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Cooperative Transportation of an Object based on Fractional Order Controllers

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Abstract *— Advanced control techniques have been used in simulations to overcome nonlinear phenomena in order to describe the performance of robots with two rotational (RR) degrees-of-freedom (dof). Given the current state-of-the-art, fractional order algorithms lead to better performance when compared to integer order controllers. Also, the development of simulation platforms allows evaluating the best control methodology. In this context, the use of RR robots attached to mobile platforms, denoted in this paper as RR mobile robots, demonstrates a remarkable ability in manipulating and transporting objects. The present work aims to study two cooperative RR mobile robots by analyzing the manipulator's trajectory and the forces applied to the common load. Are considered two robotic platforms based on an 8-bit microcontroller with inverse kinematics based on the Denavit-Hartenberg formulation and fractional order PID controllers inspired in the Grünwald-Letnikov definition.*

Keywords *— fractional calculus, mobile manipulators, multi-robot systems.*

1 Introduction

Robotic systems are effective automation tools necessary for industrial modernization improving the international competitiveness and economic integration. The increase of productivity and flexibility is closely related to the level of intelligence and autonomy of robots. Currently, the industry needs the application of intelligent systems in several production processes. However, these systems are semi-autonomous and require some human supervision. Recent intelligent, flexible and robust autonomous systems are key components to the future of medicine, biology, engineer and other areas. One of the strategies recently focused by researchers in the area of robotics is the cooperation between robots (*e.g.*, cooperative robotic manipulators) [1-2]. Using robots in a complex and dynamic system requires a high level of knowledge about the surrounding environment in order to establish an efficient control methodology, thus leading to an increase in the collective intelligence of the robotic cooperative system. Although the several agents in the robotic cooperative system, *i.e.*, multi-robot system (*MRS*), may have different tasks, they all work with a common goal. It should be noted that due to market demand all over the world, the need for a *MRS* becomes increasingly necessary. To that end, this work proposes the development of two two-rotational (*RR*) mobile robots to perform the cooperative handling of objects. The processing unit of both robotic platforms are based on 8-bit microcontroller from *Arduino* board which integrates both the inverse kinematic model of the *RR* manipulator and the fractional-order *PID* (Proportional-Integrative-Derivative) (*FO-PID*) controller[1] in order to balance the forces applied in the common load. Both mobile platforms are low cost solutions and do not explicitly communicate. The proposed cooperative system will be evaluated analyzing the trajectory and the forces performed by both manipulators while transporting the object from one location to another.

Bearing these ideas in mind, section 2 presents some related work on robotic manipulators mainly focusing on the concept of cooperation in robotics. The proposed robotic system and control strategy is presented in section 3 and thus evaluated in section 4. Section 5 summarizes the main conclusions.

2 Motivation and Context

A key driving force in the development of mobile robotic systems is their potential for reducing the need for human presence in dangerous applications. Thus, through robot cooperation it is possible to optimize the coordination of their actions and through the sharing of sensing information and computing power known in contemporary society, probably get better results than just using a single and complex robot.

2.1 Cooperative Manipulators

The concept of *cooperative work* is understood, in a broader sense, as the execution of a coordinated action between several participants (*e.g.*, employees) commonly involved in a specific task [3]. The cooperative work results from the contribution of all participants, in such way that none of the individual tasks of each participant is independent in time and space. In this context, cooperation means that each participant is able to perform their own work, taking into account the tasks performed by other participants during this process. This implies that each participant receives information about the state of other robots and their tasks [4]. In robotic manipulators, a cooperative system is seen as multiple manipulators that cooperatively work on the same task (*e.g.*, handling an object) (Figure 1).

The use of multiple manipulators to perform such tasks increases the reliability of the application, while reducing the cost and complexity of each robotic manipulators and time of execution of each task [5]. One of the main objectives of cooperative robotic manipulators is to handle an object in order to change its spatial pose following a given trajectory.

