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PREFACE

The first CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators was held on September 5-8, 1973 at CISM in Udine, Italy. The Symposium has been called RoManSy for Robot and Manipulator Systems. Indeed, RoManSy has been the very first international symposium dedicated to the Robotics field. The chairman of the first RoManSy was Professor A.E. Kobrinsky, and personalities such as Professors M. Konstantinov, I.I. Artobolevski, G. Bianchi, A. Morecki, B. Roth, M. Vukobratovic, were members of the Program Committee.

For over 35 years now, the RoManSy symposia provided a framework for fruitful exchanges between researchers around the world on modelling and design of complex robotic systems, design of control systems and interactions induced in challenging applications of robotic systems. The RoManSy has been and remains the place where scientific questions such as those related to the kinematic analysis and synthesis of complex mechanisms, the design of advanced robotic systems, the analysis of the dynamic behaviour of robotic systems and their applications in order to achieve a certain level of autonomy or adapt to changes in physical and human environment are specifically discussed.

Modelling issues of robotic systems, their physical and cognitive interactions with the environment and humans, and their dynamic control have been the core of the exchanges among attendees during RoManSy 2012. They took place based on a set of technical sessions that have involved contributions in a number of fundamental and applied aspects related the design and the control of parallel manipulators for challenging applications with a particular focus on cable-driven machines, human-robot interfaces including those for physical interactions such as those useful for physical rehabilitation, human modelling and humanoid control as well as the design of integrated perception devices, mobile robots navigation on natural terrains, etc.

Each session was introduced by a presentation placing the state of the art in the field and defining a number of scientific challenges. In *addition, the invited speakers (Professor A. Bicchi and A. Edsinger, co-founder of Meka Robotics) offered a unique perspective on particularly rich topics of research: design of bio-inspired dexterous hands and design of human friendly robots.*

Future researches on the various topics covered by the 2012 RoManSy are obviously particularly important. Clearly, by considering their impact on the development of next-generation robotic systems, they will be subject to numerous investigations in the coming years and will be major topics for future editions of RoManSy to which we wish a great success.

Philippe Bidaud, Université Pierre et Marie Curie
Oussama Khatib, Stanford University
Vincent Padois, Université Pierre et Marie Curie

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Chapter I

Parallel Robots Modelling and Analysis

Wire-driven parallel robot: open issues

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INRIA Sophia-Antipolis

Abstract Wire-driven parallel robot (WDPR) is a special class of parallel robot in which the rigid legs are replaced by wires, with potential advantages in terms of intrusivity and workspace. Although the study of WDPR seems to be a well-addressed subject, we will show that there are still numerous challenging open issues in this field.

1 Wire-driven parallel robots

Wire-driven parallel robot (WDPR) is a special class of parallel robot in which the rigid legs are replaced by wires. As for classical parallel robot, motion of the platform may be obtained either by changing the lengths of the wires (*type 1*) or having fixed wires lengths and modifying the location of the attachment point A of the wires on the base (*type 2*). In the first case wire lengths may be modified by using either a coiling winch or by using a linear actuator with a pulleys system (Merlet, 2010). We may also distinguish *completely restrained* robot where the wires fully constrained the n d.o.f. of the platform (in which case the number of wire must be at least $n+1$ (Ming et al., 1994)) and *cable suspended* robot with at least n wires, gravity playing the role of a virtual downward pulling wire.

WDPR have been introduced in the 80's (Landsberger and Sheridan, 1985),(Miura and Furuya, 1984) as an alternate to parallel robot with rigid links. The foreseen advantages was less intrusive legs, a simpler mechanical structure (passive joints are eliminated) and potentially larger workspace for the type 1, as the amount of leg lengths variation may be much larger than with rigid legs. WDPR shares with classical parallel robots the ability to manipulate large load and to be energy efficient. But the major difference is that wires can be pulled but not pushed, which imposes an unilateral constraint: that must be checked. We will see that this constraint greatly complexifies the analysis of WDPR.

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Several prototypes have been built in the 90's, among them the famous ROBOCRANE (Albus et al., 1993), the FALCON robot (Kawamura et al., 1995) and the rescue robot of Tadokoro (Tadokoro et al., 1999), while the principle was partly patented (Thompson and Campbell, 1996). In the 2000's further prototypes have been developed such as the SEGESTA robot (Hiller et al., 2005) and other prototypes (Barrette and Gosselin, 2005),(Fattah and Agrawal, 2005).

Recently there has been a renewal of interest for WDPR in view of new applications: wind tunnel (Yaqing et al., 2007), biomechanic and rehabilitation (Wu et al., 2011), haptic interface (V. Zitzewitz et al., 2009), rescue robotics(Merlet and Daney, 2010) and telescope (Z-F et al., 2011) to name a few. Type 2 robots are illustrated in (Michael et al., 2009) in which several quadrotors are used to tow a load.

In spite of all these works it appears that many issues that have been investigated for such robots need to be revisited as they are not fully understood.

2 Kinematics

We first define the *wire configuration* of a WDPR at a pose as the set of wire numbers which are under tension. Clearly the unilateral constraint imposed on wires requires to connect kinematics and statics. Indeed, the geometrical constraint that relates the wire length ρ to the distance d between the wire anchor points on the base and platform must take into account the tension τ in the wire (with $\tau > 0$ if the wire is under tension). More precisely we have $\rho = d$ if $\tau > 0$ and $\rho \geq d$ for $\tau = 0$ i.e. the number of kinematic equations will depend upon the wire configuration. This does not impact the inverse kinematics (IK) if we consider that it provides d (or equivalently the location of A for type 2 robot). But the direct kinematics (DK) is another story. Indeed it must be noted that the sensors of the robot provide the measurement of ρ, while the pose of the platform is a solution of the IK which uses only d. If we assume that $\rho = d$ (i.e. all wire are under tension) we end up with the DK problem of classical parallel robots, which has usually several solutions. But nothing guarantee that in the current pose of the robot all wires are under tension. If we focus on a n wire spatial cable suspended robot, the IK provides m equations (for the $m \leq n$ wires under tension), $n - m$ inequalities $\rho \geq d$, while the mechanical equilibrium provides 6 equations. As the number of unknowns is $6 + m$ (the 6 pose parameters and the m τ) we always end up with a square system, whatever is the wire configuration. All possible DK solutions will be obtained by considering all the systems obtained for $m = 1 \dots n$.

