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ENERGY CONSUMPTION OF REDUNDANT PLANAR PARALLEL MANIPULATORS: A COMPREHENSIVE STUDY.

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Abstract. *One of the main purposes of the robotic industry nowadays is to improve the energy efficiency of their robots and manipulators. Hence, novel manipulators architectures have been widely studied during the last decades. On this respect, parallel manipulators represent an alternative to the classical serial manipulators in certain tasks. Several authors have shown that parallel manipulators possess some advantages when compared to serial ones: higher load-carrying capacity, improved accuracy, increased stiffness, among others. However, the common presence of singularities in parallel manipulators represents an important issue. Numerous works have proved that the addition of kinematic and actuation redundancy can promote a reduction of singularities in parallel manipulators. The objective of this manuscript is to investigate if redundancy is also a good alternative to design energy efficient machines. This is performed by the comparison between the non-redundant manipulator 3RRR, the actuated redundant manipulator 4RRR and the three times kinematically redundant manipulator 3PRRR, in terms of energy efficiency. In order to do so, the three manipulators are forced to execute a predefined trajectory. The rational use of the redundancy is defined by the minimization of the consumed energy along the trajectory using a genetic algorithm. The results show that the addition of redundancy may improve the energy efficiency of the parallel manipulators.*

Keywords: *Energy Efficiency, Parallel Planar Manipulator, Redundancy*

1. INTRODUCTION

The improvement of the energy efficiency of mechatronic systems is one of the mean concerns of the robotic industry. Several authors have developed energy efficient strategies on different areas, such as energy harvesting (O'Regan and Grätzel, 1991; Beeby *et al.*, 2006; Mitcheson *et al.*, 2008; Infante *et al.*, 2015), path planning (Diken, 1994; Verscheure *et al.*, 2008; Pellicciari *et al.*, 2011; Kim and Kim, 2014), component and design optimization (Fuerstenau and Abouzeid, 2002; Grassi, 2015), iteration between machines (Vergnano *et al.*, 2012) or factory network planification (Karnouskos *et al.*, 2009; Neugebauer *et al.*, 2011). The continuous growth of the applications suited for robotic manipulators leads to the development of original manipulator architectures. Parallel manipulators possess advantages compared to serial ones as higher load-carrying capacity, improved accuracy and increased stiffness (Merlet, 2006), therefore, they are more adapted to certain tasks where a substantial workspace is not required. Furthermore, under specific circumstances, parallel manipulators can be more energy efficient than serial ones (Bone, 2001). Nevertheless, the common presence of singularities represents a drawback in parallel manipulators (Gosselin and Angeles, 1990). Several authors propose the use of redundancy to avoid singularities in parallel manipulators (Liu *et al.*, 2001; Cha *et al.*, 2007; Ebrahimi *et al.*, 2007; Kotlarski *et al.*, 2009). The addition of redundancy provides many other benefits, higher accuracy in the end-effector poses (Kotlarski *et al.*, 2008), increased transmissibility of movements and forces Xie *et al.* (2011) and improved dynamic performance (Fontes, 2014; Wu *et al.*, 2011) among others. However, the capacities of redundancy in parallel manipulators in relation to energy efficiency are weakly explored. Pasand and Naderi (2013) proposes an optimization method to reduce the energy consumption of the manipulator 3PRRR, Lee *et al.* (2015) investigate the benefits of the actuation redundancy in the energy consumption. The purpose of this paper is to provide a comprehensive study of the effects of redundancy in the energy efficiency of parallel planar manipulators. In order to do so, the three parallel manipulators illustrated in Fig. 2, the non redundant 3RRR, the three times kinematically redundant 3PRRR and the once actuated redundant 4RRR, are compared in relation to their power usage. The manipulators are forced to execute a trajectory described in section 2, a brief description of cinematic and dynamic models is presented in section 3, the energy usage model based on a DC motor is presented in section 4, the presence of kinematic redundancy implies a infinite number of solutions in the inverse

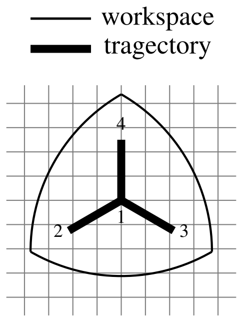


Figure 1. Performed Trajectory.

