

ON PKM WITH ARTICULATED TRAVELLING-PLATE AND LARGE TILTING ANGLES

Sébastien Krut, François Pierrot, Olivier Company

LIRMM, UMR 5506 CNRS – Université Montpellier 2

161 rue Ada, 34392 Montpellier CEDEX 5, France

<krut, pierrot, company>@lirmm.fr

Abstract This paper discusses some ways to achieve large tilting motions with PKM by resorting to articulated travelling plate. Different options are firstly presented: remote actuation, hybrid architectures, redundancy, rotation-amplification and translation-to-rotation transformation. Starting from two of those features, the aim of this paper is to go one step further and to show that it might be possible to design a 5-DoF (Degrees of Freedom) mechanism with large tilting angles about two axes.

Keywords: PKM, articulated travelling-plate, large tilting angles.

1. Introduction

The idea of parallel mechanisms resorting to a non-rigid (or articulated) moving platform (traveling plate) which includes passive joints has been introduced recently and a few academic prototypes have already demonstrated the effectiveness of this principle (Pierrot et al., 1999; Krut et al., 2003). These prototypes implement Scara motions. Indeed, the 4 DoF of Scara motions are well adapted to pick-and-place tasks: 3 translations to carry an object from one point to another, plus one rotation about a given axis in world coordinates for the orientation. For efficient pick-and-place a 360-degree orientation range is expected. Robots inspired from Delta architecture (Clavel, 1985) encountered a real commercial success achieving this task because of their high dynamics (acceleration capability) that has a strong influence on cycle time. This is due to their lightweight (actuators are fixed on the base) parallel (having closed kinematics chains) design. However, the **RUPUR** central kinematic chain (R: Revolute, U: Universal, P: Prismatic, bold letter stands for actuated joint) that transmits the rotational motion from a revolute actuator fixed on the frame to the effector may become a weak point. This is particularly true for Delta with huge workspace or, even more, with linear Delta that might be used for designing machine-tools.

Most of recent researches in that field have proposed different designs to obtain Scara motions either for serving as pick-and-place robots, or for

being a part of a more complex machine-tool; some of them are parallel mechanisms, like Kanuk (Rolland, 1999) or H4 (Pierrot et al. 1999), some others have non-fully-parallel designs (Angeles et al., 2000). Other 4-DoF parallel mechanisms have been studied in the past, but they are dedicated to different applications such as Koevermans' flight simulator (Koevermans et al., 1975) and Reboulet's four-DoF wrist (Reboulet et al., 1991). Even more recently, a machine with a moving platform including passive prismatic joints and a "Translation-to-Rotation" transformation system has been introduced (Krut et al., 2003); in the latest paper it was shown that it was possible to get a realistic practical design for a very specific design: (i) four linear motors in the same plane and aligned on the same direction, (ii) a three-part moving platform. Moreover, it induces very simple kinematics model in closed form for both Inverse and Forward problems.

The aim of this paper is to go one step further and to propose two ideas:

1. It might be indeed possible to obtain a 4-DoF design which compares directly with commercially available Delta-based robots (e.g. the FlexPicker, an ABB Robotics piece of hardware) in terms of technology, workspace, and performance while avoiding the RUPUR kinematic chain.
2. It might be possible to design a 5-DoF machine with large tilting angle about two axes.

To do so, we have designed the prototype of a robot (we call Eureka) by resorting to several components from the industrial FlexPicker robot. A prototype is about to be built. Its design can be seen as an "extension" of the principle of articulated travelling plate with passive linear joints. Hence, it also combines actuation redundancy so that we obtain a 5-DoF, large-tilting-angle solution.

In this paper, this prototype is described and the way to achieve the desired rotations is discussed. Then, geometrical models are derived (a nice feature for this robot is that the forward geometrical model can be written in a closed form). Afterwards, a kinematic modelling able to witness all the singularities of the robot is established. It is based on a detailed modelling of the so-called "spatial parallelograms" which are described here for what they really are: two SS chains. It shows up the geometrical condition that must be verified in order to achieve the desired motions.

2. Getting large tilting angles

It is well established that PKM suffers from different types of singularities that are often said to belong to two families:

- Serial-type (or under-mobility) when the mechanism loses one (or more) degree of freedom;
- Parallel-type (or over-mobility) when the mechanism's stiffness vanishes in one (or more) direction.