If $m = 1, 2$ the DK system can easily be solved, while for $m = 6$ the system may be decoupled into 2 sub-systems: the DK of a classical parallel robot (problem A) whose solving provides the pose parameters, and the linear system of the mechanical equilibrium that will provide the τ: the DK solutions will be obtained for the one of problem A for which the τ are positive. But the problem is much more complex for $m = 3, 4, 5$, for which there is no decoupling, and which have respectively 9, 10 and 11 equations, although it must be noted that it is possible to reduce the system to 6 equations. Indeed the mechanical equilibrium condition is equivalent to have the wires lines and the vertical line going through the center of mass of the platform spanning a linear complex, resulting in $6 - m$ geometrical conditions, which, added to the m IK equations, provide the necessary 6 equations (note however that after solving the system it is necessary to check the τ and to retain only the solutions which have positive tension).

We have recently used this approach to exhibit a solution for $m = 3$ (Carricato and Merlet, 2011). After some intensive calculation we have been able to reduce the system of 6 equations to an univariate polynomial of degree 158. But solving the DK for $m = 4, 5$ is still eluding us and this is clearly a major issue for WDPR. We have also here a practical issue regarding numerical solving: the algebraic approach apparently leads to high degree polynomial that cannot be safely numerically solved. Consequently we will have to rely on other numerical approaches. Interval analysis has been successfully used for $m = 3$, but preliminary work for $m = 4, 5$ have shown that the task was much more demanding. Real-time solving of the DK is not an issue, provided that 1) a guaranteed solving scheme is used (Merlet, 2004)), 2) the number of wire under tension does not change (see section 3). For large-scale robot other factor may influence the IK and DK such as the sagging of the wire or their elasticity (Kozak et al., 2006),(Gouttefarde et al., 2012),(Riehl et al., 2009). Stability of a pose should also be evaluated to eliminate unstable DK solutions (Bosscher and Ebert-Uphoff, 2006),(Carricato and Merlet, 2011).

Determining the current pose of the platform without a priori information on the pose is still an open issue.Adding information is necessary (e.g. measuring the wire tensions or directions of the wires) but such measurement is noisy and it is unclear how robust the calculation will be.

3 Singularities

Up to now it is considered that singularity analysis of WDPR does not differ from the one for classical parallel robots (Ottaviano and Ceccarelli, 2007). A first note is that for cable-suspended robot the mechanical equilibrium condition is equivalent to the singularity analysis of a set of lines (with a close connection to grasping (Ebert-Uphoff and Voglewede, 2004). A second note is that the singularity of fully constrained WDPR is still an open issue. This is especially true as we have to consider that the the infinitesimal motion obtained in a singularity may possibly leads to a different wire configuration and hence to a different set of kinematic equations whose jacobian may become full rank. A companion question for cable-suspended robot is to determine the singular configuration in which the wire tension may indeed become infinite. This is a complex issue because we cannot restrict the study to a local analysis: in the vicinity of a singularity the wire configuration may change in such way that the robot will never be in the wire configuration for which the singularity has been determined.

We propose also to classify as singularity the pose at which there are multiple possible wire configuration. Indeed the control law will depend upon the current wire configuration and may thus fail if an undetected change of wire configuration occurs. Furthermore as for classical singularity the platform may gain uncontrollable d.o.f. at such pose.

4 Workspace and planning

Workspace analysis for WDPR must consider that a pose lie within the workspace if the geometrical constraints are fulfilled but also if the tension in the wires are positive. Hence the load has to be considered: it may be fixed (e.g. for cable-suspended robot), or its components may be restricted to lie within some ranges or it may be arbitrary (*wrench feasible workspace*). There have been numerous works on this subject see for example (Barrette and Gosselin, 2005), (Diao and Ma, 2008), (Gouttefarde et al., 2011), (McColl and Notash, 2011), (Riechel and Ebert-Uphoff, 2004), (Stump and Kumar, 2006), (Verhoeven, 2004). Wire interference has also been considered Merlet (2004) although interference is less damaging and may be accepted (Y. et al., 2008). But we have to extend workspace calculation to take into account singularity and possible change in wire configuration. Similarly for trajectory planning a path planner should avoid singularity (in the broad sense defined in the previous section), while it is necessary to determine in real-time if a wire configuration change may occur in the vicinity of the current pose. A further issue is to be able to detect a wire configuration change: this may obtained either by wire tension measurements and/or measurements of the wire directions. However both measurements are noisy and the detection, if any, will not occur immediately after a change in wire configuration. We will then have to design a recovery strategy to get the robot back on track and with all wires under tension, whenever it is possible. Other criteria may be taken into account by the planner, such as energy.Clearly dimensional synthesis is also an open issue, especially as WDPR hardware may be designed in a modular way for allowing easy change in their geometry (provided an efficient communication means between the components of the WDPR).

5 Redundancy and control

Redundancy in WDPR is not a well addressed problem. From the kinematic viewpoint a WDPR is not a redundant robot as the IK has usually a single solution. It may however be thought that a WDPR is redundant from a static viewpoint, so that we can modify the tension distribution while keeping the platform at the same pose (Pott et al., 2009). Unfortunately its seems that this is not possible for cable-suspended robot with non-elastic wires such as the $N-1$ ($N \geq 4$ wires connected at the same point on the platform) as this robot will have always at most 3 wires under tension (Merlet, 2012). For completely restrained robot and non-elastic wires we have a control problem as we cannot control both the wire length (to keep the platform at the same pose) and the tension in the wires. For elastic wires the situation may be different as wire length control is basically equivalent to tension control in that case. But we still have the problem of wire configuration changes: it seems that such changes does not modify drastically the platform pose, while on the other hand large changes in the wire tensions will occur (Merlet, 2012). It appears also that small uncertainties in the wire stiffness have a small influence on the pose but a large one on tension in the wires. Hence position and velocity control should work fine while force control will be difficult Krut et al. (2004),(Oh et al., 2005) and should be robust with respect to error in the stiffness estimation (Yu et al., 2010) Clearly we have to find better ways to fully exploit the possible redundancy of WDPR. A possible approach and intriguing problem is related to the kinematics and tension distribution in multiple WDPR whose platforms and even wires may be interconnected in a flexible way by wires (with fixed lengths or variable lengths).