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[1] The proposed fractional-order *PID* library for Arduino can be found at http://www2.isec.pt/~micael/contributions/FOPID/FOPID.zip

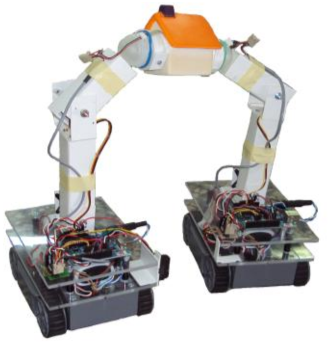

Figure 1: Cooperation between two *RR* Mobile Robots.

Summarizing, the cooperation between robots is defined by actions that take place in a coordinated manner to accomplish a task or achieve a common goal. The robots cooperate to perform a well-defined task (*e.g.*, transport an object), usually only when a robot is not able to do so (*e.g.*, torque-limited).

2.2 Related Work

Robots that were built to mimic the movement of the human body (*e.g.*, trunk and upper limbs) represent a good solution to fit two essential skills in robotics: *1*) skillful manipulation; and *2*) grasping objects [6]. Furthermore, industrial robots are mainly used in structured environments, in which the position and shape of objects to be manipulated are well determined. In unstructured environments, multi-arm robotic systems need highly redundant control architectures, both active and reactive, in order to safely interact in the environment while avoiding collisions. The robust reactive algorithm proposed in [6], denoted as the “skeleton algorithm” is used to generate real-time collision-avoidance.

One of the most well-known examples of a dual-arm cooperative manipulator that simulates human movements was created by *Motoman*. The *SDA20D* high speed model is equipped with two seven-axis arms, and offers the flexibility of human movements, by rotating through the central axis. The robot supports loads of 20 kg, with a resolution of 0.1 mm and can be applied in assembly lines, transfer of goods and machinery care. The robot is able to keep a piece in one arm while the other uses a tool (*e.g.*, tighten screws), or transfer an object from one arm to the other without the need to drop it in a predefined location. Another similar robot was developed in the *Institute of Robotics and Mechatronics German Aerospace Centre* (*MRI*) which has a long history in designing robots [7]. Justin is a humanoid robot equipped with two manipulators that were developed for application areas different than the classical industrial robotics. Its arms are equipped with strength and position sensors in the joints that provide a similarity to our kinaesthetic sense - the way we use our muscles and tendons to know where our limbs are without looking. This ability makes Justin a suitable robot safe enough to work alongside with humans. However, as Laurel and Hardy show [8], the coordination between arms may be a problem and one of the major issues resides in the design and implementation of control architectures since real robotic arms present several nonlinearities. One of our previous works proposed different control methodologies to overcome nonlinearities such as backlash, friction, flexibility and saturation in a simulation environment [1] [9]. *NASA* researchers have shown that interconnected robots can work together to move large objects

[10-11]. The capabilities that robots have to transport large objects could be used in space exploration, military and manufacturing. The work of Ashley *et al.* [12] presents the first results of a *Robotic Construction Crew* (*RCC*), in a construction scenario, where robots cooperate in tasks such as transportation and positioning accuracy. The collective intelligence is evenly distributed between each pair of robots. However, all the information about the terrain, the payload, positions and velocities of each robot is shared. In other words, they are constantly aware of each other's state using explicit communication which shows some limitations in terms of fault tolerance and reliability, because it typically depends upon a noisy, limited bandwidth communications channel that may not continually connect all members of the robot team [13].

Next section presents a cooperative system of two *RR* mobile robots that implicitly communicates using sensors to directly observe the actions of the teammate.

3 Cooperative *RR* Mobile Robots

The basic principle of the proposed sensorial system and controller architecture presented in this section is based on Newton's 3rd Law which shows the exchange of forces between bodies. This law says: "*For each action there is an equal and opposite reaction*". In other words and applied to the proposed work, at each iteration, there is an action of one manipulator and a reaction of the other that ultimately keep the object in a state of equilibrium.

3.1 Robotic Platform

Both developed platforms are illustrated in Figure 1 and Figure 2. Each arm is equipped with a *RR* manipulator.