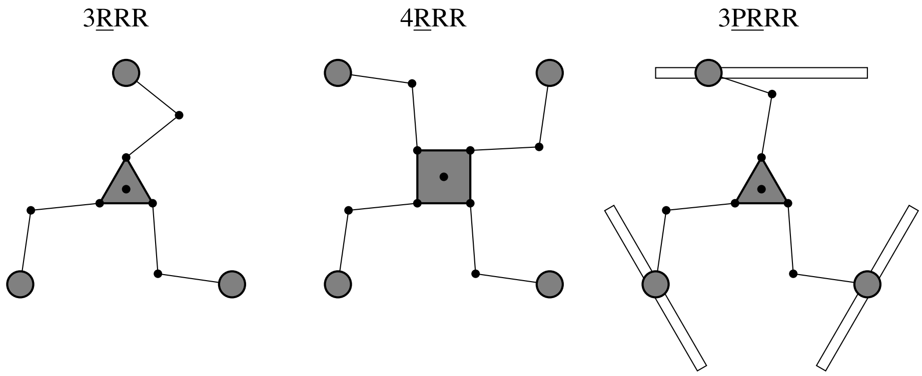


Figure 2. The three compared parallel planar manipulators.

kinematics problem, therefore, in section 5 an optimization method is presented, the results are presented and commented in section 6, further discussions and conclusions are introduced in section 7.

2. TRAJECTORY PLANNING

In order to make an analysis of the performance of any manipulator it is required to predefine a task, therefore, the end-effector of the three manipulators under study are compelled to execute the trajectory shown in Fig. 1. This trajectory is composed by several straight segments, each segment is described by fifth degree polynomial, the initial conditions of velocity and acceleration for each segment are zero, thus, using the methodology presented in Mark W. Spong (2006), it is possible obtain the coordinates of the end-defector (x, y) . The end-effector is crossing over the numbers represented in Fig. 1 in this direction, $1 \rightarrow 2 \rightarrow 1 \rightarrow 3 \rightarrow 1 \rightarrow 4 \rightarrow 1$. The manipulators under study here, are planar, therefore, three coordinates describe its pose, two Cartesian coordinates (x, y) and the orientation angle α, in this paper it is assumed a constant value for the orientation angle equal to zero degrees. In Fig. 1, the distance from point 1 to any of the other points is 0.15 meters.

3. CINEMATIC AND DYNAMIC MODELS

In this section is presented a brief explanation of the methodology explained in our last work and based in the approach presented by Wu *et al.* (2011) and Fontes (2014). In order to apply this approach is necessary to set some constant parameters, the basic manipulator's parameters are specified in Fig. 4.(a) and Fig. 4.(c), the numerical values associated with those parameters are common to the three compared manipulators and are detailed in Tab. 1. The purpose here is to obtain the expressions for the torques and velocities of the active rotational joints. This method is applied to one of the kinematic chains and can be generalized to the others. The first step is to solve the inverse kinematics problem in order to obtain the angles of the active and passive joints, once obtained, it is possible to compute the jacobian matrix, the jacobian relates the velocities of the active joints with the velocity of the end-effector. Next, the partial accelerations and velocities of each manipulator body (actuator, first link, second link and end-effector) must be obtained. Knowing the partial velocities and accelerations it is possible to compute the partial forces and moments. With all the previous information available the virtual work principle can be applied to obtain the expressions for the torques τ of each active joint.

Table 1. Geometric parameters of the manipulators

Mass of the actuators	0.4 Kg
Mass of the links	0.2 Kg
Length of the links (l_1, l_2)	0.2 m
a	0.25 m
h	0.05 m

4. DC MOTOR MODELLING

The torques τ are produced by an actuator, in this section, a model for the actuators based on a permanent magnet DC motor is presented. Basically, a DC motor has a rotor that can turn inside a stator, the stator contains a permanent magnet that produces a magnetic flux ϕ, this flux generates the armature current i_a in the rotor, as a consequence, the rotor is able to turn with a torque τ and a velocity $\dot{\theta}$, the generated torque can be expressed as

$$\tau = K\phi i_a \tag{1}$$

Where K is a constant, in the case of permanent magnet DC motors the magnetic flux ϕ is constant, therefore the Eq. (1) can be rewritten as

$$\tau = K_m i_a \tag{2}$$

Where K_m is known as torque constant, the Eq. (2) shows that the torque of DC motor is controlled by means of the armature current i_a.