6 Dynamics

Dynamics of WDPR is clearly simpler than for classical parallel robots (Bruckman et al., 2008),(Korayem et al., 2010). It may even be used to increase the workspace of the robot (Barrette and Gosselin, 2005), (Gosselin et al., 2012). But an open issue is to investigate if dynamics can also be used to manage wire configuration.

7 Conclusion

Surprisingly although numerous works have been devoted to WDPR it appears that numerous issues, even fundamental one e.g. kinematics, are still not fully understood. The unilateral constraint imposed by the wire tension imposes to revisit all these topics. It greatly complexify the problems, leading to many of the more challenging contemporary problems in kinematics but is worth investigating as WDPR have a large potential for applications.

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A New 3-DOF Translational Parallel Manipulator: Kinematics, Dynamics and Workspace Analysis.

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Abstract A translational parallel manipulator with three degrees of freedom and three kinematic chains is considered. Each kinematic chain contains five revolute joints. Kinematics, workspace, singularities and dynamics of the proposed mechanism are discussed.

1 Introduction

Since the moment when famous Clavels Delta robot was presented (Clavel, 1987), parallel manipulators with three translational degrees of freedom have attracted much attention from researchers (Ceccarelli, 2004, Gogu, 2009) and manufacturers, as it was discovered that such manipulators are very useful in many areas (Merlet, 2006). Usually, this kind of spatial mechanisms consists of base plate, moving platform (end-effector) and three symmetric kinematic chains, also called legs or limbs (Kong and Gosselin, 2007). For instance, Delta robot has three R-R-Pa-R legs and provides pure translational motion to its moving platform in three dimensions. This mechanism is widely used in packaging and pick-and-place operations because of its phenomenal speed capability and low inertia. Another variation of Delta mechanism was proposed by Tsai (Tsai and Stamper, 1996). The inverse variation of Delta was also studied by Briot (Briot et al., 2008). Another conceptual approach was presented by Wenger and Chablat (Wenger and Chablat, 2000). Their Orthoglide mechanism has three P-R-Pa-R identical kinematic chains. The moving plate of this mechanism is capable to achieve various complicated trajectories and the workspace of this robot is very close to a cube shape. All these manipulators are constructed using parallelograms, which are widely used in 3-DOF translational parallel manipulators, as a parallelogram directly constrains rotation about a certain axis. Carricato (Carricato and Parenti-Castelli, 2004) has discussed 3 R-U-R-R mechanism that could be treated as 3 R-R-R-R-R mechanism. Each

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leg prevents the moving platform from rotating around a certain axis and, as all three axes are linearly independent, this mechanism does not exhibit constraint singularities. Lee (Lee and Hervé, 2006) has presented a concept of the 3-R-R-R-R-R mechanism that is similar to one which presented in this paper.

In this paper, we present a 3-DOF translational parallel mechanism with three legs consisting of five revolute joints. We analyze its kinematics, workspace, singularities and dynamics. Singularity analysis is based on both Jacobian matrix (Gosselin and Angeles, 1990) and screw theory (Dimentberg, 1965, Glazunov, 2010) and dynamics is analyzed by Lagrange-D'Alembert principle. All obtained theoretical results are tested on a virtual model of the mechanism within MATLAB/Simulink environment. The main contribution of this paper is that the new type of the mechanism is discussed and analyzed. It is also shown that the proposed mechanism has no singularities within the workspace.

2 Structure, kinematics and workspace of 3-RRRRR translational parallel mechanism

The proposed mechanism is shown in Figure 1.

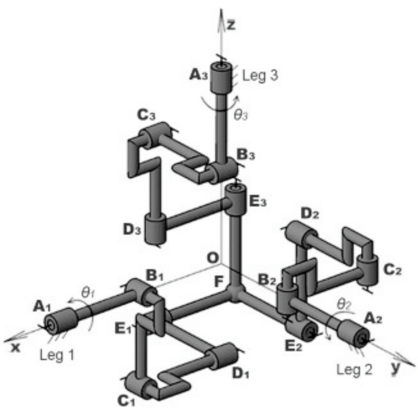


Figure 1: Kinematic scheme of proposed mechanism.

Each leg of the mechanism is constructed as follows:

- the axis of the first revolute joint of i-th (i-1, 2, 3) leg is x-, y- or z-axis (for Leg 1, Leg 2 and Leg 3, respectively) of the three dimensional Cartesian coordinate system;

– the axes of the second and the third revolute joints in each leg are orthogonal to the axis of the first revolute joint in the same leg and are parallel to each other;
– axes of the fourth and the fifth revolute joints are parallel to the axis of the first revolute joint.

Note that all three legs are symmetrical and the first R-joint in each leg is actuated. One can see that in the initial configuration of the mechanism (as shown in Figure 1) all the angles between links in each leg are right angles and following conditions must be satisfied:

$$l_4 = l_2; l_A + l_2 = l_1 + l_3 + l_5. \tag{1}$$

Here $l_1 = A_iB_i, l_2 = B_iC_i, l_3 = C_iD_i, l_4 = D_iE_i, l_5 = E_iF, l_A = OA_i$. Taking (1) into account, it was found that for the discussed mechanism a basic system of equations that represents a relationship between Cartesian coordinates x, y, z and generalized coordinates θ_1, θ_2, θ_3 can be written as follows:

$$\begin{cases} (y - l_x \sin\theta_1)^2 + (z + l_x \cos\theta_1)^2 - l_2^2 = 0; \\ (z - l_y \sin\theta_2)^2 + (x + l_y \cos\theta_2)^2 - l_2^2 = 0; \\ (x - l_z \sin\theta_3)^2 + (y + l_z \cos\theta_3)^2 - l_2^2 = 0; \end{cases} \tag{2}$$

where

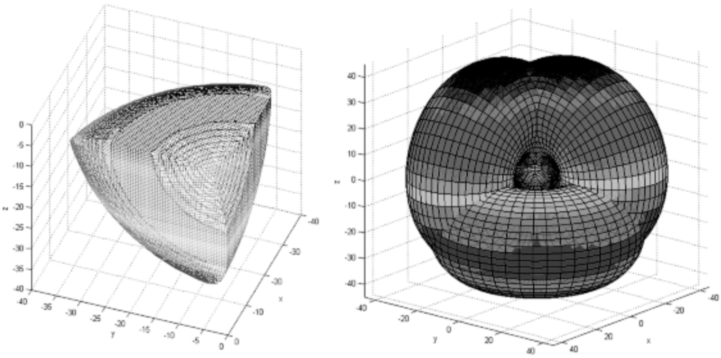
$$l_x = l_2\sqrt{1 - \left(\frac{x + l_2}{l_2}\right)^2}, l_y = l_2\sqrt{1 - \left(\frac{y + l_2}{l_2}\right)^2}, l_z = l_2\sqrt{1 - \left(\frac{z + l_2}{l_2}\right)^2}$$