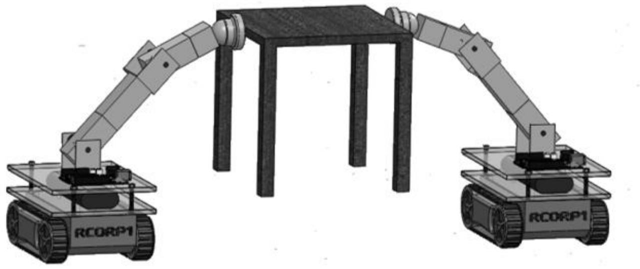

Figure 2: 3D SolidWorks illustration of two *RR* mobile robots cooperatively transporting a table.

Figure 3 shows the structure of the platform divided into three sections. The control and the interface between the three sections are performed by the *Arduino Uno* board. The base platform is the *RP5 Pololu* which consists on a small plastic structure with two *DC* motors coupled at rubber tracks. The robots can control the position of their own manipulator since actuators are servo-motors standard *Hitec Servo* (*HS-311*) equipped with position encoders that directly measure the angles of the joints. Since the objective is to control the position of the object, it is necessary to express the joint angles in terms of the position of the end-effectors leading to the implementation of the inverse kinematics in the *Arduino* board. Since the *Arduino* board has no sufficient current output to power the *DC* motors from the locomotion system, a *TB6612FNG* driver from *Toshiba* was used. These are encoder-free motors, as there is a proximity sensor *GP2Y0A21YK Sharp* with which it is possible to find out the distance that a robot is in relation to the other thus synchronizing their movement.

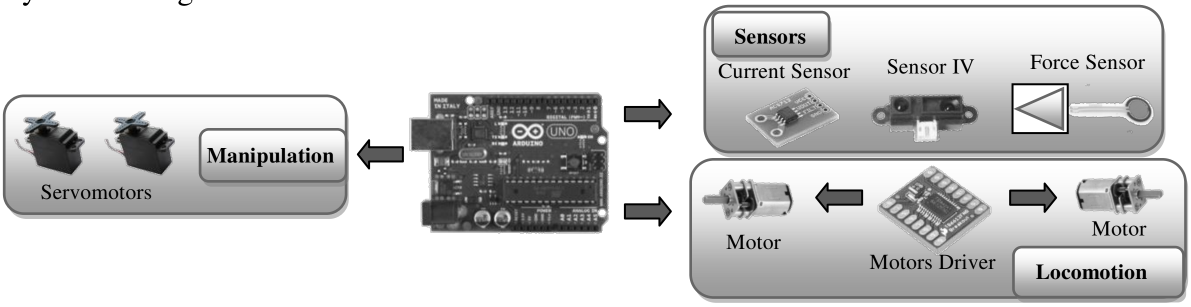

Figure 3: Structure of the mobile platform.

The *Force Sensing Resistors 402 Interlink Electronics* are force sensors which allow establishing the action/reaction force pair applied in the object by both robots. They are located in the end-effector that makes contact with the object, sending a signal that is amplified thus giving a higher resolution of the applied force. To understand the torque distribution of servomotors, each robot was equipped with two current sensors *ACS712* from *Allegro MicroSystems*.

3.2 Control Architecture

When two robots grasp an object (Figure 5), transporting it from one location to another, a coordinated motion is required. In order to get good performances it is necessary to specify not only the desired motion of each robot but also the corresponding handling force. Such specifications require a robust control architecture. In this work, the control architecture (Figure 4) is inspired by the impedance and compliance regimes. In order to control the dual-arm robotic manipulator, it was implemented a cascade control for each of the *RR* arms where x_d and F_d are the desired coordinates of the load and the contact forces [14].

