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OPTIMAL TIME TRAJECTORY WITH OBJECT AVOIDANCE FOR THE DOMESTIC ROBOT HERA'S MANIPULATOR

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Abstract. *Robotics make life easier for people in industries with automated assembly lines, and in homes, robots can help with repetitive household tasks, but since there is a wide range of activities and interactions with the humans in home, these activities need to be tailored. With the current technological advances, the reality where the robots are inserted inside the residences is becoming more and more possible. In a domestic environment, it is important to have control over movement of the domestic robot so that it can interact with humans in a safe way. For this, one of the necessary things is to optimize the movement of the robotic arm respecting movement constraints so that there are no collisions with the robot itself and with the environment. This article deals with the optimization of the trajectory of a 2D robotic manipulator with obstacle avoidance and attainment of the target in minimum time. The problem was formulated as an optimal control problem using the PROPT software, an extension of TOMLAB for MATLAB, focusing on domestic environments, using the existing domestic robot HERA as reference. The obtained results will support a next study on sub optimal-trajectory-based heuristics to enable a real-time implementation.*

Keywords: *Optimal Trajectory, Manipulator, Service Robots, Home Care*

1. INTRODUCTION

The industrial robots perform repetitive and tiring activities, reducing the cost of production and labor of a workstation, but granting other possibilities of work with the use of the robots. Usually these applications are static, that is, the robot has a small and fixed workstation and performs previously defined activities.

These fixed robots with mechanical arms are no longer the focus of the industries as they were and the attention is being addressed to mobile robots, able to move around the environment in which they are, with levels of autonomy. They can be classified in Autonomous Mobile Robots (AMRs) and Intelligent Autonomous Vehicles (Jung *et al.*, 2005). For AMRs to be able to perform several tasks with diverse complexities such as navigation and autonomous operation, it is necessary to use an "Intelligent Robotic Control", a term referring to the use of robust planning and control techniques (Wolf *et al.*, 2009).

Robots can help people in home environments, such as looking for lost objects, alerting them to health issues, being their pet and cleaning the house, tasks that robots such as AIBO (Sony, 2019) and Roomba (iRobot, 2009), already perform.

Robotics have been developing in recent years also research about Human-Robot Interaction to bring more household robots to homes. Robots like HERA (Home Environment Robot Assistant), designed by the group RoboFEI@HOME of Aquino Junior *et al.* (2019) for domestic activities and support for the residents of a home where it operates, must be robust to carry objects, resistant to possible impacts and compliant with human interaction.

Because domestic robots need to work in the same place as humans and other animals in the home, it is necessary to have control of the movement of the robot and its components, such as robotic arms (Agah and Tanie, 1997).

A robotic arm consists of joints and links that, according to the DOF (Degrees of Freedom), form the work volume of the arm. According to Hu *et al.* (2018), this set is a multibody system where motors in the joints are responsible for moving the links. The control of these robotic manipulators is a challenge to assure high performance of the trajectory tracking.

Sage *et al.* (1999) have analyzed robust controls for this purpose by means of linear and nonlinear control, sliding mode control, Lyapunov method, and robust adaptive control. Hu *et al.* (2018) classifies two categories of control strategies for manipulators, centralized and decentralized control. The proposal of Hu *et al.* (2013) is to use a decentralized control

where the dynamics of the actuators in a multibody system was considered in a recursive algorithm. In that algorithm, the dynamics of each body were analyzed independently while the interactions between the two adjacent bodies were estimated. On the other hand, in Hu *et al.* (2018) the recursive dynamics is in the interaction between the two adjacent joints, developing a decentralized robust control to deal with the trajectory tracking so to assure uniform stability using the Lyapunov method. The robust control proposed by Tang *et al.* (2000) is a decentralized control based on the limitation of the high order of interconnections and was combined with a recursive dynamic model.