This system of equations can be used to solve forward and inverse kinematic problem, i.e. finding x, y, z with given θ_1, θ_2, θ_3, and vise versa. As far as system (2) is determined, we can analyze the workspace of the mechanism by iteration method. As we can see from (2), each Cartesian coordinate can be changed only within the $[-2l_2; 0]$ interval, because exceeding this limits would result into complex roots. We can analyze all the points of the volume (a cube) restricted by these limits, and points corresponding to real number solutions of (2) will form the workspace of this robot. The result of such numerical analysis with the step equal to $0.025l_2$ between analyzed points and $l_2 = 20$ is shown in Figure 2a. This volume corresponds to an intersection of three tori with orthogonal axes (Figure 2b).

One can notice that the size of the workspace depends only on the value of l_2, as long as conditions (1) are satisfied.

3 Singularity and velocity analysis

In this section, we present results obtained after the analysis of singularities and velocities carried out by methods based on Jacobian analysis and the



(a) Workspace volume (b) Intersecting tori

Figure 2: The workspace of the mechanism

screw theory. While using Jacobian analysis method, we are assuming that each equation from system (2) could be treated as an implicit function of four variables: $F_1(x, y, z, \theta_1) = 0$, $F_2(x, y, z, \theta_2) = 0$, $F_3(x, y, z, \theta_3) = 0$ for first, second and third equation, respectively. According to Angeles and Gosselin, the relationship between input angular velocities ω_1, ω_2, ω_3 and corresponding velocities of the moving platform v_x, v_y, v_z can be written as follows:

$$\mathbf{A}\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} + \mathbf{B}\begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} = 0, \qquad (3)$$

where

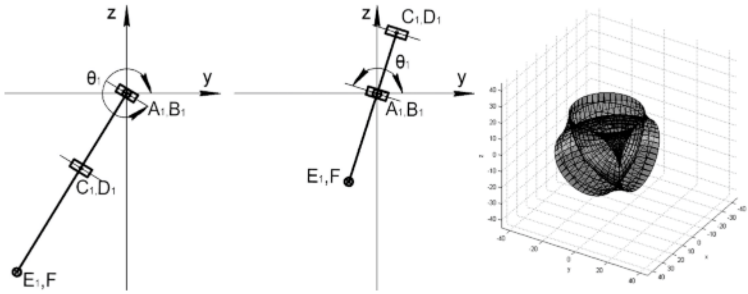
$$\mathbf{A} = \frac{\partial \mathbf{F}}{\partial \mathbf{x}}, \mathbf{B} = \frac{\partial \mathbf{F}}{\partial \mathbf{q}} \qquad (4)$$

Here $\mathbf{x}$ and $\mathbf{q}$ are vectors of Cartesian and generalized coordinates, respectively. Using (3) we can easily find corresponding input velocities for any desired velocities of the moving platform and vise versa. Matrices (4) can be used for the analysis of all three types of singularities (Gosselin and Angeles, 1990). It was found that the Type 1 singularity (occurs when matrix $\mathbf{B}$ is singular) corresponds to at least one of nine following conditions:

$$x = 0; x = -2l_2; y = 0; y = -2l_2; z = 0; z = -2l_2. \qquad (5)$$

$$y = -z\tan\theta_1; z = -x\tan\theta_2; x = -y\tan\theta_3. \qquad (6)$$

It was also found that Type 3 singularity (when both $\mathbf{A}$ and $\mathbf{B}$ are singular) occurs when at least one of conditions (5) is satisfied. One can notice that conditions (5) correspond to the limit points of the $[2l_2; 0]$ interval. Conditions (6) correspond to the situation when all links of any leg lie on the same plane (Figure 3a). Thus, it is easy to conclude that the conditions (6) can be satisfied only at the edge of the workspace. In Figure 3b the singular surfaces for (6) are shown.



(a) Examples of singular positions for the first leg (view from the end of the leg)

(b) Singular surfaces

Figure 3: Type 1 singularities

For Type 2 singularities (occurs if matrix **A** is singular) no analytical conditions were found using Jacobian analysis. Numerical analysis of the workspace proves that there is no point within the workspace where $det(\mathbf{A})$ is zero. Moreover, at every analyzed point $det(\mathbf{A})$ is less than zero.

We have also carried out the analysis based on the screw theory and obtained the same analytical conditions for Type 1 and Type 3 singularities, as when we used previous method. For Type 2 singularities we have found that for discussed mechanism the rank of the following matrix consisting of Plücker coordinates of wrenches (force and torque screws) must be less than six:

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 1 & W_1^0 z \\ W_1' x & 1 & W_i' z & W_1'^0 x & 1 & W_i'^0 z \\ 0 & 0 & 0 & W_2^0 x & 0 & 1 \\ W_2' x & W_2' y & 1 & W_2'^0 x & W_2'^0 y & 1 \\ 0 & 0 & 0 & 1 & W_3^0 y & 0 \\ 1 & W_3' y & W_3' z & 1 & W_3'^0 y & W_3'^0 z \end{pmatrix}$$

However, one can see that the rank of this matrix is always 6, as all the rows and columns cannot become linearly dependent. This means there is no Type 2 singular points exist for this mechanism, as we concluded it before using the Jacobian analysis. Calculations of velocities via screw theory method have shown the same result as the calculations via Jacobian method.

The general conclusion for this section is that the proposed mechanism has no Type 2 singularities and all Type 1 and Type 3 singular points lie on the theoretical edge of the mechanism's workspace.