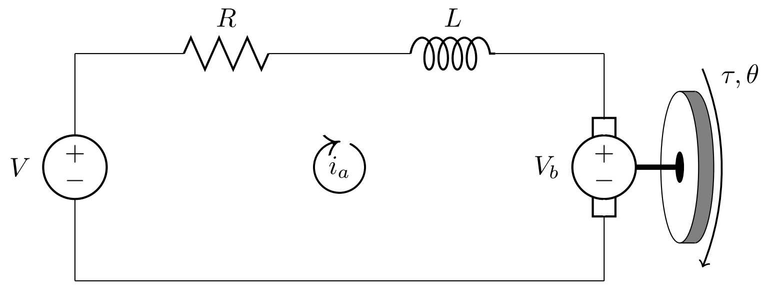


Figure 3. DC motor circuit.

The voltage V of the circuit in Fig. 3,can be computed as

$$V = V_b + L\frac{di_a}{dt} + Ri_a \tag{3}$$

Where V_b, L and R are the back emf, the armature inductance and the armature resistance respectively. The back emf can be expressed as $V_b = K_b\dot{\theta}$, where K_b is the back emf constant and $\dot{\theta}$ is the rotor velocity, thus, the Eq. (3) can be rewritten as

$$V = K_b\dot{\theta} + L\frac{di_a}{dt} + Ri_a \tag{4}$$

The constants K_m, K_b, L are R are characteristics of each DC motor. The instant power can be computed as

$$P_{elec} = V \cdot i_a \tag{5}$$

Then, the total power usage of a a manipulator with n DC motors during a task executed in a period of time T can be expressed as

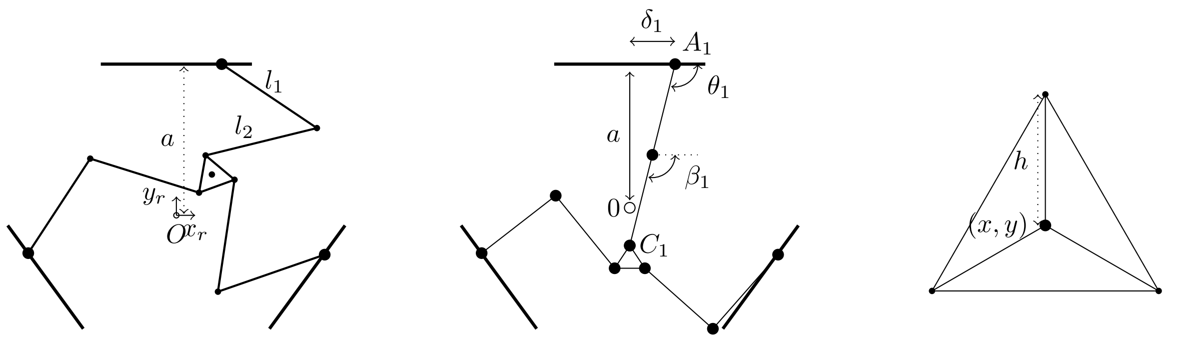
$$P_{total} = \sum_{j=1}^{n} \frac{1}{T}\int_0^T |P_{j_{elec}}|dt \tag{6}$$

5. OPTIMIZATION

The addition of kinematic redundancy in the manipulator 3PRRR leads to an inverse kinematics problem with infinite number of solutions, this means that there exist infinite manipulator configurations for which the end-effector remains in the same pose, therefore, an optimization method is needed in order to chose one of the solutions according to some criteria. In this paper, a genetic algorithm is used as optimization method (Holland, 1992), the variables to optimize are the linear guides displacements denoted as δ_i, and the objective or fitness function is the Eq. (6), then the optimization problem can be described as

$$\begin{aligned} \underset{\delta_i}{\text{minimize}} \quad & \sum_{j=1}^{n} \frac{1}{T} \int_0^T |P_{j_{elec}}| dt \\ \text{subject to} \quad & LB \leq \delta_i \leq UB \end{aligned} \tag{7}$$