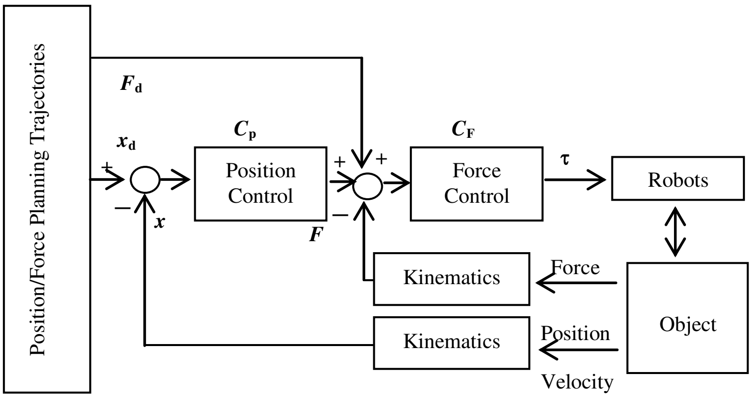

Figure 4: Architecture of position/force control.

The purpose of this control architecture is to ensure that a sequence of planned movements is correctly performed even when unpredictable errors resulting from computational accuracy limitations and mechanical unwanted effects (*e.g.*, friction, backlash, others) appears, and also to compensate other external perturbations (*e.g.*, collisions). One of the most popular control methods is the *PID* controller. Conventional controllers such as *PID* and other advanced control methods are useful in the control of linear processes. However, in practice, most processes are classified as nonlinear since there may be countless variations on the system behavior. More recently, fractional-order controllers, such as the *FO-PID*, have been studied and positively compared to integer order controllers [9] [15-16]. Nevertheless, both *PID* and *FO-PID* controllers have several parameters (*e.g.*, the gains) that need to be tuned for each application [1] [15-19].

In order to tune the controllers and find the best solution to our application, a simulation environment was developed in *MatLab*. In the system under study the contact of the robot gripper with the load is modeled through a linear system with a mass M, a damping B and a stiffness K. It is also considered that the load has length l_0 and orientation θ_0. On the other hand, we consider two manipulators each with two rotational joints the robots have link lengths l_1 and l_2 and the shoulders are separated by the distance l_b. The dynamics of a robot manipulator with n links interacting with the environment is modeled as:

$$\boldsymbol{\tau} = \mathbf{H(q)\ddot{q}} + \mathbf{C(q,\dot{q})} + \mathbf{G(q)} - \mathbf{J}^{\mathrm{T}}\mathbf{(q)F} \tag{1}$$

where $\boldsymbol{\tau}$ is the $n \times 1$ vector of actuator torques, $\mathbf{q}$ is the $n \times 1$ vector of joint coordinates, $\mathbf{H(q)}$ is the $n \times n$ inertia matrix, $\mathbf{C(q,\dot{q})}$ is the $n \times 1$ vector of centrifugal/Coriolis terms and $\mathbf{G(q)}$ is the $n \times 1$ vector of gravitational effects. The matrix $\mathbf{J^T(q)}$ is the transpose of the Jacobian matrix and $\mathbf{F}$ is the force that the load exerts in the robot gripper.

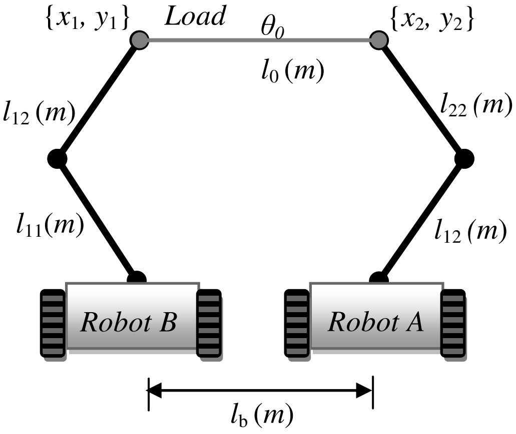

Figure 5: Two cooperating robots manipulating an object.

The numerical values adopted in the simulation were obtained based on the real application (*i.e.*, previously presented platforms and a specific object) are $m_1 = 0.02\ kg$, $m_2 = 0.02\ kg$, $r_1 = 0{,}141\ m$, $r_2 = 0.110\ m$, $J_{1\mathrm{m}} = J_{2\mathrm{m}} = 3.0\ kgm^2$, $J_{1\mathrm{g}} = J_{2\mathrm{g}} = 3.0\ kgm^2$ $l_b = l_0 = 0.15\ m$ and $\theta_0 = 0\ deg$, $B_1 = B_2 = 0.10\ Ns.m^{-1}$ and $K_1 = K_2 = 1\ Nm^{-1}$.