4 Dynamics and computer based simulation

The Lagrange-D'Alembert principle was used to analyze dynamics of the mechanism. In order to simplify the calculations, we are assuming that the masses of the links (m_1, m_2, m_3, m_4) in each leg and the mass of the moving plate m_P are distributed as shown in Figure 4

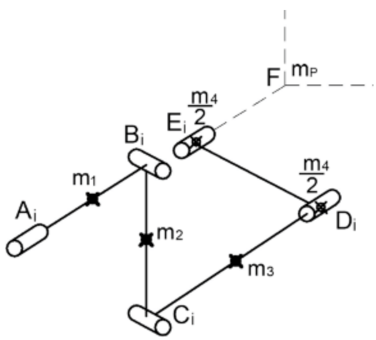


Figure 4: Distribution of the masses in a leg.

With this assumption the basic system of equations (in matrix form) which represents the dynamics of the mechanism can be written as follows:

$$J\begin{pmatrix} M_1 + M_{Fg}^1 + M_{FI}^1 \\ M_2 + M_{Fg}^2 + M_{FI}^2 \\ M_3 + M_{Fg}^3 + M_{FI}^3 \end{pmatrix} + \left(m_3 + m_P + \frac{m_2 + 4m_4}{2}\right)\begin{pmatrix} g_x - a_x \\ g_y - a_y \\ g_z - a_z \end{pmatrix} = 0 \quad (7)$$

Here M_i is a torque in actuated joint of $i-$th leg; M_{Fg}^i and M_{FI}^i are torques produced in $i-$th leg by gravity force and inertia forces, respectively; a_x, a_y, a_z are accelerations of the moving plate along axes x, y, z respectively; g_x, g_y, g_z are parts of the gravitational acceleration; J is the Jacobian matrix. Note that this system of equations represents only dynamics of the mechanism itself without taking in account any external forces and dynamics of the actuators.

In order to test theoretical dynamics model and results of the kinematics and velocity analysis, we have carried out a computer based simulation of the proposed mechanism within MATLAB/Simulink environment.

For this simulation the desired motion (position, velocity and acceleration) of the moving platform is given. Then we have solved inverse kinematics, velocity and acceleration problems obtaining angular position, velocity and acceleration of the actuated joints, and then used these parameters as input signals for the Simulink model. All motion parameters of the moving platform obtained through simulation were equal to desired motion. Thus, we can conclude that the results of the theoretical solution of the kinematics, velocity and acceleration problems are correct. As for dynamics, we have measured torques in actuated joints corresponding to the desired motion of the moving platform and then compared them with torque values obtained theoretically. In Figure 5 results of the theoretical torque calculation (gray) and computer simulation (black) are presented.

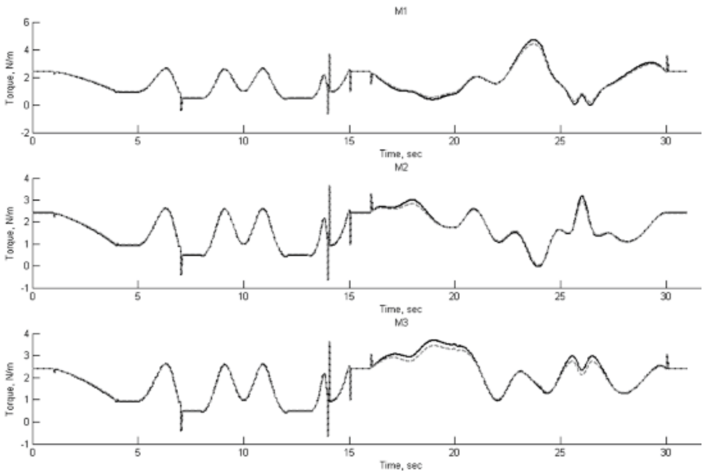


Figure 5: Torques in actuated joints.

5 Conclusion

In this paper, a 3-DOF translational parallel mechanism with five revolute joints is presented. Its kinematics, workspace, singularities and dynamics are analyzed. All the results of the theoretical analysis were tested with computer based model and were proven to be adequate. It was also shown that the mechanism has no singular points inside its workspace but only at the edge of the workspace. Thus, the mechanism is capable of moving freely within the workspace and performing various complicated moves.

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On the accuracy of $N-1$ wire-driven parallel robots

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Abstract A $N-1$ wire-driven parallel robot is a robot for which all the $N \geq 3$ wires are connected at the same point of the platform, allowing to control the location of this point. We are interested in the positioning accuracy of such a robot. If the wires are not elastic we show that the influence on the accuracy of the co-location errors of the wire anchor points on the platform is moderate, although a full analysis is a very difficult task. If the wires are elastic we study the influence of the the wire lengths measurement errors and inaccurate estimation of the stiffness of the wires. Again we show a moderate influence but very large changes in the tensions in the wires that probably prohibit the use of the redundancy to optimize the tension in the wires. In all cases the complexity of the forward kinematics of such a robot makes accuracy analysis a very demanding task that requires an in-depth investigation.

1 The $N-1$ wire-driven parallel robot

In a wire-driven parallel robot (WDPR) wires are attached at specific anchor points on the robot platform and can be coiled and uncoiled through an actuation system with a fixed output point for the wires. WDPR have been introduced in the 80's (Landsberger and Sheridan, 1985),(Miura and Furuya, 1984) as an alternate to parallel robot with rigid links. They share with them the ability to manipulate large load and to be energy efficient (Li and Bone, 2001) while they allow for larger workspace (as the amount of leg lengths variation is much larger) and present a simpler mechanical design. However their major drawback is that wires can be pulled but not pushed, which increases the complexity of their kinematics as statics has to be taken into account (for example the forward kinematic problem is an open issue (Carricato and Merlet, 2011)).

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There has been recently a renewal of interest for WDPR in view of new applications: wind tunnel (Yaqing et al., 2007), biomechanic and rehabilitation (Wu et al., 2011), haptic interface (V. Zitzewitz et al., 2009), rescue robotics (Takeda et al., 2005),(Merlet and Daney, 2010). However an important point has not been addressed completely in this field: positioning accuracy. This is a very well addressed field for parallel robots with rigid links (Merlet, 2006) but still an open issue for WDPR whose kinematics is much more complex (Ottaviano et al. (2002); Thomas et al. (2002)).

