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A novel XY-Theta precision table and a geometric procedure for its kinematic calibration

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ABSTRACT

Spatial precision positioning devices are often based on parallel robots, but when it comes to planar positioning, the well-known serial architecture is virtually the only solution available to industry. Problems with parallel robots are that most are coupled, more difficult to control than serial robots, and have a small workspace. In this paper, new parallel robot is proposed, which can deliver accurate movements, is partially decoupled and has a relatively large workspace. The novelty of this parallel robot lies in its ability to achieve the decoupled state by employing legs of a different kinematic structure. The robot repeatability is evaluated using a CMM and so are the actual lead errors of its actuators. A simple geometric method is proposed for directly identifying the actual base and mobile reference frames, two actuator's offsets and one distance parameter, using a measurement arm from FARO Technologies. While this method is certainly not the most efficient one, it yields a satisfactory improvement of the robot accuracy without the need for any background in robot calibration. An experimental validation shows that the position accuracy achieved after calibration is better than 0.339 mm within a workspace of approximately 150 mm × 200 mm.

1. Introduction

Parallel robots are often said to be more precise than serial robots because they do not suffer from error accumulation. While this might be true in theory [1], the real reason is that parallel robots can be built to be stiffer without being bulkier.

Spatial precision positioning devices are often based on hexapods (e.g., those manufactured by PI and ALIO Industries) or tripods (e.g., the SpaceFAB manufactured by MICOS). However, when it comes to planar three-degree-of-freedom (3-DOF) positioning, virtually all commercial so-called *XY-Theta positioning tables* are based on the well-known sandwich setup illustrated in Fig. 1. This serial configuration has the advantage of simple motion control. However, being "serial" means that the first actuator has to support the weight of all the other actuators. As a result, the device would have to be large enough not only to support itself, but to absorb any vibrations caused by the motors. This means that such a device would be relatively large and sluggish as well.

Planar parallel robots have received considerable attention (see [2] and the references therein), yet very few of them are used in industry. Most precision positioning prototypes based on planar parallel robots rely on the use of flexures (e.g., [3,4]). Yet, such robots have a very limited workspace-to-footprint ratio, and are not an alternative to the XY-Theta stage in Fig. 1.

Among the few existing planar 3-DOF parallel robot prototypes that do not employ flexures, one is based on a symmetric 3-*PRP*[1] architecture [5], where the base actuators form an equilateral triangle and the platform linear guides form a star. This robot has a very limited workspace though. In contrast, the 3-*RRP* robot first disclosed in [6], then studied in [7], and of which a first prototype was reported in [8], offers unlimited rotation in addition to excellent stiffness in the vertical direction. However, the achievable accuracy of such a robot is questionable, since it relies on the use of a perfectly circular rail.

The only commercially available parallel XY-Theta positioning table, manufactured by Hephaist Seiko and at least two other Japanese companies, is the one shown in Fig. 2. This robot is also based on the 3-*PRP* architecture, but its design is asymmetric. The resulting positioning table is very rigid, since its mobile platform glides directly on top of three linear guides. Unfortunately, this design is highly coupled, meaning that to move in certain directions all three actuators must work in conjunction with one another. Furthermore, its workspace is severely limited, as illustrated in [9].

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[1] It is customary to refer to parallel robots using the symbols *P* and *R*, which stand for prismatic and revolute joints, respectively. When a joint is actuated, its symbol is underlined.

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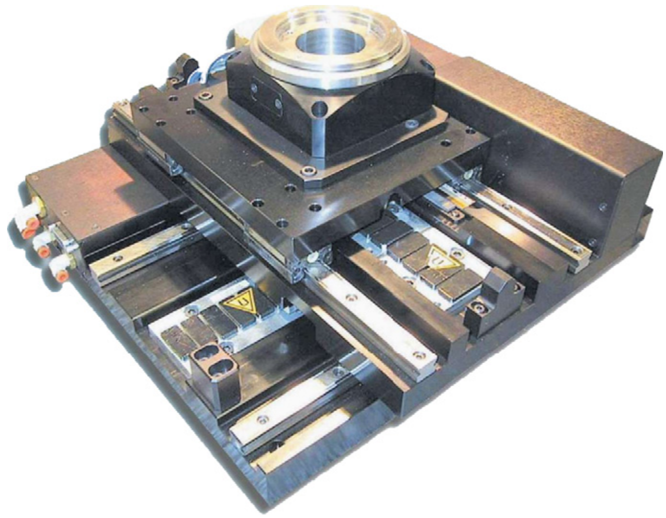

Fig. 1. A serial XY-Theta positioning table (courtesy of Newport Corp.).

