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SIMULATION AND IMPLEMENTATION OF IMPEDANCE CONTROL IN ROBOTIC HAND

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Abstract: *Human-like robotic hands is a field of study in robotics that receives huge attention in the recent scientific community due to the numerous advantages that it performs as an end effector, such as, its dexterousness and flexibility. This work presents the early results regarding the design, construction and control of a robotic hand. The concept of an under-actuated robotic hand with rigid fingers was developed with CAD software and simulated using Simulink/Matlab in order to validate an impedance/PID controller for the finger systems projected in this work.*
After the validation of both the finger system and the controller scheme, the tuning of the impedance controller was accomplished using Particle Swarm Optimization (PSO). The depiction of this process is documented explaining the composing of the cost function.
Finally the results of the optimization gave a behaviour where the experiments demonstrate that the proposed approach follows the reference in a satisfactory way.

Keywords: *Cartesian Impedance Control, Particle Swarm Optimization, Robotic Finger, Robotic Hand.*

INTRODUCTION

Grasping and manipulation is a very important task in robotics. Several end-effector tools and grasping control techniques the have been recently developed by the scientific community in order to explore the capabilities of biomimetic robot hands Lee *et al.* (2017); Calderon *et al.* (2017); Johansen *et al.* (2016); Beschi *et al.* (2017); Shi and Koonjul (2015); Cipriani *et al.* (2014); Varley *et al.* (2015).

Grasping methods can be grouped in two main categories: 1) classic motion planning with collision detection and 2) grasp synthesis by the calculation of grasp contacts based on closure. Bohg *et al.* (2014) provides an extensive review on the first category and point out that data-driven approaches classify in three subcategories according to the available knowledge about the object to be grasped: 1) the object is well known, 2) the object is familiar and 3) the object is unknown. This work focuses in the last subcategory.

When the object model is unknown the grasp planner resolves the grasp scheme based on the information provided by the system sensors. One relevant observed magnitude is the force / torque that the robotic hand applies to achieve the grasp as reported in Lee *et al.* (2017); Beschi *et al.* (2017); Choi *et al.* (2011); Petit *et al.* (2015). One commonly used technique is the impedance control that, according to Hogan (1985b,a), aims to control the dynamics in which the robot interacts with its environment.

Impedance control has been previously used to carry out grasping tasks with robotic hands or grippers as can be seen in Beschi *et al.* (2017); Xu (2013, 2015); Choi *et al.* (2011); Biagiotti *et al.* (2003). There are several schemes for impedance control that can be adapted to an application. In this work, the cartesian impedance controller approach was employed for a robotic finger mechanism.

The main contributions of this work are: (i) The process of adjusting the impedance controller coefficients was formulated as an optimization problem and the Particle Swarm Optimization (PSO) algorithm was used to solve the optimization problem; (ii) A simulator tool for a robotic finger mechanism was developed in Matlab-SimMechanics allowing for validations of the impedance controller during the execution of the optimization algorithm. Numerical simulations demonstrate that the achieved controller resulted in a stable dynamic behaviour of the robotic finger upon closing.

This paper is organized as follows: Section 2 presents a short theoretical background regarding force and impedance control as well as the particle swarm optimization algorithm. Section 3 describes the finger system simulator tool developed to perform the optimization process. Section 4 formulate the optimization problem, the decision variables and specify the controller tuning procedure. Before concluding, Section 5 presents the results of the proposed method for adjusting the impedance controller coefficients applied to te robotic finger mechanism.

1. BACKGROUND

As stated by Featherstone and Orin (2008) a robot's dynamic is the relationship between the contact forces and the acceleration of the resulting movement. Villani and De Schutter (2008) defines the dynamic control as the intent to moderate the robot's physical contact with its surroundings, this is a fundamental requirement to perform manipulation tasks. One of the advantages of this type of control is the feasibility for performing robust and flexible behaviours interacting in unstructured environments .

Villani and De Schutter (2008) also declares that active dynamic or force control schemes can be divided in two types: a) indirect force control and b) direct force control. The first one pursues dynamic control through kinematic control without force or torque feedback. In contrast, the second type uses force and torque feedback. Impedance control belongs to the first type, however, in this approach it is used a variant introducing some force feedback, as explained in the next subsection.

1.1 IMPEDANCE CONTROL

Impedance control (or admittance control) according to Villani and De Schutter (2008) can be basically described as a complex scheme behaving as a second order dynamic system. Figure 1 represents the impedance control scheme using a mass-damper-spring system. In this relationship, impedance is the passive reaction that a robot performs when it is disturbed by external forces. In contrast, admittance control is the active reaction of the robot to such external forces.

