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Ultra-flat, high-speed planar stage based on parallel kinematics

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Abstract
Planar stages are widely used but usually designed as multiple stacked single-axis systems. As stacked systems offer several known disadvantages, in this paper, an ultra-flat, high-speed planar stage is presented. It is based on an extended planar 3-P̲RR parallel kinematic where P̲ denotes driven prismatic joints and R passive rotary joints. The mechanism is designed in such a way that two drives run on a common axis and in parallel to a third (or even a fourth) drive. This allows higher positioning accuracies and lower costs due to lower tolerance requirements. Another highlight of the planar stage is the embedded sensor technology that uses the advantages of both indirect and direct pose measurements. In this paper, the mechanism's design, kinematics as well as first experimental results are presented.

Parallel Kinematics, XY Stage, Planar Stage, High-Precision, High-Speed, Ultra-Flat

1. Introduction

High-precision planar stages are widely used in numerous positioning applications such as microscopy, automatic optical inspection, laser marking and cutting, scanning, and metrology. For planar XY stages, usually stacked single-axis systems are used (see, for example, the V-741 high-precision XY stage by Physik Instrumente (PI) [1]). Stacking single-axis systems allows building complex multi-axes systems in a cost-efficient way. Furthermore, motions can be decoupled. Stacked systems, however, have several known disadvantages due to the serial structure. The dynamic properties of stacked axes are not equal since the lower axis has to move the upper axis as well as the external load, whereas the upper axis only has to move the external load. In the worst case, the lower axis requires bigger motors for similar performances (lower axis in this case indicates the closest axis to the fixed world while upper axis indicates the closest axis to the external load). Stacking furthermore increases the height of the overall system according to the number of axes so that very flat systems are not possible. Last but not least, positioning errors of each axis accumulate.

In contrast to that, parallel kinematics offer the advantages of lower moving masses, lower drive forces, higher stiffness, and thus better dynamic performances. Furthermore, positioning errors of each axis do not accumulate.

In order to use the abovementioned advantages of parallel kinematics, we present an ultra-flat, high-speed planar stage. It is based on an extended planar 3-P̲RR parallel kinematic where P̲ denotes the active prismatic joints and R the passive rotary joints. A photography of the presented planar stage is shown in Figure 1. The proposed planar stage has two special features that are described in detail later in the paper. Due to its symmetry, an additional motor can be implemented resulting in a 4-P̲RR parallel mechanism. This can be used for overactuation, observation as well as simple in-field replacement. Another highlight of this planar stage is the embedded sensor technology where indirect and direct pose measurement is available. This allows sensor and kinematic calibrations and an elaborated pose control.

Figure 1. Photography of the proposed planar stage.

The paper is structured as follows. In Section 2, the kinematics of the 3-P̲RR parallel mechanism is described. This is followed by Section 3 where the mechanical design of the proposed planar stage is presented, and the special features of the design are discussed. In Section 4, first experimental data are presented.

2. Kinematics

Imagine a parallel mechanism as illustrated in Figure 2 where three actuated prismatic joints can move along the triangle formed by the base structure. Limbs connect the revolute joints next to the prismatic joints with those on the moveable manipulator platform. By moving the prismatic joints up and down, the manipulator platform's pose can be controlled in three degrees of freedom.

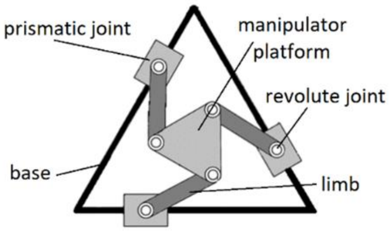

Figure 2. Kinematic structure of a planar 3-P̲RR parallel mechanism.

The kinematic description of such a state-of-the-art 3-PRR parallel mechanism is quite easy and presented in several papers (e.g. [2-4]). While the inverse kinematics can be solved straight forward, the direct kinematics problem needs to be solved iteratively, e.g., by using a Newton-Raphson algorithm.

For the planar parallel mechanism shown in Figure 2, the prismatic joints run on separate linear guides. Consequently, three individual linear guides need to be aligned resulting in high tolerances and costs. In order to reduce the complexity, a scissor-like motion concept is adopted as illustrated in Figure 3. Here, two prismatic joints share a linear guide. The intersection points of their limbs can therefore perform motions in x- and y-direction. A rotation can be achieved with the third prismatic joint. By placing a fourth prismatic joint on the same linear guide as the third joint, an overactuated mechanism with a highly symmetrical design can be achieved whose advantages are discussed in the next section.