This work focuses on robots of domestic service applied to the robot HERA and its objective is the optimization of the trajectory of its robotic manipulator with obstacle avoidance and attainment of the target in minimum time. The problem was formulated in 2D as an optimal control problem using the PROPT software, an extension of TOMLAB (2018) for MATLAB (MathWorks, 2019). The obtained results will support a next study on sub optimal-trajectory-based heuristics to enable a real-time implementation.

2. ROBOT HERA

The HERA robot (Figure 1) consists of a set of sensors such as cameras, laser, ultrasound and infrared for mapping the environment and identifying people and objects. It has actuators for locomotion, movement of objects and possible movements in the interactive process with the house and people.



Figure 1: Robot HERA

The HERA robot participates in domestic service robot competitions in the @HOME category (Aquino Junior *et al.*, 2019), where participants need to resolve evidence with tasks in a domestic context, such as recognizing the speech of a person asking for a drink, going to the kitchen, identify and pick up the correct object and deliver it to the person who ordered the drink. Functions must be executed by the robot as autonomous navigation (Gazignato and Aquino Junior, 2019), (Perez and Aquino Junior, 2019), auto spatial location at home (Meyer and Aquino Junior, 2019), interaction of objects using manipulators (Gonbata *et al.*, 2019) and mechanical adaptation for positioning in ergonomically defined environments for humans (Yagui and Aquino Junior, 2019).

3. METHOD

According to Dissanayake *et al.* (1991), for the realistic implementation of a trajectory the torques of the manipulator joints that will be controlled and the properties of the robotic arm need to be well known. The proposed optimum control problem is for the minimum time for the trajectory of a robotic arm with joint torques. The formulation of the problem was coded in TOMLAB's PROPT, an extension for MATLAB by Rutquist and Edvall (2010) and comprises a two-link system (see Figure 2) and using the properties and dimensions of the robotic arm of the HERA robot.

According to the optimal control proposal by Dissanayake *et al.* (1991), the objective function in Eq. (1) is the time to accomplish the task, subject to (2), the equation of motion of a n DOF manipulator.

$$\min J = t_f \tag{1}$$

$$H(q)\ddot{q} + h(q, \dot{q}) = T \tag{2}$$

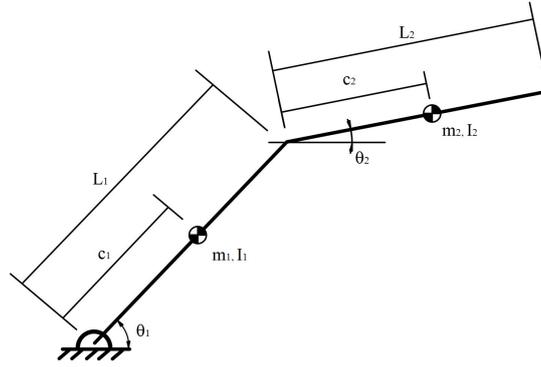


Figure 2: Planar two-link robotic arm

Using the Lagrangian formulation for a two-link system, equations 3 and 4 are obtained, where T_1 and T_2 , respectively, are the joint torques 1 and 2, c_1 and c_2 are the positions of the center of mass, m_1 and m_2 are the link mass, I_1 and I_2 represent the moment of inertia and the total length of links are L_1 and L_2 .

$$\begin{cases} T_1 = H_{11}\ddot{\theta}_1 + H_{12}\ddot{\theta}_2 + 2h\dot{\theta}_1\dot{\theta}_2 - h\ddot{\theta}_2^2, \\ T_2 = H_{22}\ddot{\theta}_2 + H_{12}\ddot{\theta}_1 + h\dot{\theta}_1^2 \end{cases} \quad (3)$$

$$\begin{aligned} H_{11} &= c_1 + c_2 + m_1c_1^2 + m_2(L_1^2 + c_2^2 + 2L_1c_2\cos\theta_2), \\ H_{12} &= c_2 + m_2c_2^2 + m_2L_1c_2\cos\theta_2, \\ H_{22} &= c_2 + m_2c_2^2, \\ h &= m_2L_1c_2\sin\theta_2 \end{aligned} \quad (4)$$