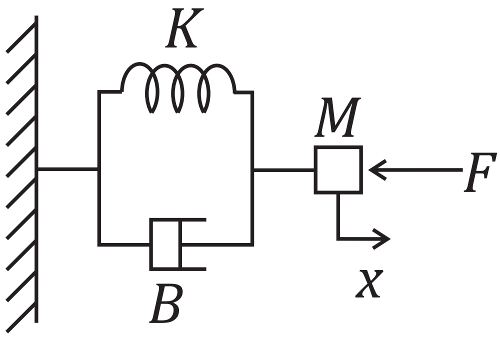

Figure 1. Mass-Damper-Spring system representing an impedance controller behaviour. On this system, the "spring constant" K defines the force output for a tension or compression of the spring produced by a force F and the "damping constant" B is the force output for a velocity input of the displacement x

The system depicted in Fig. 1 can be modelled in time domain by a second order differential equation, as represented in Equation 1

$$M\ddot{x}(t) + B\dot{x} + Kx = F(t) \tag{1}$$

where M, B and K are respectively mass, coefficient of viscous friction and spring constant. These values are user-defined and can be tuned to virtually any value; however, to obtain a stable system, these coefficients depend on the system that is being controlled. Adjusting these values often involves hard calculus on the robotâĂŹs dynamics. Bioinspired optimization algorithms are metaheuristic that have proven to be feasible to solve this kind of problem. In this work the Particle Swarm Optimization (PSO) algorithm was used to optimize the controller coefficients values. The next subsection describes the PSO algorithm.

1.2 PARTICLE SWARM OPTIMIZATION - PSO

The PSO algorithm simulates the social behaviour of schooling fish that avoids predators or flocking birds looking for food.

Weise (2009) describes the algorithms as follows: In a swarm of S particles every particle has a position x_i of N-dimensionality and it represents a possible solution to the optimization problem. Each particle i measures its fitness through a cost function $f(x_i)$ and keeps the historical best solution by using an individual memory $\overrightarrow{y_i}$ and a collective memory $\overrightarrow{y_s}$. The movement across the search-space is performed with a random velocity $\overrightarrow{v_i}$ associated to every particle, calculated using (2), and the next particle position $\overrightarrow{x_i}$ is calculated using (3).

$$v_{ij}^{(t+1)} = wv_{ij}^{(t)} + c_1 \overbrace{U_{1j}(y_{ij}^{(t)} - x_{ij}^{(t)})}^{\text{cognitive component}} + c_2 \overbrace{U_{2j}(y_{sj}^{(t)} - x_{ij}^{(t)})}^{\text{social component}} \tag{2}$$

$$x_{ij}^{(t+1)} = x_{ij}^{(t)} + v_{ij}^{(t+1)} \tag{3}$$

where, w is the inertial factor which decreases with every iteration, c_1 is the cognitive coefficient or self-confidence coefficient, c_2 is the social coefficient or swarm confidence coefficient, U_1 and U_2 are uniformly distributed random numbers in the range $[0, 1]$. This process is repeated until the stopping criteria is reached, generally when the maximum number of iterations Max_{iter} is reached or a fitness threshold is surpassed. Algorithm 1 presents the pseudo-code of the PSO.

Algorithm 1 Pseudo-code for the PSO algorithm

function BASIC-PSO(S,N,c_1,c_2,Max_{iter},threshold)
  Start swarm;
  $iter = 1$
  repeat
    for i **do** 1 S
      if $f(x_k) \leq f(y_{ik})$ **then**   Evaluation and detection of the best fit individual
        $y_{ik} \leftarrow x_k$;
    calculate y_s using the S fitness values $f(y_{ik})$ Global best
    for i **do** 1 S
      for j **do** 1 N
        $v_{ij}^{(t+1)} \leftarrow wv_{ij}^{(t)} + c_1 U_{1j}(y_{ij}^{(t)} - x_{ij}^{(t)}) + c_2 U_{2j}(y_{sj}^{(t)} - x_{ij}^{(t)})$ Actualization
        $x_{ij}^{(t+1)} \leftarrow x_{ij}^{(t)} + v_{ij}^{(t+1)}$
  $iter = iter + 1$
until $(f(y_{y_s}) < threshold)||(Iter <= Max_{iter})$
return position of the best fit particle x and its fitnes $f(x)$

2. SIMULATOR OF ROBOTIC FINGER SYSTEM

The system dynamics that is meant to be controlled in this work is a robotic finger. This robotic finger system is aimed to be used ultimately in a robotic hand system. The critical part of the concept of the robotic hand is the design of the robotic fingers, this is due to the amount of DoF (Degrees of Freedom) existing in the hand and the small amount of space between joints. By taking this into account it was decided that the fingers would be under actuated via 4-bar mechanisms, allowing the number of joints to stay almost the same as a human hand and the number of DoF to decrease dramatically. The design and validation of the finger mechanism is better detailed in Pertuz *et al.* (2016).