The *FO* controllers considered in this work, for both position and force, were developed adopting the Grünwald-Letnikov definition.

$$D^{\alpha}[x(t)] = \lim_{h \to 0}\left[\frac{1}{h^{\alpha}}\sum_{k=1}^{\infty}\frac{(-1)^k\Gamma(\alpha+1)}{\Gamma(k+1)\Gamma(\alpha-k+1)}x(t-kh)\right] \tag{2}$$

where Γ is the gamma function and h is the time increment. In this case, for the implementation $C(s) = K\, s^{\alpha}$, $-1 < \alpha < 1$, algorithms, discrete time approximations using 4th order Pade fractions were adopted.

$$G_P(s) \approx K_P\left(\frac{a_0 z^k + a_1 z^{k-1} + \cdots + a_k}{b_0 z^k + b_1 z^{k-1} + \cdots + b_k}\right) \tag{3}$$

where K_P is the gain.

The *FO-PID* controller is also known as $PI^{\lambda}D^{\mu}$ controller. If λ and μ are equal to 1, the result is the same as a traditional *PID* (*a.k.a.*, integer *PID*, as opposed to fractional-order *PID*). If $\lambda = 0$ ($Ti = 0$) we obtain a PD^{μ} controller. All these types of controllers are particular cases of the $PI^{\lambda}D^{\mu}$ controller. The results demonstrate that the fractional-order algorithm is superior, revealing a good performance and a high robustness for the following parameters depicted in Table 1.

	K_p	K_i	K_d	α	β
q_1	0.20	$1\text{x}10^{-3}$	0.25	0.3	0.9
q_2	0.20	$1\text{x}10^{-3}$	0.25		

	K_p	K_i	K_d	α	β
F_X	$1.0\text{x}10^{-3}$	0	$1.0\text{x}10^{-3}$	0.3	0.9
F_Y	$1.0\text{x}10^{-3}$	0	$1.0\text{x}10^{-3}$		

Table 1: *FO-PID* Controller Parameters tuned with the *PSO* method.

4 Experimental Results

This section presents the experimental results obtained when both manipulators need to hold an object of 11g with a constant force of 30g while the mobile platforms perform a straight trajectory of 4 meters length.

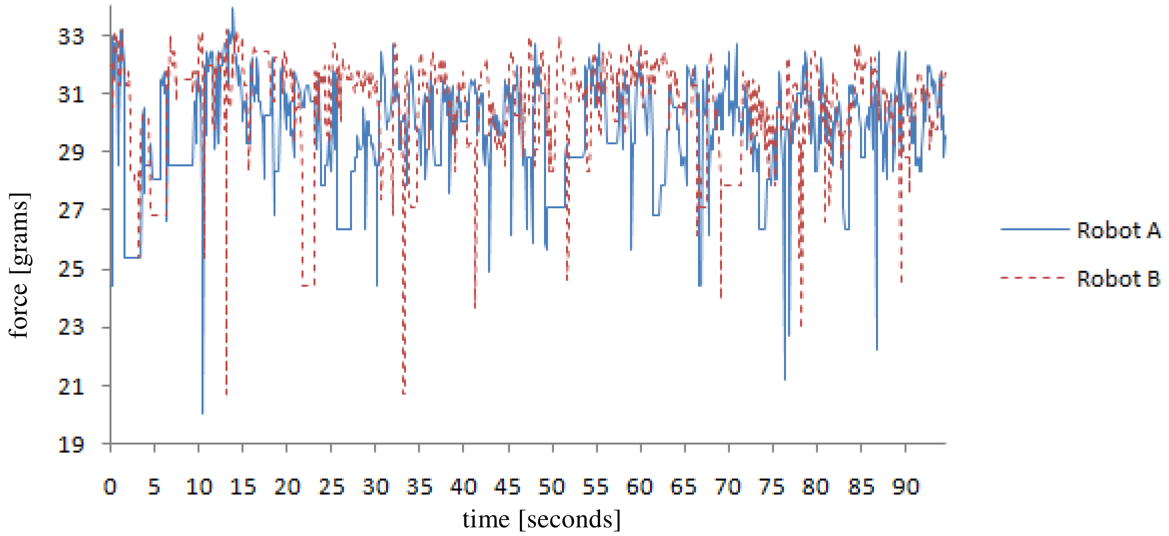

Figure 6: Forces applied to the object by robots A and B.

