TRIFLEX: Design and Prototyping of a 3-DOF Variable-Configuration Parallel Manipulator with Self-Alining

Roberto Simoni\textsuperscript{1}, Henrique Simas\textsuperscript{2} and Daniel Martins\textsuperscript{1, 2}

\textsuperscript{1}. Center of Mobility Engineering, Federal University of Santa Catarina, Joinville 892180-000, Brazil
\textsuperscript{2}. Center of Mechanical Engineering, Federal University of Santa Catarina, Florianopolis 88040-900, Brazil

Abstract: This paper presents the design and prototyping of a fully decoupled 3-DOF variable-configuration parallel manipulator with self-aligning called TRIFLEX. This parallel manipulator can change their form to carry out different tasks in different places, this change is managed by additional self-aligning degrees-of-freedom. These degrees-of-freedom of self-aligning do not interfere in the motion of the moving platform, they are passive/null degrees-of-freedom that only permit changes in the form of base of the parallel manipulator. This paper also presents the mobility analysis of the 3-DOF TRIFLEX.

Key words: TRIFLEX, parallel manipulator, variable-configuration, self-aligning, screw theory.

1. Introduction

Parallel manipulators are designed as closed-loop kinematic chains \cite{1}. The closed loop kinematic chain of a parallel robot imposes constraints on the moving platform to apply the degrees-of-freedom specified in the design of the robot. Without a change in the design of the robot, it is not possible to change its geometry before or during the execution of a task. Due to the closed-loop kinematic chain, in general, parallel robots require high manufacturing precision because any misalignment in the joint axes can cause internal over-constraints which are harmful to the robot.

This paper presents the design and prototyping of a fully decoupled 3-DOF variable-configuration parallel manipulator with self-aligning called TRIFLEX. This paper also presents the mobility analysis of the 3-DOF TRIFLEX.

A characteristic of the variable-configuration parallel manipulator presented in this paper is that its form can be changed without changing the degrees-of-freedom and the characteristics of the motion of the moving platform. The change in the configuration of this new class of parallel manipulator is managed by additional degrees-of-freedom called degrees-of-freedom of self-aligning. These additional degrees-of-freedom of self-aligning are passive nulls, they permit a change in the configuration before starting the task execution but during the task execution they do not have any influence, i.e., their velocities are nulls \cite{2}. Misalignment in the joint axes, which can cause internal over-constraints harmful to the robot, can also be managed by these additional degrees-of-freedom of self-aligning.

The remainder of the paper is organized as follows: First, we present a review of the 3-DOF translational parallel manipulators. Then, we present the design and prototyping of a 3-DOF TRIFLEX inspired by the Tripteron \textsuperscript{3} and the Cartesian parallel manipulator \textsuperscript{4}. Next, we present the mobility analysis of the 3-DOF TRIFLEX. And, finally, we present the conclusions
and further works on this new class of parallel manipulators.

2. 3-DOF Translational Parallel Manipulators

Since 1980, there has been an increasing interest in the development of parallel manipulators [1]. Early research on parallel manipulators concentrated primarily on 6-DOF parallel manipulators. In the last decade, parallel manipulators with fewer than 6-DOF have attracted the attention of industry and academia. For several industrial applications, in particular in the machine-tool field, a parallel manipulator with fewer than 6-DOF is sufficient. Indeed, the study of this type of parallel manipulator is of great importance. A low-DOF parallel manipulator exhibits interesting features compared to 6-DOF parallel manipulators such as: simpler mechanical design, lower manufacturing and operating costs, larger workspace volume (reducing the legs interference), and simpler control [5]. Therefore, the study of low-DOF parallel manipulators has recently become a main area of focus in the robotics research community.

Kim and Tsai [4] presented a 3-DOF translational parallel manipulator called Cartesian Parallel Manipulator with three PRRR legs. They analyzed rotative and linear actuation, but rotative actuation was discarded because of the existence of singularities within the workspace. Linear actuation was thus selected and the effects of the misalignment of linear actuators on the motion of the moving platform are discussed. Tsai and Joshi [6] enumerated 3-DOF parallel manipulators and chose the 3-UPU parallel manipulator for the design analysis and optimization. Kong and Gosselin [7] presented a method for the type synthesis of 3-DOF translational parallel manipulators based on screw theory. Gosselin and Kong [3] presented a 3-DOF translational parallel robot, with fully decoupled input-output equations, in a Canadian provisional patent application. Di Gregorio and Parenti Castelli [8] presented a 3-DOF parallel robot with three RRPRR legs. They presented the kinematic model and the singularity analysis for this robot. Bonev [9] presented a novel 3-DOF fully decoupled translational parallel robot called the Pantopteron which is similar to the Tripteron parallel manipulator proposed by Gosselin and Kong [3].