The characters *LB* and *UB* describe the lower and upper bounds of the variables δ_i, the quantities *LB* and *UB* are arranged for avoid first type singularity, this kind of singularity is illustrated in Fig. 4. This situation occurs when the links of one



(a) (b) (c)

Figure 4. (a) Manipulator basic parameters. (b) Type 1 singularity to avoid. (c) End-effector basic parameters.

of the kinematic chains are totally extended, then $\beta_1 = \theta_1$. In order to evade this singularity it is necessary to achieve

$$|\mathbf{r}_{A_i} - \mathbf{r}_{C_i}| < l_1 + l_2 \tag{8}$$

Where l_1 and l_2 are the lengths of the first and second link of each kinematic chain respectively. The left term in Eq. (8) can be approximated by

$$|\mathbf{r}_{A_1} - \mathbf{r}_{C_1}| > \sqrt{(x - \delta_1)^2 + (y - a)^2} \tag{9}$$

Where (x, y) are the Cartesian coordinates of the end-effector given by the trajectory planning, then, combining the Eq. (8) and the Eq. (9) results

$$\sqrt{(x - \delta_1)^2 + (y - a)^2} \leq l_1 + l_2 \tag{10}$$

Therefore, from Eq. (10) the variable δ_1 can be bounded by

$$-\sqrt{(l_1 + l_2)^2 - (a - y)^2} - x \leq \delta_1 \leq \sqrt{(l_1 + l_2)^2 - (a - y)^2} + x \tag{11}$$

Finally, it is possible to define the quantities *LB* and *UB* as

$$\begin{aligned} LB &= -\sqrt{(l_1 + l_2)^2 - (a - y)^2} - x \\ UB &= \sqrt{(l_1 + l_2)^2 - (a - y)^2} + x \end{aligned} \tag{12}$$

For the remaining kinematic chains, the process is analogous. The described strategy excludes the type 1 singularities from the set of configurations available to the optimization problem.

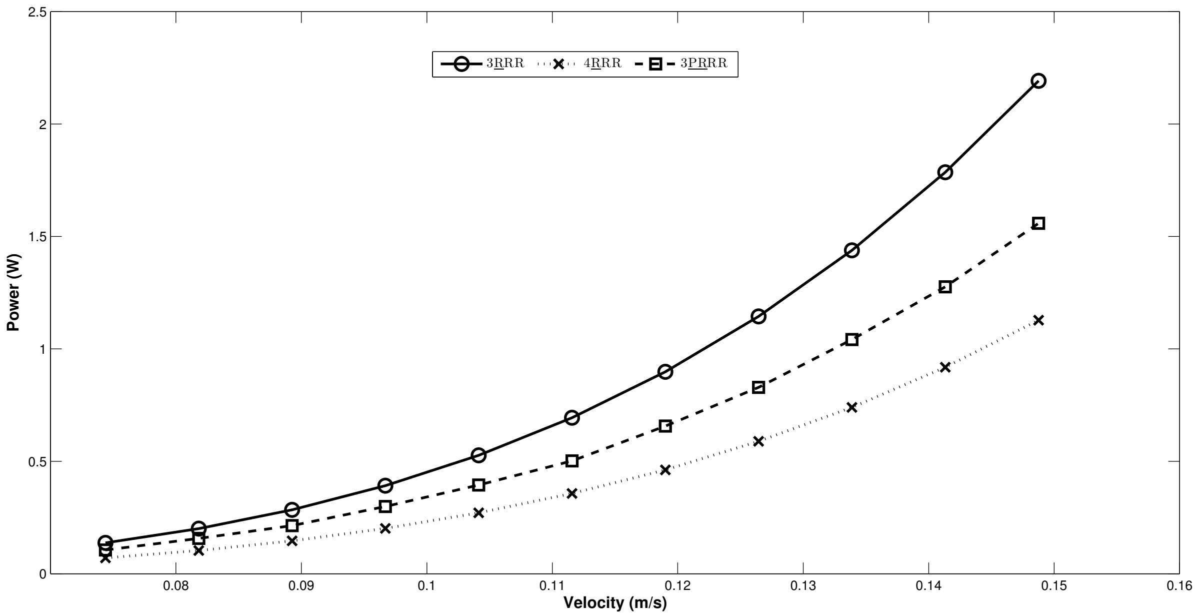


Figure 5. Power usage versus trajectory execution velocity.