Rewriting the equations in the state space for the optimal control formulation, we get Eq. 5 for the choice in (6).

$$\begin{cases} \dot{x}_1 = x_3, \\ \dot{x}_2 = x_4, \\ \dot{x}_3 = \frac{2hH_{22}x_3x_4 + hH_{22}x_4^2 + hH_{12}x_3^2 + H_{22}T_1 - H_{12}T_2}{H_{11}H_{22} - H_{12}^2}, \\ \dot{x}_4 = \frac{-2hH_{12}x_3x_4 - hH_{11}x_3^2 - hH_{12}x_4^2 + H_{11}T_2 - H_{12}T_1}{H_{11}H_{22} - H_{12}^2} \end{cases} \quad (5)$$

$$\begin{aligned} x_1 &= \theta_1, \\ x_2 &= \theta_2, \\ x_3 &= \dot{\theta}_1, \\ x_4 &= \dot{\theta}_2 \end{aligned} \quad (6)$$

The torques and angular velocity are limited according to the servomotors specification used in the robotic arm, which are shown in Eq. 7.

$$\begin{cases} T_{1min} \leq T_1 \leq T_{1max}, \\ T_{2min} \leq T_2 \leq T_{2max}, \\ \dot{\theta}_{1min} \leq \dot{\theta}_1 \leq \dot{\theta}_{1max}, \\ \dot{\theta}_{2min} \leq \dot{\theta}_2 \leq \dot{\theta}_{2max} \end{cases} \quad (7)$$

The trajectory considered has the initial position with arm at rest and the target destination is close to the limit of the workspace.

Since the manipulator is fixed in a workspace with obstacle of its own, as can be seen in Fig. 3a, it is necessary to include obstacles such as the top of the robot, in the problem formulation. In some RoboCup tests, manipulation is the main focus and in some tests it is possible that there are objects that obstruct the path to the target object, requiring a deviation to reach the goal, being represented in Fig. 3b.

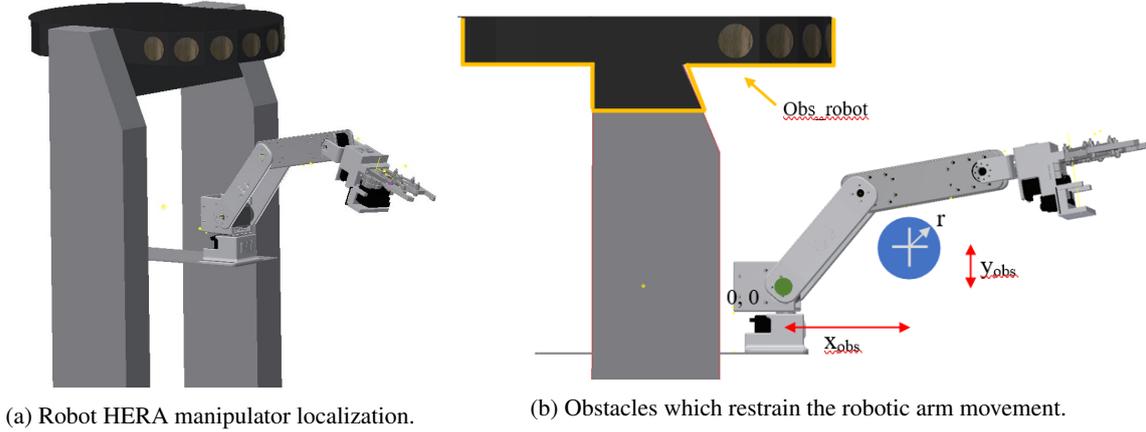


Figure 3: Movement Restriction.