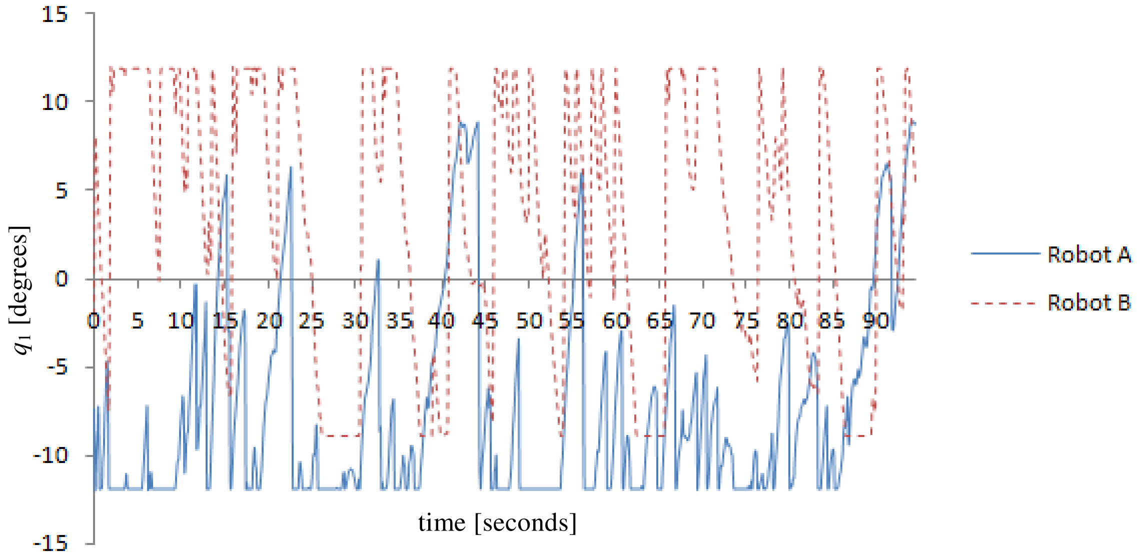

Figure 7: Angular position of joint $q_1(t)$ of robots A and B.

The variables being analyzed are the forces applied to the object, the position of each joint and the cartesian position of the end-effector (Figures 6-9).
As it is possible to verify in Figure 6, both robots maintain an applied force near 30g. More specifically, Robot A presents an applied force of 29.78±1.79g while Robot B presents an applied force of 30.55±1.82g. Note that the position of each joint and, consequently, the cartesian position of the end-effector, are limited by upper and lower saturation values to ensure that the forces applied by both robots are the most equally distributed as possible. Both angular position of joints, $q_1(t)$ and $q_2(t)$, remains near the initially programmed configuration with some minor deviations in order to adjust the applied force in the object.