We will address this problem for a specific class of WDPR, the $N-1$ WDPR which has N wires attached at the same point on the platform, allowing to control the location of this point but not the platform orientation. We will consider two different cases for the wires: non-elastic and elastic.

2 Non-elastic wires

Although this is not the scope of this paper, an important result has to be presented if $N > 3$:

At any pose a $N-1$ robot with non-elastic wires will have at most 3 wires under tension whatever is $N > 3$

This new result, that will be presented at ICRA 2012, is important as it allows to reduce the accuracy analysis of a $N-1$ robot to the accuracy analysis of the four 3-1 robots that are derived from the initial robot.

The exit point of the wire system i will be denoted by A_i, its wire length as ρ_i and the tension in the wire as τ_i. The platform pose is determined by the coordinates x, y, z of C, the center of mass of the load, in a reference frame where the $\mathbf{z}$ axis is vertical. The anchor points of the wires will be denoted by B_i (ideally $B_i = C$). Note that the inverse kinematics (IK) is straightforward as we have

$$\rho_i^2 = ||\mathbf{A_i B_i}||^2 \tag{1}$$

Let us assume that the platform is submitted to a force $\mathcal{F}$. The relation between this force and the tension in the wires is given by:

$$\mathcal{F} = \mathbf{J}^{-T}\tau \tag{2}$$

where $\mathbf{J}^{-T}$ is the transpose of the inverse jacobian matrix of the robot. The ith column J_i^{-T} of this matrix is: $J_i^{-T} = \mathbf{A_i C}^T/\rho_i$. Note that with this convention wire i is under tension if τ_i is positive. For this robot the sources of inaccuracy are errors in the wire lengths, in the location of the exit points of the wire systems and in the location of the common attachment point. Influence of the wire lengths errors is a well studied topics (Murphy, 2007),(Thomas et al., 2002) and will not be considered here. We will also assume that the location of the A_i are well known . Hence remains possible errors on the location of the B_i.

2.1 Three distinct attachment points B_i

We will first assume that the 3 wires are attached at three distinct points on the platform, that are close to C but distinct from it. To study the accuracy of the robot we will assume a given position of C and we will calculate the wire lengths with equation (1). Then we will assume that the B_i are different from C (which implies that the wire lengths affect the orientation of the platform) and solve the forward kinematics (FK). The difference between the obtained pose and the theoretical one will give us the positioning error. Unfortunately we are confronted to a major issue: the FK for a 3-3 robot is still an open problem. For the FK we have as unknowns the 6 parameters of the pose of the platform and the 3 tensions in the wires while we have 3 kinematics equations (1) and 6 statics equations (2). It has been shown that the solution(s) of this system may be calculated in theory by solving a 158th order univariate polynomial (Carricato and Merlet, 2011) but the high order of this polynomial makes the solving quite difficult. In our case we rely however on an alternate approach based on interval analysis. As an example we will consider the 3-1 robot with $A_1(0,0,0), A_2(400,0,0), A_3(0,400,0)$ and consider that the B_i lie on a circle of radius 5 so that $CB_1(-5,0,0)$,$CB_2(-2.5, 2.5\sqrt{3}, 0)$, $CB_3(2.5, 2.5\sqrt{3}, 0)$.

For C defined by (176.375, 192.375, -147.93) the theoretical wire lengths are 300, 310, 330 and the FK admits two solutions with positive tensions: (171.72, 187.24, -152.66) with the Euler angles in radian (-0.727, -0.387, -1.62) and (178.465, 194.68, -163.99) with the angles (-0.76, 0.324, 1.55). We are confronted here with a difficulty of the FK of WDPR that may admit several solutions, this increasing the complexity of the accuracy analysis. However we note the moderate positioning errors with a distance between the solutions and the theoretical one of 8.39 and 16.36. If the radius of the circle for the B_i's is reduced to 1, then we still get 2 solutions at a distance 1.99 and 2.0 from the theoretical one.

2.2 Attachment points B_i on a common ring

We will consider here that the 3 wires are connected to a ring of center U and radius r and are free to slide on this ring, although their motion must respect their initial connecting order. We will assume that the plane that includes the ring is perpendicular to the platform and that U, C lie on the same normal to the platform (figure 1).

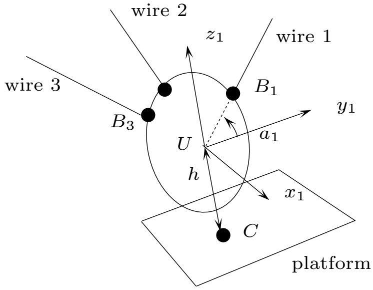

Figure 1. The wires may slide on a ring that is attached to the platform

We define a frame $\mathcal{F}_1 = U, \mathbf{x_1}, \mathbf{y_1}, \mathbf{z_1}$ attached to the ring so that $\mathbf{x}_1$ is perpendicular to the ring plane. In this frame the coordinates of B_i are

$$\mathbf{UB_i}^1 = (0, r\cos(a_i), r\sin(a_i))$$

where a_i is the angle between $\mathbf{UB_i}$ and the $\mathbf{y}_1$ axis. We then define the mobile frame of the platform $\mathcal{F}_r = (C, \mathbf{x_r}, \mathbf{y_r}, \mathbf{z_r})$ so that $\mathbf{z_r}$ is parallel to $\mathbf{z_1}$. Hence the coordinates in $\mathcal{F}_r$ of a vector $\mathbf{u}$ whose coordinates are known in $\mathcal{F}_1$ are obtained as $\mathbf{R}_1\mathbf{u}$ where $\mathbf{R}_1$ is the rotation matrix for a rotation around the axis $\mathbf{z}_r$ of angle ψ_1. As U lies on the $\mathbf{z}_r$ axis we have $\mathbf{C}U_r = (0, 0, h)$. If we define $\mathbf{R}$ as the rotation matrix between the reference frame and $\mathcal{F}_r$ we get:

$$\mathbf{CB_i} = \mathbf{RCB_i^r} = \mathbf{R}(\mathbf{CU_r} + \mathbf{R}_1\mathbf{UB_i}^1)$$

while

$$\mathbf{A_iB_i} = \mathbf{A_iO} + \mathbf{OC} + \mathbf{CB_i}$$

Equation (2) is now a linear system of 6 equations in the 3 unknowns τ_i, which is dependent upon the 3 unknowns a_i and the 6 pose parameters. Three of these equations may be used to obtain the τ_i as functions of the a_i and of the pose parameters and will remain three constraint equations.