As the top profile of the robot does not have a simple form of representation, for simplicity a sixth-degree polynomial, Eq. (8), was used to approximate the shape. The object in the workspace was considered with a circular shape and aims to represent one of the possible objects in a house that could be an obstacle. Equation (9) represents the constraint associated with the circular object, where r is the distance between the (x, y) coordinate of the robotic arm and the obstacle to be deflected at (x_{obs}, y_{obs}) .

$$y = 10^3(9.2620x^6 + 8.1510x^5 + 2.33488x^4 + 0.2018x^3 - 0.0059x^2 - 0.0005x + 0.0002) \quad (8)$$

$$r \leq \sqrt{(x - x_{obs})^2 + (y - y_{obs})^2} \quad (9)$$

To ensure that the manipulator does not collide with the obstacles, the shapes have been discretized at several points.

4. RESULTS

The optimal control problem was solve using a PC with an Intel Xeon processor with 3.7 GHz, 16 GB RAM running Windows 10 Operating System of 64 bits.

The robotic arm numeric values used for the optimal control are presented in the Tab 1. Notice that the grip was not considered in the calculation.

Table 1: Robot HERA robotic arm properties

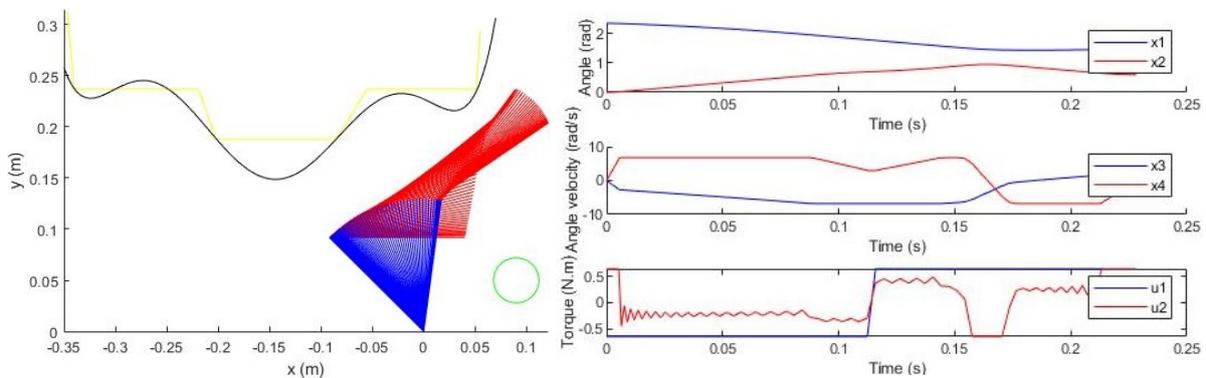
	Link 1	Link 2
Total length - L (m)	$130 \cdot 10^{-3}$	$132 \cdot 10^{-3}$
Distance between link and center of mass - c (m)	$239 \cdot 10^{-6}$	$64.192 \cdot 10^{-3}$
Moment of Inertia - I (kg.m ²)	$1.325 \cdot 10^{-3}$	$1.325 \cdot 10^{-3}$
Mass - m (kg)	$171 \cdot 10^{-3}$	$292 \cdot 10^{-3}$

For the simulation, the rest position of the robotic arm was used as the initial position. The final position was chosen randomly within possible limits of movement and the values can be seen in Tab. 2. In this table it is also possible to obtain the minimum time of the trajectory (cost function) and the time spent for solving the optimization problem.