6. RESULTS

The analysis exposed here contributes to the study of the effects of redundancy in the energy efficiency of planar parallel manipulators. In this paper, three parallel planar manipulators are compared, the non redundant 3RRR, the once actuated redundant 4RRR and the three times kinematically redundant 3PRRR. The three manipulators are forced to execute the trajectory illustrated in Fig. 1. For the case of the 3PRRR, an optimization method is needed, a genetic algorithm is used for this purpose. In order to get an expression for the total power usage, the actuators are modeled as permanent magnet DC motors with $K_b = 7.5\,V/krpm$, $K_m = 0.06\,N \cdot m/A$, $L_a = 0.8\,mH$ and $R = 1\,ohm$. The mean result of this analysis is shown in Fig. 5, in this graphic the total combined power usage of all actuators for each manipulator is plotted in function of the mean velocity at which the end-effector performs the hole trajectory. The graphic shows that the power usage is lower for the redundant manipulators 4RRR and 3PRRR than for the non redundant 3RRR, this effect is even more acute when the execution velocity increases.

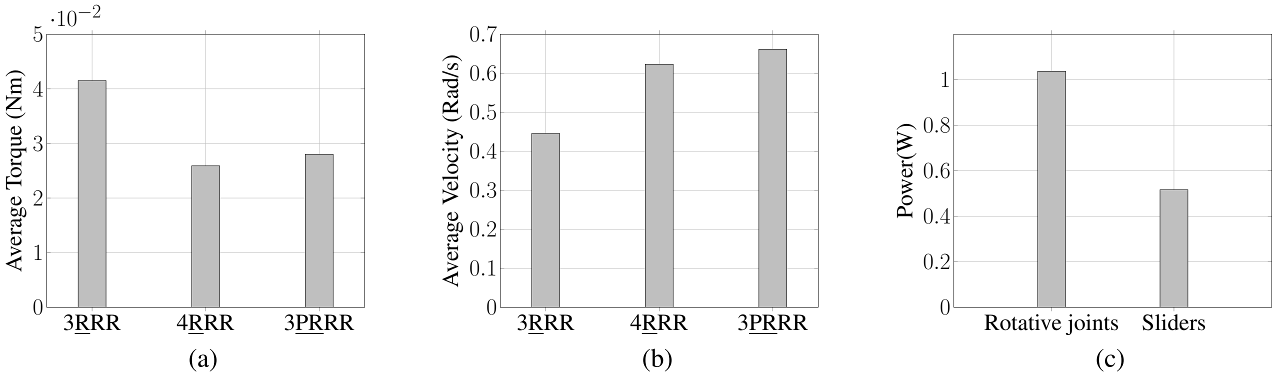


Figure 6. (a) Rotative joints average torque. (b) Rotative joints average velocity. (c) 3PRRR power usage distribution.

The data used in Fig. 6 corresponds to the case in which the execution velocity is 0.15 m/s. Figures 6.(a) and 6.(b) represents the average torque and velocity of the rotative actuators for the three manipulators respectively, it is clear that the addition of kinematic and actuation redundancy achieves a reduction in the rotative joints average torques and an increasing in the rotative joints average velocity. The Fig. 6.(c) represents the quantity of power used by the rotative and prismatic actuators for the 3(P)RRR, it can be seen that the prismatic actuators consume one third of the total power usage.

7. CONCLUSIONS

In the proposed comparative, the actuated planar parallel manipulator 4RRR gets the lowest power usage. The three times kinematically planar parallel manipulator 3PRRR gets a lower power consumption than its homologous non redundant 3RRR. The reconfiguration capacities of the 3PRRR due the kinematic redundancy allows the manipulator to avoid singularities. The DC motor model proposed for the actuators do not include effects as friction, further studies must include power losses due to friction in the models. The linear guides torques in the manipulator 3PRRR are modeled as a constant multiplied by the respective torques, further works must include a more accurate model of the linear guides. In this work is shown that both, kinematic and actuation redundancy contributes positively to the energy efficiency of planar parallel manipulators reducing the power usage during the execution of a task.

8. ACKNOWLEDGMENTS

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