In the following section, this paper will discuss this description of singularities (even explaining that additional problems exist) but it is nevertheless true that the tilting angles are often limited by parallel-type singularities. So far, different solutions have been proposed to overcome that problem and getting larger tilting angles, as described in the following sub-sections:

Remote actuation – One way to get large tilting angles is to arrange one revolute joint on the travelling plate (in a “serial” way) and, to limit the moving parts masses, to place the actuation in a fixed remote location, that is, the base. It is the option selected for most Delta robots, using a telescopic fourth chain (with an **RUPUR** arrangement) dedicated to tool rotation. This principle allows the rotation range to be as large as for serial chains (indeed, the last rotation is actually arranged in a serial way...) while keeping the moving masses low because all motors are still fixed on the base.

Hybrid architecture – Kinematic optimization is always an open option when a PKM has to be designed, and it is often feasible to select an “optimal” set of design parameters (position of actuators, length of legs, etc.) to maximize the workspace of a mechanism in terms of tilting angles range. Obviously, this optimization process is made easier if some constraints are removed, for example if the machine is designed for tilting purpose only. This solution leads to machines made with two sub-parts, each of them specialized in only a part of the task.

Redundancy – The general concept of “redundancy” applied to mechanism theory can be roughly stated as follows: installing more actuators than the number of the TCP's (Tool Control Point). For serial chains, this gives, for a given position of the TCP, and infinite number of actuated joints positions. Selecting properly a set of joint positions may help in avoiding singularities. This option (called “kinematic redundancy”) exists for PKM but it has been used in a very limited number of cases. The principle is here to select among the possible joint positions, one position that is far enough from singularities.

Moreover, PKM offer the ability to create a different type of redundancy, called “actuation redundancy”, that can be described as follows: for a given set of external load, an infinite number of joint force sets exist for balancing the external load. In that case, the principle is to choose among the possible sets of joint forces, one set of forces which

guarantees a good stiffness (see Ryu et al., 1998, for a good implementation of such a principle).

This type of redundancy has been studied in more details for PKM than the previous one (for kinematic redundancy most efforts had been dedicated to the serial case) and several prototypes have been built, giving researchers the opportunity to evaluate control schemes. Indeed, control is here the key issue since actuation redundancy leads to over-constrained mechanisms. Consequently internal forces may exist, and control schemes have to cope with that.

Rotation amplification – In recent years, we have studied such an option in some details, by proposing different mechanism architectures based on one key principle: designing a travelling plate which includes passive revolute joints. This was the base of H4 architecture, a mechanism for “Scara-like motions”, already described. H4 is based on 4 identical elementary chains ($\mathbf{R}[\text{SS}]_2$ chains) and on an articulated travelling plate equipped with 3 passive revolute joints. The last revolute joint is moved by a coupling system about a 360 degree range, which relates its motion to the motion of another passive revolute joint that has only a 90 degree range by using an additional gear-based amplification.

Translation-to-Rotation transformation – It has been shown that H4 is an architecture providing Scara motions. However, some of its limitations can be pointed out:

- When tool orientation changes, the Jacobean matrix condition number may vary a lot, leading to important changes in machine behaviour;
- It has been proved that the relative positions of the four “spatial parallelograms” must be properly selected to avoid singular cases;
- Its forward geometrical model has not been established in analytical form, except for specific arrangements.

It was proposed in Krut et al., 2003, to build travelling plates with prismatic passive joints instead of revolute joints. It is always possible to transform this translational motion into a rotational one by means of rack-and-pinion, belt or cable-and-pulley devices. This solves most difficult points due to revolute joints: models are simpler, load balance is easier to achieve, general design is simpler, etc.

3 Combining redundancy and T-to-R Transformation

This section of the paper introduces a novel mechanical architecture which combines two of the previous features. Eureka, the proposed machine, is redundant (6 actuators for 5 DoF provides actuation redundancy) and is based on an articulated three-body travelling plate with two linear joints. The machine offers 3 translations and 2 rotations with large tilting capabilities in two directions; the first axis of rotation

has a constant direction with respect to a fixed frame, the second axis is orthogonal to the first one.