Table 2: Robotic Arm Position

	Initial Position		Final Position		Time	
	$\theta_{1initial}$ (rad)	$\theta_{2initial}$ (rad)	θ_{1final} (rad)	θ_{2final} (rad)	Trajectory (s)	Simulation (s)
Case1	2.356	0.000	1.475	0.600	0.2282	55.7482
Case2	2.356	0.000	0.975	-0.500	0.3562	63.5554
Case3	2.356	0.000	1.650	0.800	0.3275	36.4543
Case4	2.356	0.000	1.075	0.300	0.3144	106.3900

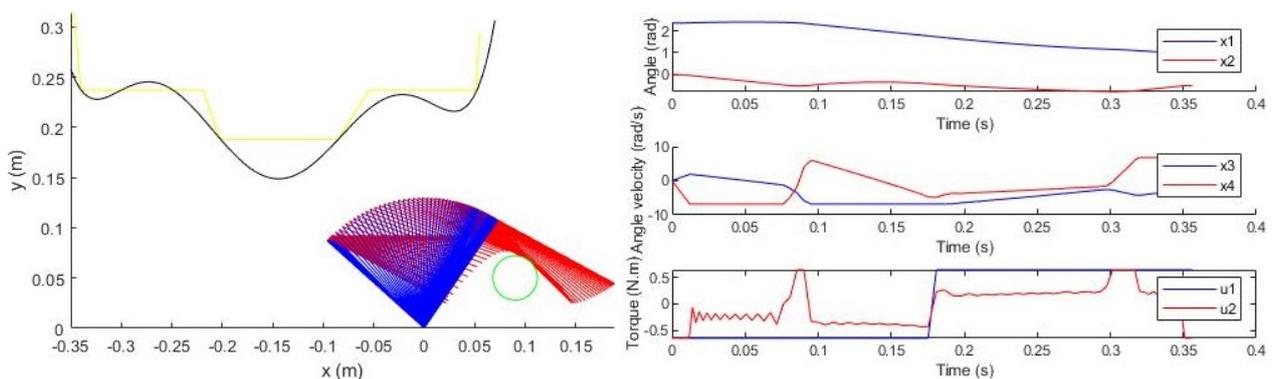
With these boundary conditions the minimum time trajectory was obtained without collision with any of the objects, as can be seen in Fig. 4a. The set formed by the blue and red straight lines represents the manipulator, the yellow curve is an approximation of the shape of the robot top, the black cube is the polynomial that approximates the shape of the robot, the green circle is the obstacle. Figure 4b shows the time series plots of the kinematic variables of the trajectory and joint torques.



(a) Robotic arm trajectory with the obstacle of the robot and one circular object of case 1
 (b) Angle, angular speed and manipulator torque on simulator graphics of case 1

Figure 4: Trajectory simulation of case 1

In the Figure 5, to minimize time, the trajectory passes tangentiating the object, as in the third case, Fig. 6, which goes tangentiating the circular object and the polynomial function, for that, both trajectory time are bigger than the time for case 1.

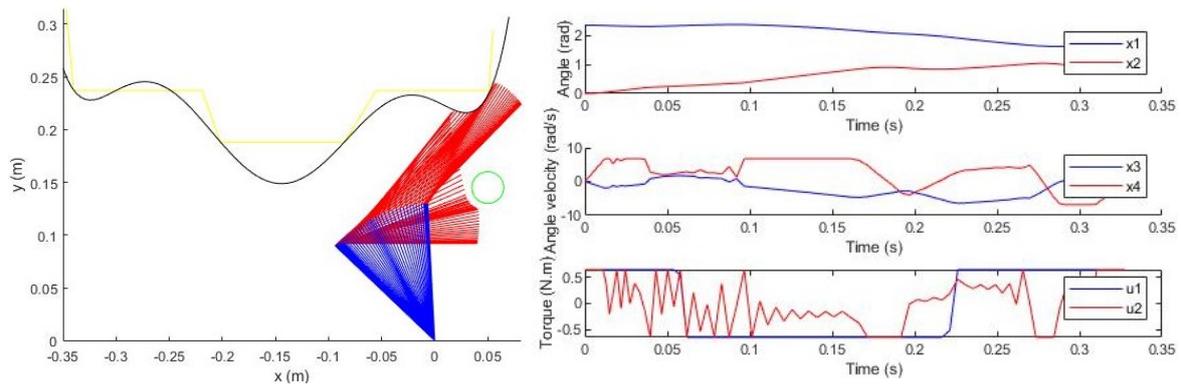


(a) Robotic arm trajectory with the obstacle of the robot and one circular object of case 2
 (b) Angle, angular speed and manipulator torque on simulator graphics of case 2