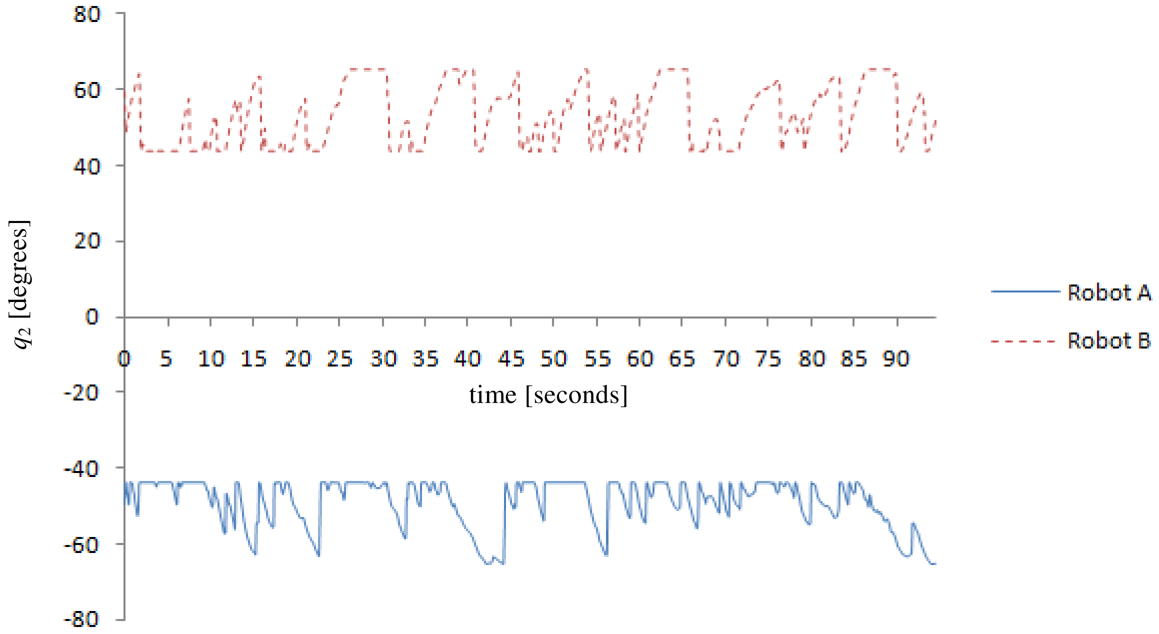

Figure 8: Angular position of joint $q_2(t)$ of robots A and B.

Figure 9 depicts the cartesian position of the end-effector of both robots. As it is possible to verify, when a manipulator end-effect gets closer to the *y*-axis ($x = 0$), the manipulator of its teammate move away from the *y*-axis in order to overcome the applied force in the object.

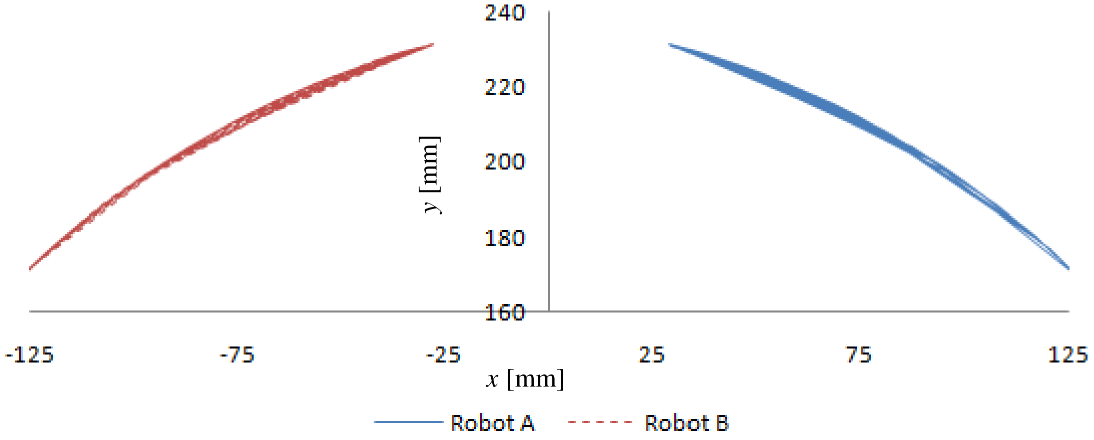

Figure 9: Trajectories in the cartesian space (x, y) of the end-effector of robots A and B.

5 Conclusions

In cooperative mobile manipulators it is necessary to successfully control the position and force applied in the common load in order to efficiently complete the task. This paper presents the implementation of fractional order controllers in two swarm mobile *RR* manipulators in order to cooperatively carry an object. Experimental results analyses the applied forces as well as the angular positions of the joints and the cartesian position of the end-effector demonstrating the influence and stability of each manipulator in the cooperative task.

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