There are several 3-DOF translational parallel manipulators proposed in the literature. However, none has variable-configuration, i.e., it is not possible to change the geometry of these parallel manipulators. Once the parallel manipulator is manufactured, its architecture can not be changed with a few adjustments, but only with a new design. By considering this limitation, emerged the idea to design a parallel manipulator with three degrees-of-freedom which has a variable-configuration and works independently of the variation in configuration.

Simoni et al. [2] presented a new class of parallel manipulators, variable configuration parallel manipulators with self-aligning, called TRIFLEX. TRIFLEX are parallel manipulators designed as open loops kinematic chains, vacuum suckers are used to fix the base on the floor closing the kinematic chain. The kinematic chains of variable-configuration parallel manipulators with self-aligning can be considered as a non-Assur group [10]. Fig. 1a shows the open-loop kinematic chain of variable-configuration parallel manipulators with self-aligning. The elements that compose this new class of parallel manipulators are: feet, legs and moving platform. The feet can be assembled using a flexible rail with vacuum suckers which will be fixed to the floor and the flexible rail permits the modeling of the shape of the floor (the floor is suitable to use vacuum suckers). When all feet are attached to the floor/base, Fig. 1b, we have the closure of the kinematic chain defining the base platform as shown in Fig. 1c. The base platform is defined by the shape of the floor. Closing of the kinematic chain defines a new kind of parallel manipulator. The ability of the feet to attach in different ways is managed by additional degrees-of-freedom of self-aligning in the leg.
These degrees-of-freedom are passive degrees-of-freedom which permit only the feet to be attached in different ways and, when set, do not interfere in the motion of the moving platform.

All advantages of parallel manipulators are applied to this new class of parallel manipulators, and to these we can add

- increase and/or decrease in the workspace volume to adapt itself to different tasks;
- change the geometry of the parallel manipulator for tasks in confined environments;
- improve portability since it can be carried and fixed anywhere as its topology can easily be adapted to any base (floor).

To the best of the authors’ knowledge, there is currently no parallel manipulator that can combine one or more of the following capabilities: to change its original shape to adapt to another form of the floor/base, to work in confined environments, to increase or decrease its workspace volume, to become stronger, and so on.

3. Design and Prototyping of a Fully Decoupled 3-DOF TRIFLEX

This section presents the design and prototyping of a fully decoupled 3-DOF TRIFLEX. This parallel manipulator has the structure composed by feet, legs and moving platform, when all feet are attached into the floor a closed loop kinematic chain is obtained and the geometry of the floor define the movement of the base platform.

The kinematic structure of this new parallel manipulator was initially inspired by the fully decoupled 3-DOF translational parallel manipulators introduced by Gosselin and Kong [3] and Kim and Tsai [4].

The kinematic chain of the manipulator is presented in Fig. 2. The new parallel robot is composed of three feet (to be fixed on the floor), three legs and a platform (to be moving). The feet can be assembled using a flexible rail with vacuum suckers which will be fixed to the floor and the flexible rail permits the modeling of the shape of the floor (the floor is suitable to use vacuum suckers). The three feet, when attached to the floor, originate the base platform of a parallel manipulator and the form of the base platform is defined by the shape of the floor. Each leg is formed by a PRRRR serial kinematic chain. The first P joint is connected to the shoe (flexible rail) and the last R joint is connected to the moving platform. The P joint is the actuated joint, and each P joint is responsible for a
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Translation of the moving platform. The first R joint is responsible for the self-aligning of the robot, it manages the change in the base shape and it permits the adaptation of the feet on the floor. Also, misalignment in the joint axes, which can cause internal over-constraints harmful to the robot, can be managed by the first R joint. The axis of the first R joint is perpendicular to the axes of the other three R joints in the leg, as shown in Fig. 2. The last three R joints permit the planar motion in the three planes perpendicular to the axes of all joints in the leg. The moving platform connects the three legs. The second link of each leg has a gap to allow the insertion of the third link; this gap allows the rotation of the prismatic joint around the axis of the second R joint.