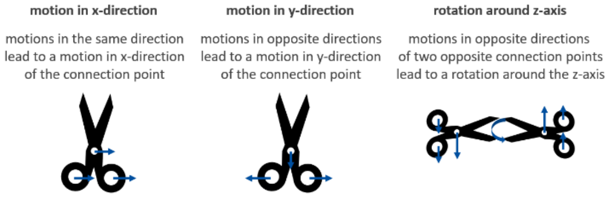

Figure 3. Scissor-like motion concept for the presented planar 3-PRR parallel mechanism.

3. Mechanical Design

The mechanical design of the proposed planar stage is shown in Figure 4. The stage consists of a fixed frame (not shown for simplicity) where the two parallelly arranged linear guides and magnetic tracks are mounted. Two linear sliders move on each of the linear guides and are actuated by magnetic drives. Each motor has its own encoder. The two motors on the same linear guide share a linear scale. Limbs with revolute joints on both sides connect the linear sliders and the mobile manipulator platform. As revolute joints, ball bearings are used as they are less expensive and offer a wider range of motion compared to flexure joints. The flyer is designed as a rectangle. On the lower side of the flyer, a 2d scale is attached and a 3d pose sensor is mounted in the center of the frame. On top of the flyer, an extension can be attached as shown on Figure 1.

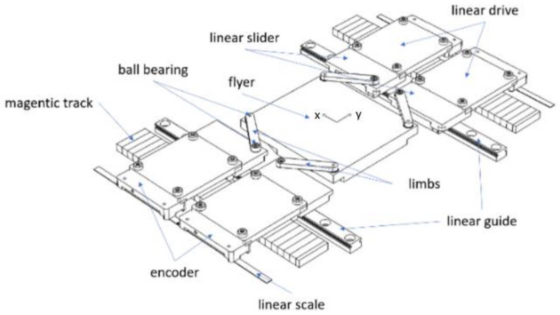

Figure 4. Mechanical design of the proposed planar stage.

The distances between the revolute joints on the flyer as well as the lengths of the limbs and the distance between the two linear guides determine the kinematic properties of the mechanism. For the proposed planar stage shown in Figure 1, the following specifications can be obtained. The size of the stage is 298 x 182 x 32,5 mm. The achievable workspace is ± 25 mm (in x-direction), ± 9 mm (in y-direction), and ± 15° (around z-axis). The stage is controlled with the new ACS ECMsm module [5] and velocities of up to 500 mm/s can be achieved.

3.1. Feature I – Two instead of three linear drives

Due to the symmetry, a fourth linear motor can easily be implemented enabling various advantages. On the one hand, it can be used as a possible in-field replacement for one of the other linear drives. In fact, switching between the actuated linear motors is possible so that the lowest-performing motor can be made passive. On the other hand, the fourth linear motor can be used for overactuation. By introducing a preload into the system, its dynamic behavior can be influenced. Finally, the fourth motor can be used as an observer, e.g., for calibration.

3.2. Feature II – Indirect as well as direct pose measurement

By using the sensors at the motors as well as at the manipulator platform, various advantages can be achieved. The direct pose measurement allows knowledge about the actual pose of the manipulator platform. By switching between indirect and direct pose measurement (as indirect pose measurement is essential for pose control), the advantages of both methods can be combined, see, e.g. [6]. Alternatively, a Kalman-filter can be used to fuse both sensor information continuously. The sensor redundancy can also be used for auto-calibration so that possible joint- and axes offsets can be removed, and the kinematic model can be adopted according to the sensor information.

4. Experimental Results

The first experimental results are promising. Currently, a minimum incremental motion of 100 nm (for the x-axis) and 150 nm (for the y-axis) step sizes are resolvable. Here, only the indirect pose measurement is used.

The direct pose measurement is working but, at the moment, not implemented for pose control. Figure 5 shows the planned implementation of the direct and indirect pose control.

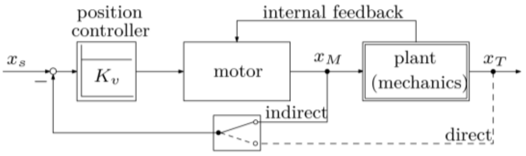

Figure 5. Possible concept of a direct and indirect pose control [6].

5. Summary and Outlook

In this paper, an ultra-flat, high-speed planar stage is presented. It is based on an extended planar 3-PRR parallel mechanism and offers two special features – the possibility for overacutation and the possibility of using both direct and indirect pose measurement for an enhanced pose control. The first experimental results look promising, but the advantages of the presented features still need to be implemented and reviewed.

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