A detailed kinematic analysis is carried out and leads to geometrical conditions to be verified by the mechanism for proper functioning. Then a kinematic modelling illustrates the mechanism simplicity and provides a first evaluation of the machine's workspace. Finally, preliminary information is given regarding practical implementation of this new architecture.

3.1 General concept

The proposed machine is a 6-actuator / 5-dof parallel mechanism. In Fig. 1, a joint-and-loop graph is depicted: grey boxes represent actuated joints; white boxes passive joints and circles express a kinematic coupling between two joints.

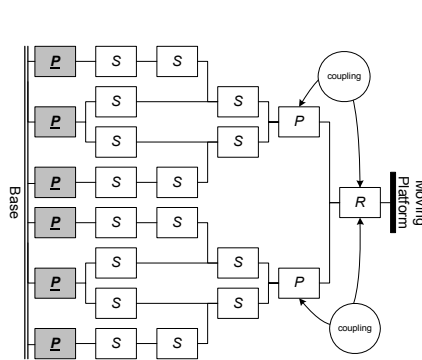


Figure 1. Joint-and-loop graph

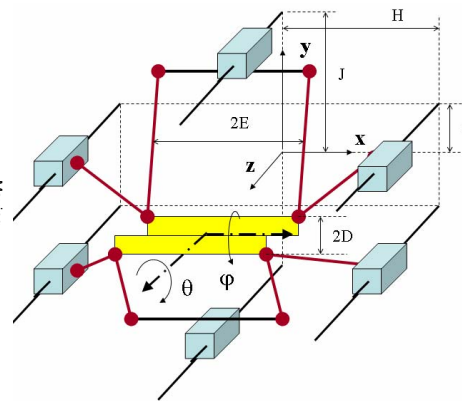


Figure 2. Kinematics scheme

As for Delta and H4 architectures, the actuators are fixed on the base. Actuators may be rotational or linear; one S-joint per chain may be replaced by U-joint (to get rid of internal motions). One must notice the machine's symmetrical architecture: the machine's upper and lower parts are identically made of a "spatial-parallelogram" and two single rods. Each single rod is connected to the "spatial parallelogram".

Note that, in a general matter, the "spatial-parallelogram" chains (that is, the $P(SS)_2$ chains) only add one constraint on a mechanism (3 translations and 2 rotations remain feasible) while a "spatial-parallelogram" made of $PR(RR)_2R$ chains (as done on the Orthoglide, see Chablat et al., 2002) adds two constraints on the mechanism (3 translations and 1 rotation remain feasible).

The travelling plate is the one introduced in Krut et al., 2003, with the I4L robot: while the two sub-parts shift one relatively to the other, a mechanical device transforms this motion into a rotation. Two types of travelling plates exist (see Fig. 3): *Type 1* is made of two prismatic joints and two kinematically coupled rack-and-pinion systems. It has a symmetrical design, which is good for balancing the loads among all the parts. *Type 2* is made up with one part less, but loses *Type 1*'s symmetrical design.

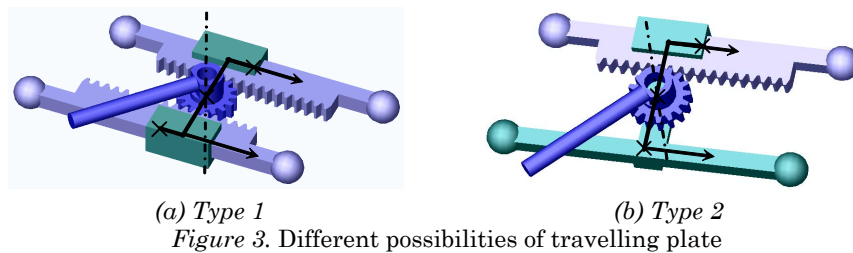


Figure 3. Different possibilities of travelling plate

3.2 A remark on singularity analysis

Singularities analysis is often based on the analysis of the standard Jacobean matrices J_x and J_q representing the input-output velocity relationship:

$$J_q \dot{q} = J_x \dot{x}, \quad (1)$$

where \dot{q} and \dot{x} are respectively the joint velocity vector and the operational velocity vector.