2.1 IMPEDANCE CONTROLLER SYSTEM

As it stated before, the dynamic of the controller is given by Equation 1, however, in this work the discrete integration method proposed by Caccavale *et al.* (2005) is used to perform the impedance control. This method consist of three steps:

1. Discretize the Equation 1 as follows:

$$\ddot{x}(k) = M^{-1}(\Delta T(k) - Kx(k) - B\dot{x}(k)) \tag{4}$$

where the force F in Eq. 1 is substituted with the torque error ΔT in the instant k, $x(k)$ is the displacement and $\dot{x}$ is the movement derivative.

2. The result of the previous equation $\ddot{x}$ is integrated to obtain $\dot{x}$

$$\dot{x} = \int_{k-1}^{k} \ddot{x} dx \tag{5}$$

3. Finally, repeating the integration it is possible to obtains x which is the system desired position to achieve the goal dynamics.

$$x = \int_{k-1}^{k} \dot{x} dx \tag{6}$$

The Fig. 2 shows the schematic representation in Matlab/Simulink (Matlab R2015a (8.5.0.197613-win64)) for developing the impedance control model.

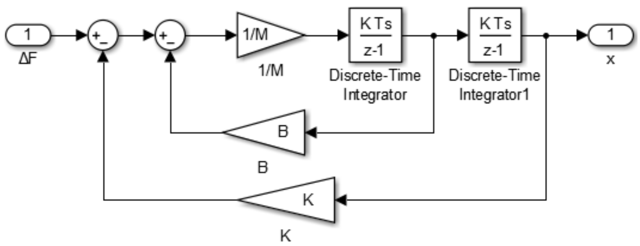

Figure 2. Impedance controller schematic in Matlab/Simulink. The Discrete-Time Integrator blocks accomplish the integration with Forward Euler Method

This impedance control scheme is implemented in the finger system as shown in Fig. 3. The proposed control reaches a desired torque ($setpoint$) comparing it with the estimated torque acquired from the *Torque Estimator* block. Then, the calculated desired position is corrected by a Proportional Integral Derivative (PID) position controller that calculates the necessary voltage level to be applied to the motor in the finger.

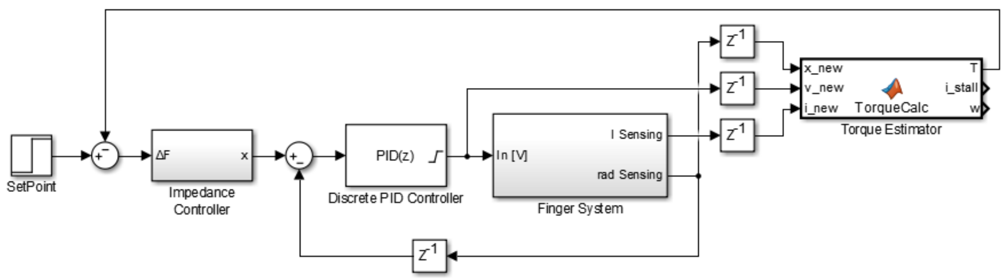

Figure 3. Finger system control scheme in Matlab/Simulink. The impedance controller block is depicted in Fig. 2

The *Torque Estimator* block estimates the motor generated torque T on its axis. The equation used was obtained using the motor sensed current (i), the supplied voltage (v), the estimated axis angular velocity (ω) and the motor efficiency (E) as follows:

Having $P_{in} = i\ v$, $P_{out} = T\ \omega$, where P_{in} and P_{out} are the input and output power respectively, and $E = P_{out}/P_{in}$ hence

$$T = \frac{ivE}{\omega} \tag{7}$$

From the previous equation it can be seen a discontinuity when $\omega = 0$. The used solution for this problem is to ignore velocity values that are too small, given that it means the motor is stalled and the torque generated is the stall torque.

2.2 ROBOTIC FINGER SIMULATOR

The *Finger System* block was also modeled in Matlab/Simulink to simulate its dynamics and aid the design of the controller as well as to analyze its performance (see Figure 4).