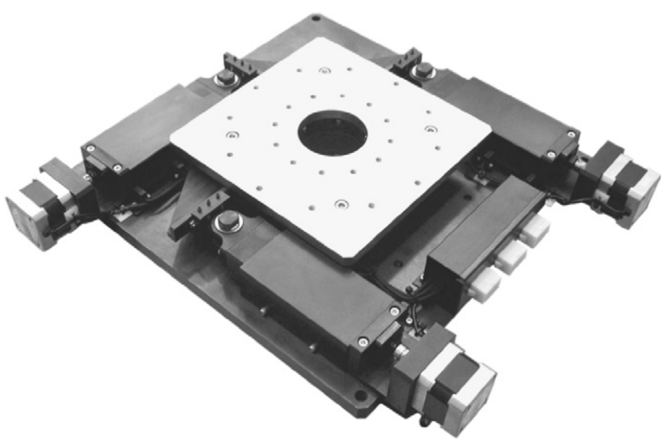

Fig. 2. NAF3 alignment stage (courtesy of Hephaist Seiko Co., Ltd.).

This paper presents for the first time the prototype of a novel patented XY-Theta parallel architecture [10], dubbed the PreXYT, that is both partially decoupled, rigid in all directions, and having a relatively large workspace, and proposes a geometric procedure for the kinematic calibration of the robot. In particular, Section 2 briefly recalls from [9] the kinematic analyses of the PreXYT, but in a slightly more general fashion. Section 3 discusses the actual prototype and Section 4 presents the results on the repeatability of that prototype, as assessed using a CMM (a Coordinate Measuring Machine). Section 5 briefly presents the identification of the lead errors for all three actuators, using the same CMM. Section 6 describes the proposed calibration procedure based on the use of a measurement arm and Section 7 presents the results on the improved accuracy. Finally, conclusions are provided in Section 8.

2. Kinematic analyses

2.1. Direct and inverse kinematic analysis

PreXYT is a parallel robot with one $\underline{P}$PR leg and two $\underline{P}$RP legs, as shown in Fig. 3. The directions of the actuators in legs 2 and 3 are parallel to the y axis of a base reference frame, while the direction of the actuator in leg 1 is parallel to the x axis. The two passive prismatic joints on the mobile platform are parallel and the axes of the three revolute joints are parallel and coplanar.

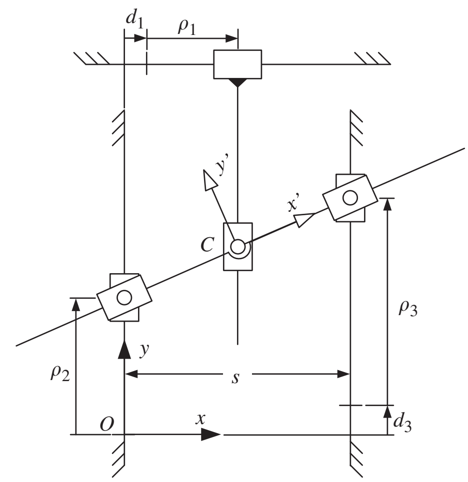

Fig. 3. Schematic diagram of the PreXYT.

The directions of the two prismatic joints in leg 1 are normal. Consequently, if the two parallel actuators move in conjunction with one another at the same rate, the mobile platform is only translated along the y axis. If the two move in opposite directions, a pure rotation about the z axis could occur. Finally, the other actuator directly controls the x coordinate of the platform's center.

Referring to Fig. 3, the base reference frame Oxy is fixed at the base so that the axis of the revolute joint of leg 2 always intersects the y axis, and a mobile reference frame $Cx'y'$ is fixed to the mobile platform so that the axes of the revolute joints of legs 2 and 3 always intersect the x' axis. The origin C lies on the axis of the revolute joint of leg 1. Finally, θ is the angle between the x and x' axes, measured counterclockwise.

Furthermore, ρ_1 is the active-joint variable associated with leg 1 and is defined as the distance between the y axis and (the axis of) the revolute joint of leg 1 minus an offset d_1 as illustrated in Fig. 3. Similarly, ρ_3 is the active-joint variable associated with leg 3 and is defined as the distance between the x axis and the revolute joint of leg 3 minus an offset d_3. The active-joint variable ρ_2 is defined as the distance between the x axis and the revolute joint of leg 2, i.e., the offset $d_1=0$. These offsets represent the relative positions of the mechanical limit switches. Finally, s is the distance between the y axis and the axis of the revolute joint of leg 3.

Given the active-joint variables, we are able to uniquely define the position and orientation of the mobile platform (i.e., of the mobile reference frame). The orientation angle is easily obtained as

$$\theta=\tan^{-1}\left(\frac{\rho_3+d_3-\rho_2}{s}\right), \tag{1}$$

While the position of the mobile platform is given by

$$x=\rho_1+d_1, \tag{2}$$

$$y=\rho_2+(\rho_1+d_1)\left(\frac{\rho_3+d_3-\rho_2}{s}\right). \tag{3}$$

As can be observed, the direct kinematic equations of the PreXYT are relatively simple, and the platform's x coordinate is directly defined by actuator 1, which is why our parallel robot is partially decoupled.

The inverse kinematics are also simple. Given the position and orientation of the platform, the active-joint variables are defined by

$$\rho_1=x-d_1, \tag{4}$$

$$\rho_2=y-x\tan\theta, \tag{5}$$