But other kind of singularities can occur (Zlatanov et al., 1998). To reveal them, a deeper analysis is required. At first, we will recall the fact that “spatial parallelograms” can be seen in two different ways. The realistic case where spherical joints are modelled as 3-DoF joints and not as 2-DoF joints is considered here. Then, two types of modelling will be given: one suggesting that the linear guide is a cylindrical joint (isostatic modelling), and another assuming that it is a prismatic joint (over-constrained modelling). In both cases, geometrical constraints, which must be fulfilled to get rid of internal singularities, will be derived.

According to Hervé’s notations (see Hervé, 1999) about displacement subgroups, $\{T\}$ stands for the subgroup of spatial translations and $\{X(\mathbf{u})\}$ stands for the subgroup of Schoenflies displacements (or Scara motions), where \mathbf{u} is a unitary vector collinear to the rotation axis. If a closed loop mechanism is composed of two chains producing Schoenflies displacements with $\mathbf{v} \neq \mathbf{u}$, then:

$$\{X(\mathbf{u})\} \cap \{X(\mathbf{v})\} = \{T\} \quad (2)$$

that is to say that such a mechanism will produce only three translations. The case of machines with $\mathbf{RR}(\mathbf{RR})_2\mathbf{R}$ chains (Fig. 4-a) is easily handled with such a technique since those chains correspond to Schoenflies subgroup.

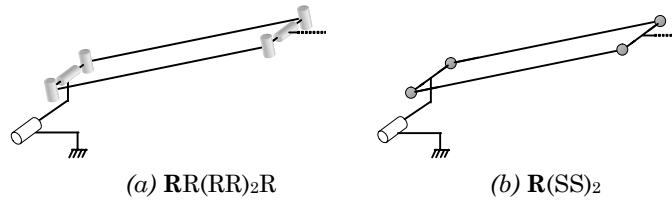


Figure 4. Two ways to model “spatial parallelograms”

The case of machines with $\mathbf{R}(\mathbf{SS})_2$ chains (Fig. 4-b) is more complex: each chain provides 5 DoF, 3T-2R, and does not correspond to a group. Indeed, it is possible that the union (\cup) of two 3T-2R chains generates a 3T-3R motion.

This implies the recourse to a more complex analysis when dealing with mechanisms based on $\mathbf{R}(\mathbf{SS})_2$ chains: for lack of space, this is recalled here, but the reader may find relevant information in Company et al., 2006.

3.3 Workspace analysis

In this section, the focus is given to a particular design, where the six linear motors are all collinear with vector \mathbf{e}_z : this guarantees a large workspace in this particular direction. The selected geometrical parameters are as follows $H = 0.45$ m, $I = 0.08$ m and $J = 0.4$ m (See Fig. 2 for geometrical parameters explanations). The travelling plate is of *type 1*. The values of geometrical parameters are: $D = 0.05$ m, $E = 0.06$ m and $k_i = -0.05$ m/rad. Note that the amplification ratio $|k_i|$ is chosen equal to D in order to have same rotation capabilities for θ and φ (± 90 degrees for this design). Lengths of rods are: $l_i = 0.9$ m, $i \in \{1, \dots, 6\}$. Actuators limits are: $0 \leq q_i \leq 1.3$ m. Fig. 5 presents the domain where the condition number of the normalized Jacobean matrix is smaller than 8 (note that along the Z direction corresponding to \mathbf{z} , the workspace is only limited by the actuators’ stroke).

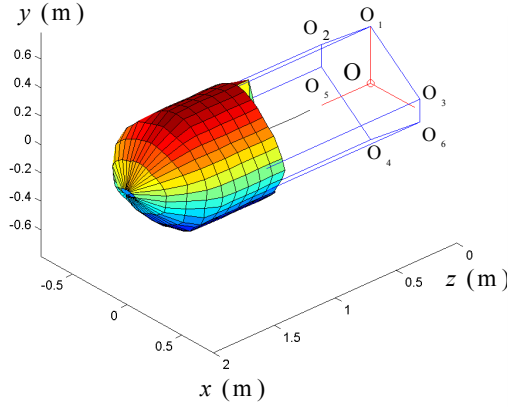


Figure 5. Workspace for $\text{cond}(\mathbf{J}_q^{-1} \mathbf{J}_x \mathbf{W}_x^{-1}) < 8$