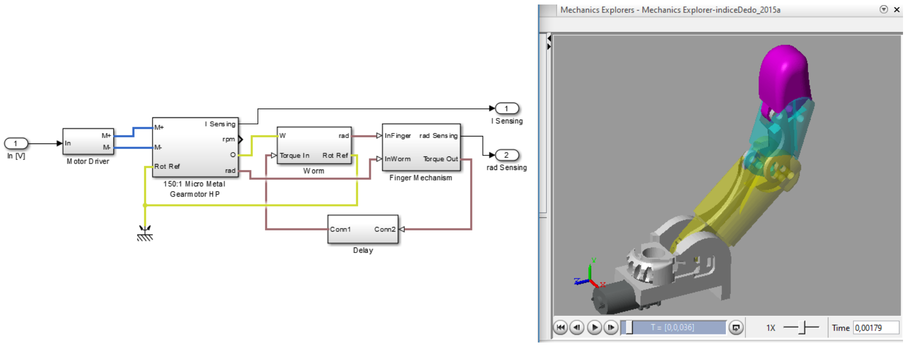

Figure 4. Finger System model in Matlab/Simulink. The CAD model was initially design in SolidWorks, in order to simulate the dynamics of the system in Matlab an integration with SimMechanics was conceived.

The result of the concept design of the robotic finger is presented in Figure 5. Each finger system has 3 DoF and 1 Degree of Actuation (DoA). The system also includes one position sensor in the first joint (see Figure 5(b)). A current sensor for the motor was used for torque estimation as mentioned in the previous subsection.

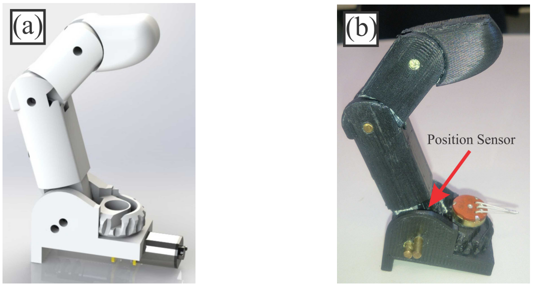

Figure 5. Finger of robotic hands (a) CAD of finger (b) Fabricated finger

The position of the finger is controlled through a PID controller. The PID has as input the error between the desired position and the sensed position. As output it delivers the motor's voltage level. The coefficients K_P, K_I and K_D of the PID were tunned using Ziegler and Nichols (1993), which is a heuristic manual method that creates an aggressive controller with a proportional gain and high over-impulse.

The impedance controller receives the error between the desired torque (*torque setpoint*) and the estimated torque. The M, B and K coefficients are tunned using the PSO algorithm as described in the next Section.

3. IMPEDANCE CONTROLLER TUNING USING PSO

Using meta-heuristics as tuning methods for control algorithms is not a new thing; however, there is not a unique method for solving these problems, neither a correct or perfect one. For bioinspired algorithms, such as PSO, the most difficult task when performing optimization from the designer's point of view is the design of the cost function and the choosing of the decision variables. In this work PSO is used to decide the tuning coefficients of the impedance controller, the next subsection describes the cost function designed for this problem and the decision variables.

3.1 PROBLEM DEFINITION

In this work the optimization problem is to define the coefficient values (M, K e B) of the impedance controller that determines the desired dynamic behaviour of the robotic finger system which is under-damped. To determine this, the damping ratio ζ is calculated. For a mass-damper-spring system (impedance controller) the damping ratio is

$$\zeta = \frac{B}{2\sqrt{KM}} \tag{8}$$

A system is under-damped if $\zeta < 1$; however, according to Shinners (1998) for most applications a value of ζ between $0.4 < \zeta < 0.7$ gives a desirable response. Hence, the decision variables for the optimization problem are K, B and ζ, where M is calculated using Eq. 8.

The cost function is calculated by taking into account the $over-impulse$ of the system, the response time (t_r) and the

MSE error, which is estimated by comparing point-to-point the output response of the torque estimation and the setpoint. These values are then weighted with empirical values as stated in the following equation:

$$f\_cost = 0.05(over - impulse) + 0.3(t_r) + 0.65(MSE) \tag{9}$$

Resuming, the optimization problem in this work is a mono-objective, 3-dimensional and minimization problem. The following section will study the results obtained for the proposed approach.

4. RESULTS AND DISCUSSIONS

The PID was tuned manually minimizing the overshoot and the damping (see Fig. 6). The tuned PID achieved a rise time of 0.3137 seconds and a settling time of 0.5645 seconds.