Fig. 3 presents a CAD model of the proposed 3-DOF translational variable configuration parallel manipulator indicating the additional degrees-of-freedom of self-aligning, i.e., three rotational degrees-of-freedom indicated by $\theta_1$, $\theta_2$ and $\theta_3$. The range of rotation is under the axis of the second R joints managed by the gap of the second link, $\theta_4$, $\theta_5$ and $\theta_6$. Any displacement of the moving platform will involve translation of each single prismatic joint and when all legs are connected to the moving platform, the possibility of rotation of the moving platform is removed. The additional degrees-of-freedom of self-aligning of the legs are imposed by permitting a change in the geometry of the base platform to give more dexterity to the parallel manipulator and to allow complex applications such as operations in confined environments.

Fig. 4 shows a prototype of the TRIFLEX. The main parts of the prototype were built on a rapid prototyping machine and the prismatic joints are rails printers, however, it is possible to use flexible rails. Note in the pictures that the geometry of the base is defined when all feet are fixed to the base by vacuum suckers (detail in Fig. 5) as shown in Fig. 6. Many configurations of the base of the TRIFLEX are shown in Fig. 7.

4. Mobility Analysis of the 3-DOF TRIFLEX

As presented in Section 3, a variable-configuration
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parallel manipulator with self aligning is formed of feet, legs and a moving platform. When the parallel manipulator has all feet attached to the floor we have a structural arrangement of a parallel robot with the base platform formed by the attaching of the feet on the floor. Thus, the mobility analysis will be developed using tools for analysis of the mobility of parallel manipulators.


In agreement with Kong and Gosselin [11], the mobility (or DOF) $M$ a parallel manipulator with $m$ legs is given by

$$M = C + \sum_{i}^{m} R_{i}$$

where $C = 6 - c$ denote the connectivity of the moving platform and $\sum_{i}^{m} R_{i} = \sum_{m}(f_{i} - 6 + c_{i})$ denote the redundant DOF of the moving platform, additionally, $c$ denote the order of wrench system of the moving platform, $c_{i}$ and $f_{i}$ denote the order of the wrench system and the DOF of the $i$-th leg.

The parallel manipulator shown in Figs. 2 and 3 has its legs formed by a PRRRR serial kinematic chain where the axis of the first rotative joint R is perpendicular to the axis of the prismatic joint P and the axes of the last three rotative joint R are all perpendicular to the axis of the first rotative joint R. Therefore, the wrench system of each leg is a 1-$\zeta_{\infty}$-system 2 ($c_{i} = 1$), i.e., the only movement

1Further details on screw theory can be found in Kong and Gosselin [11], Davidson and Hunt [12] and Tsai [13].

2The notations in this section were obtained in Kong and Gosselin [11].
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restricted by each leg is the rotation orthogonal to the axes of the R joints. For parallel manipulators, the wrench system of the moving platform is given by linear combination of the wrench systems of all its legs [11]. Therefore, the wrench system of the moving platform is a 3-$\zeta_\infty$-system, i.e., $c = 3$.

Now, using $c^i = 1$ and $c = 3$ we have $R^i = 5 - (6 - 1) = 0$ and $C = 6 - 3 = 3$. Thus, by Eq. (1),

$$M = C + R = 3$$  \hspace{1cm} (2)

The mobility obtained by Equation 1 is usually instantaneous [11], but, for this parallel manipulator it is full-cycle because $c$, $c^i$ and $R^i$ do not change in any configuration of the moving platform.

As we can see, the additional degrees-of-freedom of self-aligning, which are passive/null degrees-of-freedom, do not interfere in the motion of the moving platform. In others words, the mobility or DOF of the parallel manipulator, are not affected by the self-aligning degrees-of-freedom.

5. Conclusions and Further Works

This paper presented the design and prototyping of a fully decoupled 3-DOF TRIFLEX, a variable-configuration parallel manipulators with self-aligning. A detailed description of the robot was provided and the mobility analysis was presented.

Degrees-of-freedom of self-aligning are introduced to change the parallel manipulator geometry without changing the characteristics of the motion of the moving platform, i.e., the moving platform will have always the same number of degrees-of-freedom. These degrees-of-freedom of self-aligning are passive/null, i.e., their velocities are null during the task execution, and their only function is to change the shape of the parallel manipulator.

It is important to note that the difference of this new class of parallel manipulators is the open loop kinematic chain; it becomes a closed loop only when all feet are attached to the floor.

The parallel manipulator presented in this paper has the advantage of portability since it can be carried and fixed anywhere. Another advantage of the new parallel manipulator is its flexibility to work in different confined environments because its geometry can be adapted to the geometry of the workspace volume.

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References