If we assume now that there is no contact between the attachment points B_i of the wires on the ring we write that at equilibrium the force exerted by the wires at T_i must be perpendicular to the ring tangent at B_i. In the frame $\mathcal{F}_1$ the ring tangent vector $\mathbf{T}_i{}^1$ is

$$\mathbf{T}_i{}^1 = (0, -r\sin(a_i), r\cos(a_i))$$

Hence in the reference frame we have $\mathbf{T}_i = \mathbf{R}R_1\mathbf{T}_i{}^1$. We get thus 3 additional constraint equations with

$$\mathbf{A_iB_i}.\mathbf{T_i} = 0 \qquad (3)$$

For the FK problem if we assume that all the B_i are distinct, then we have as unknowns the 6 pose parameters of the platform and the 3 a_i. We have also 3 equations (1), 3 remaining equations from the statics (2) and the 3 constraint equations (3). Solving such a system is quite difficult and furthermore not all solutions are valid: indeed the initial assembly of the robot imposes an ordering of the wires on the ring and this ordering must be respected for the FK solution. For solving this problem we use interval analysis which has the advantage of easily allowing to enforce the ordering constraint. For the same robot than in the previous section we have considered the pose for C as (92.95, 110.85, -198.02), which lead to the theoretical wire lengths (237.23, 376.72, 357.206), $r = 5$, $h = 10$ and the ordering (2,3,1) for the wires on the ring. The solving leads to 2 solutions for C, (110,100,200) and (110.84, 92.78, -204.22), with here again a relatively moderate difference between the theoretical pose and the final one. Note that the solving is computer intensive as the computation time is over 1h: it appears that the influence of errors on the location of the attachment points on the platform on accuracy is a very demanding task.

3 Elastic wires

In this section we assume that the wires are perfect linear springs. Let τ_i be the tension in wire i, l_i its length at rest, k_i the wire stiffness and ρ_i its length when under tension. We have

$$\tau_i = k_i(\rho_i - l_i) \qquad (4)$$

Let us consider a 4-1 WDPR and its inverse kinematics. For a given pose of the load the values of the ρ_i may be determined with equation (1). Equation (2) is a linear system of 3 equations in the τ_i that allows one to calculate τ_2, τ_3, τ_4 as functions of τ_1. For a given value of τ_1 we may compute the remaining τ_i and, if all the τ_i are positive, we get the value of l_i from equation (4). The choice of τ_1 is free and hence we have a redundant robot that allows, in theory, to manage the wires tensions distribution. We may choose, for example, a τ_1 such that $H = \sum_{j=1}^{j=4} \tau_j^2$ is minimized. This function is quadratic in τ_1 and hence finding the optimal τ_1 is trivial. Note however that we may have IK solutions such that not all 4 wires are under tension.

For the accuracy analysis we have to solve the FK problem. Here the l_i are given and the pose of the load has to be determined. The first equation of (4) allows one to determine τ_1. Equation (2) is used to determine the values of τ_2, τ_3, τ_4 as functions of τ_1. The three remaining equations of (4) are linear in the coordinates of C. After solving this system we report the result in the IK equations (1) which constitutes a system of 4 equations in the unknowns $\rho_1, \rho_2, \rho_3, \rho_4$. The difference between the first and second equation is linear in ρ_4 and is solved for this variable. The 3 remaining equations, denoted a_1, a_2, a_3, are of degree (6,6,2), (3,3,3), (9,9,3) in ρ_1, ρ_2, ρ_3. Successive resultants between these equations leads to a polynomial in ρ_1 only, which factors out in 2 polynomials of degree 76 and 96. Although this complete the theoretical solution the degree of the involved polynomials are too high to be used in practice and consequently we have to resort to a numerical procedure. For that purpose we solve the linear system (2) to get τ_2, τ_3, τ_4 as function of τ_1. Then the first equation of (4) is used to determine τ_1 as a function of ρ_1. The three remaining equations of (4) together with the 4 equations of (1) constitutes a system of 7 equations in the 7 unknowns $x, y, z, \rho_1, \rho_2, \rho_3, \rho_4$, which is solved using interval analysis. However we have also to consider that this system may not have a solution as in the final configuration less than 4 wires may be under tension. If 3 wires are under tension equation (2) is solved to determine the τ_i, the result being reported in equations (4) to obtain 3 constraint equations in x, y, z and the 3 ρ_i. With the 3 equations (1) we get a system of 6 equations in the 6 unknowns. As we have to consider all combinations of 3 wires among 4, we have to solve four such system.

To test the sensitivity of the solving to uncertainties on the l_i's and on k_i we have considered the 4-1 robot with $A_1(0,0,0)$, $A_2(400,0,0)$, $A_3(0,400,0)$, $A_4(400,400,0)$ and we have used the IK to determine what should be the l_i to reach the pose $x = 100, y = 200, z = -200$ with a load of 80, while minimizing $\sum_{j=1}^{j=4} \tau_i^2$, assuming an identical stiffness $k = 1000$ for all wires. The nominal values for the l_i are $l_1 = l_2 = 299.558$, $l_3 = l_4 = 412.108$ which leads to $\tau_1 = \tau_2 = 441.45$, $\tau_3 = \tau_4 = 202.238$. We have then considered 1000 values for the k_i that were randomly perturbed around their nominal values by $\pm 0.1k$. We have then calculated the FK by assuming first that all 4 wires were under tension and then the FK with only 3 wires under tension (all combination of 3 wires were considered) and assuming a perfect wire lengths control. For all 1000 tests we have obtained a single solution with 4 wires under tension with the ranges [99.95,100.045], [199.94, 200.05], [-200.054,-199.95] for x, y, z. However we have observed large variations in τ_i, that lie in the ranges [421.3, 462], [420.8, 461.5], [174.1,229.7],[174.7,230.4]. Furthermore there was always a single solution with wires (1,2,3) and (1,2,4) under tension, while the remaining wire is slack. For these solutions the ranges for x, y, z were [99.61,99.74], [199.71,200.28],[-200.23,-200.09]. In the triplet (1,2,3) the tension in wire 3 is almost constant (range: [402.78,403.35]) as it is for the tension in wire 4 for the triplet (1,2,4) (range: [402.78,403.35]) but the tension in wires 1, 2 were changing significantly for the two triplets with typical values of (295,588) for the first triplet and (588,295) for the second one. Hence force measurements will allow to determine if the wires under tension are (1,2,3,4), (1,2,3) or (1,2,4).