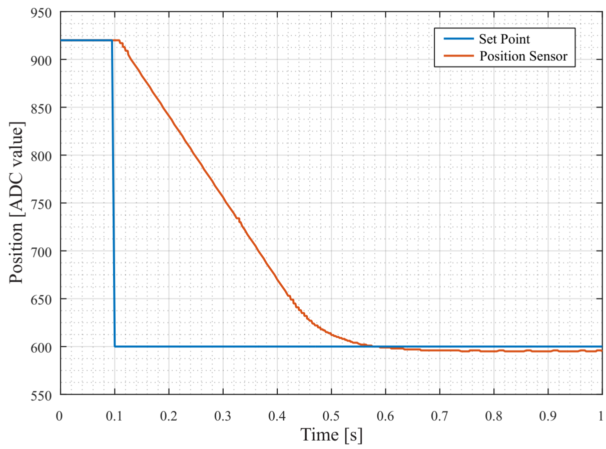

Figure 6. Simulation of PID controller with a step signal as input

The result of the impedance control tuned using PSO is shown in the Fig. 7.

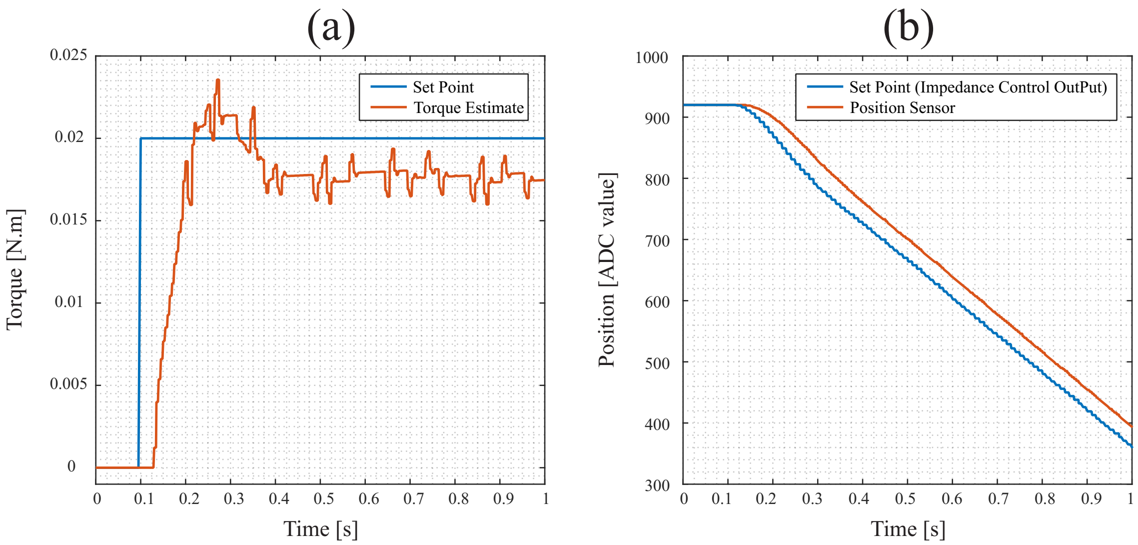

Figure 7. Simulation of impedance controller with a step signal as input (a) response of impedance controller (b) response of PID controlled variable (position) whose setpoint is connected to the impedance controller output (see Fig. 3)

It can be observed that the behavior of the impedance controller's action (see Fig. 7(a)) has oscillations. It can be explained because the controlled variable (Torque) is just an estimation and, as can be expected, it carries errors. However, these results are still very acceptable.

5. CONCLUSIONS

An impedance/position controller scheme for a robotic finger system is proposed in this work. The proposed scheme aims to control the torque that the finger executes upon closing and grasping objects. The impedance control outcome also depends on the position controller.

A bioinspired tuning methods based on the PSO algorithm and a simulator tool for the impedance controller allowed numerical simulations to be conducted. The experiments demonstrate that the proposed approach follows the reference in a satisfactory way; however, in this work, interferences and blockages in the mechanisms are not considered.

As future works a numerical analysis of the influence of the position controller on the dynamics of the robotic finger will be conducted. In addition, the proposed control method will be implemented in the complete robotic hand system (with a total of 5 fingers and 7 DoF). For that intent, the proposed impedance control algorithm will be mapped on an FPGA (Field Programmable Gate Array) allowing the performance of the critical parts of the algorithms to be improved. 5

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