frac{c_{in} - c_i}{2\,z_{in}} \quad ;$$

5. Conclusion

The novel micro-CMM design proposed by this paper provides movement in 3-DOF, translation in *z* direction, rotation around *x* axis, and rotation around *y* axis. The workspace in this arrangement provides that a very large workspace is achieved. Any point within the workspace can be reached by controlling the 3 linear actuators. This design is also singularity free within the whole workspace, Positioning error due to joints is minimized by the reduced number of joints and connections, more importantly the design considers theoretically eliminating Abbé error.

References

[1] P McKeown, "Nanotechnology-Special article," in *Nano-metrology in Precision Engineering*, Hong Kong, 1998, pp. 5-55.

[2] H.N. Hansen, K. Carneiro, H. Haitjema, and L. De Chiffre, "Dimensional micro and nano metrology," *Annals of the CIRP*, **55**, no. 2, pp. 721-743, 2006.

[3] F Gao, W M Lin, and X C Zhao, "New kinematic structures for 2, 3, 4, and 5-DOF parallel manipulator designs," *Mechanism and Machine Theory*, **37**, pp. 1395–1411, 2002.

[4] X J Liu, J S Wang, and G Pritschow, "A new family of spatial 3-DOF fully-parallel manipulators with high rotational capability," *Mechanism and Machine Theory*, **40**, pp. 475–494, 2005.

[5] R Clavel and Delta, "A fast robot with parallel geometry," in *International Symposium on Industrial Robots*, Switzerland, 1988, pp. 91–100.

[6] John J Craig, Introduction to robotics: mechanics and control, 2nd ed. New York, USA: Addison and Wesley, 1989.

[7] Cheng Gang, Shi-rong Ge, and Yong Wang, "Error analysis of three degree-of-freedom changeable parallel measuring mechanism," *Journal of China University of Mining & Technology*, **17**, no. 1, pp. 101-104, 2007.

[8] K Sugimoto, J Duffy, and K H Hunt, "Special configurations of spatial mechanisms and robot arms," *Mechanism and Machines Theory*, **17**, no. 2, pp. 119–132, 1982.

[9] T Oiwa, "New Coordinate Measuring Machine Featuring a Parallel Mechanism," *International Journal of the Japan Society for Precision Engineering*, **31**, no. 3, pp. 232-233, 1997.