Figure 5: Trajectory simulation of case 2

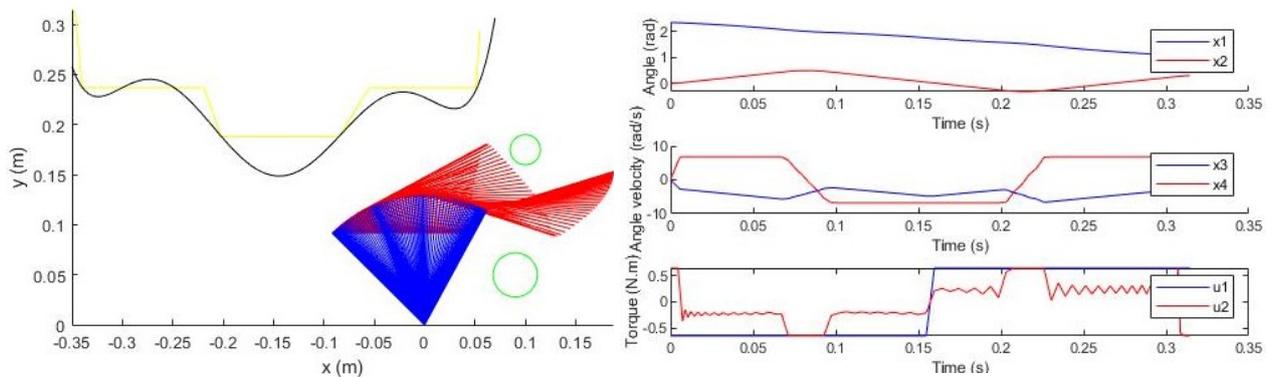
The trajectory time for the fourth case (Fig. 7) was also bigger, since it has two round objects to evade besides the robot top part, thus the trajectory time was the biggest among the simulated cases.

The time of the trajectory of case 1 was 0.2282 seconds. It should be noted that this movement can be considered too fast for the interaction with people and is not satisfactory to apply in service robots in domestic environment. However, the maneuver speed limit can be easily included explicitly as another constraint in the optimal control problem. For the application in domestic social robots, it is needed a fast trajectory calculation, for that purpose, the trajectory generation time, as in the first case with 55.7824 seconds, is considered to be too slow, which means it does not satisfies the



(a) Robotic arm trajectory with the obstacle of the robot and one circular object of case 3 (b) Angle, angular speed and manipulator torque on simulator graphics of case 3

Figure 6: Trajectory simulation of case 3



(a) Robotic arm trajectory with the obstacle of the robot and two circular objects of case 4 (b) Angle, angular speed and manipulator torque on simulator graphics of case 4

Figure 7: Trajectory simulation of case 4

requirements.

We conclude that it will be necessary to use a kind of heuristics inspired on the optimal solution to enable a real-time implementation of the generation of trajectories.

5. CONCLUSION

In this work, it was used optimal control for providing a minimum time trajectory with obstacle avoidance. The research focus on a service robot for HERA domestic activities. For human robot interaction purposes, the speed of movement obtained resulted not satisfactory, being necessary adapt the velocities to values that are comfortable and safe for the interaction with people.

The manipulator used for calculations has two links to simplify the first tests. As a proposal of continuity of the research, it is proposed to formulate and solve the problem of optimal control for three links and three-dimensional, to be able to apply in the physical robot and to propose heuristics to enable a real-time implementation of the generation of trajectories.

In addition, it is proposed to use an impedance control that overlaps over the kinematic control, in case of contact with the environment or with people and animals.

6. ACKNOWLEDGEMENTS

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