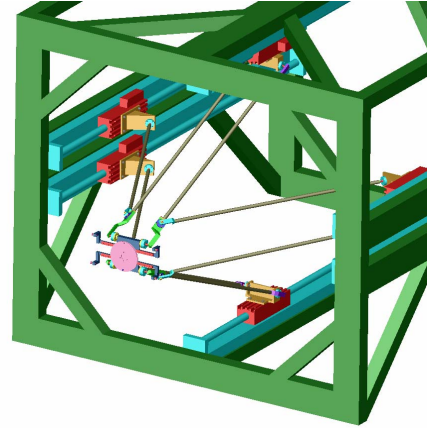


Figure 6. CAD View of the Eureka prototype

3.4 Practical design considerations

It could be interesting, for simplicity purposes, to connect the “single rods” directly to the travelling plate; however, such a practical design faces too many self-collisions. The machine depicted in Fig. 7 (left) shows such a practical design. Another architecture avoiding self-collisions is shown in Fig. 7 (right). It involves curved shapes of the single rods in order to avoid self-collisions.

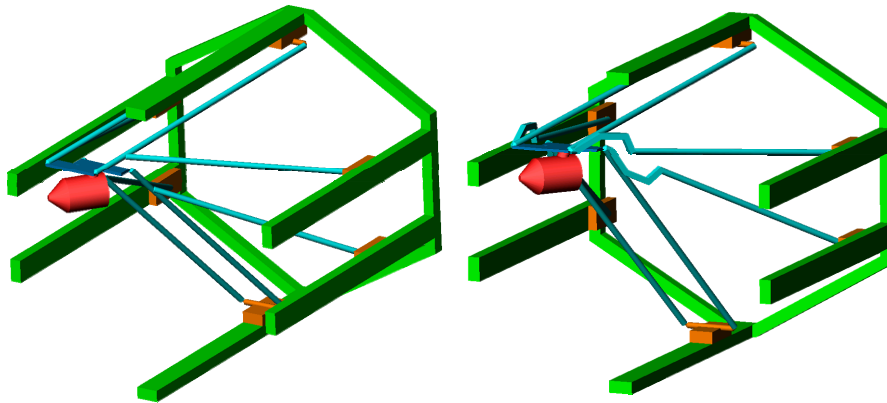


Figure 7. Self-collision-free design #1 and #2

A prototype is about to be built. The practical design is extremely simple thanks to Linear motors (Fig. 6). Dimensions are the ones introduced for computing the workspace. Rods and travelling plate are

made of aluminium. Instead of using rack-and-pinion systems, the mobile platform has been equipped with cable-pulley devices. This kinematics provides the same displacements as those of the Tricept robot. This design is well suited for the manipulation of light objects, but other applications are still possible.

A design of a haptic master arm based on this kinematics is proposed in Fig. 8. It uses revolute actuators instead of prismatic ones, so the footprint is reduced. DD motors are used in order to reduce friction. The required range for angular displacements is ± 45 degrees. This allows the use of an articulated travelling plate based on a planar parallelogram to provide the desired rotation. The translation to rotation transformation is then suppressed and friction reduced. The Eureka base provides three Translations plus two Rotations (3T-2R). The missing rotation (to get the complete master arm) is obtained using a carried revolute axis, located directly on the ending stick. This is similar to the design of classical master arms, such as the PHANToM (SensAble Technologies).

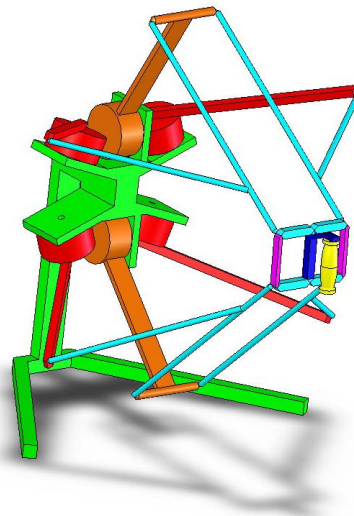


Figure 8. CAD view of the Eureka haptic arm

4 Conclusion

In this paper, several techniques for reaching high tilting angles have been presented, with a focus on solutions related to articulated travelling plates. Even though such results are still at an early stage of development, they show that it might be possible to use (i) on the one hand, travelling plates embedding passive joints which allows local motion amplification, and (ii) on the other hand, actuation redundancy as

a way to overcome some singular positions that usually limit the range of motion.

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