We then perturb both l_i (with a range of ±3) and k_i. In that case for 1000 tests, only 161 where admitting a solution with 4 wires under tension with the ranges [95.62,103.97] for x (mean value:100.18), [196.31,203.17] for y (mean value:200), [-204.22,-195.67] for z (mean value:-200.13), with large variations for the τ_i (ranges: [289.4,583.15], [290.8,590.45],[7.7, 407.2], [0.8, 402.4]). Here again there was always at least 2 solutions with 3 wires under tension with a range [94.5,104.8] for x (mean value: 99.7), [195.54,204.72] for y (mean value: 199.97), [-204.52,-195.72] for z (mean value: -200.25). For the triplet (1,2,3) τ_3 lies in the range [381.5, 426.5] while for the triplet (1,2,4) τ_4 lies in the range [383.8, 425.6]. Still force measurements allows one to determine the configuration of wire under tension as τ_1 either lies in the range [273.56,315.3] or [574.8,602.15] while τ_2 lies in the range [274.5,313.96] or [573.9,603]. Similar results were obtained for $k = 10$ and $k = 100$.

In conclusion positioning errors are moderate, while the variations of wire tensions probably prohibit the use of force control and the use of the redundancy to manage distribution of the tension in the wires.

4 Conclusion

Although WDPR have attracted a lot of interest recently there has been few works that address their positioning accuracy. We have considered a specific class of WDPR for which all wires are assumed to be attached at the same point on the platform. For non elastic wires the main source of positioning errors (beside control errors in the wire lengths) is that in practice the wires are not connected at the same point. We have shown that finding the pose of the robot when assuming close but distinct attachment points is a difficult task and seems to lead to moderate positioning errors. We have then considered WDPR with elastic wires and have shown that errors on the stiffness of the wires and/or on the wire lengths may also lead to moderate positioning errors but large variations in the wire tensions.

Accuracy analysis of WDPR is a complex task because we have to consider the FK problem for all possible combinations of wires under tension (and not only the case where all N wires are under tension), while many of these problems are open. For the $N-1$ WDPR we have shown that the positioning errors seem to be moderate but that there is large variations of wire tensions, which probably prohibit the use of force control and redundancy management. Hence this issue requires still an in-depth investigation.

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Clearance and Manufacturing Errors Effects on the Accuracy of the 3-RCC Spherical Parallel Manipulators

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Abstract This paper deals with the analysis of a spherical parallel manipulator (3RCC) to determine the error on the pose of the end effector as a function of the manufacturing errors of the different links and the presence of a clearance in the joints. The obtained model allowed us to identify the error on the platform in three cases, i.e., only manufacturing errors were considered, then only clearance in the joints was considered and finally the case of both sources of error were present in the system. It was shown, in particular, that the axial displacement in the C joints is quite important. The second result is the fact that the superposition principle does not work when we consider both the manufacturing errors and the clearance despite the assumption of small displacements.

1 Introduction

The most common architecture for SPM is the 3-RRR. However, this architecture is over constraint and some authors prefer a non overconstrained versions of the 3RRR SPM (Al-Widyan et al., 2011; Bai, 2010). The advantage of these architectures is that the assembly is always possible regardless of the manufacturing errors. But this advantage is not without affecting the desired accuracy position and orientation of the SPM. Indeed, the freedoms added to the architecture allow small displacements caused by the dimension imperfections of the links of the mechanism. Al-Widyan et al. (Al-Widyan et al., 2011) evaluated through a stochastic method the translational displacement of each cylindrical joint in the 3-RCC architecture. While these small displacements allow the mounting of the mechanism without the need to deform the links, they can yield errors on the position and orientation of the end-effector.

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This problem is studied by some authors: Yu et al. (Yu et al., 2008) used a simple geometric method to analyze and compare the accuracy of three parallel robot designs. Binaud et al. (Binaud et al., 2010, 2011) proposed two aggregate sensitivity indices to compare planar parallel manipulators with regard to their workspace size and sensitivity. Clearance in the joints is another source of errors in SPM. Frisoli et al. (Frisoli et al., 2011) studied the influence of the revolute joint clearances on the position accuracy in the SPMs using a screw theory. The authors show how the position accuracy of certain parallel manipulators is strictly dependent of the mechanism pose and its association to kinematic isotropy. Tsai and Lai (Tsai and Lai, 2008) treated the joint clearances as a virtual links in a general method for error analysis of multi-loop mechanisms with joint clearances. In this work we propose to analyze the combined effect of the manufacturing errors and clearances on the pose error of the end effector of a 3-RCC SPM. The manuscript is structured as follows: after this introduction, section 2 presents the architecture of the 3RCC. Section 3 deals with the model used to calculate the errors. The obtained results are presented in Section 4, along with a discussion. Some concluding remarks are presented in Section 5.

2 Architecture of the 3-RCC SPM

Fig.1-(a) presents the architecture of the proposed spherical parallel manipulator (SPM).Three identical legs and relate the base to the platform.

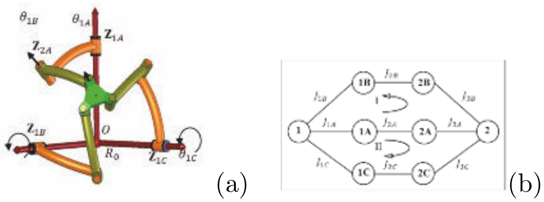

Figure 1. (a):The 3-RCC CAD Model, (b):The graph of the SPM

Each leg of the SPM is made out of two links and one revolute joint and two cylindrical joints. All the axes of the joints are intersecting in one point, called the center of the robot. Each link is characterized by the angle between the axes of its two joints. This angle is constant and it represents the dimension of the link. The three revolute joints with the base are actuated. This design is a non-overconstrained version of the 3-RRR