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Control of cooperative manipulators in holding deformable objects

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Abstract. This paper presents the implementation of a control system to control cooperative manipulators to hold deformable objects. The aim is to hold the deformable object without having information on the shape and stiffness of the deformable object beforehand. The prototype of a pair of manipulators has been designed and built to test the controller. A force sensor and a rotary encoder are used to give feedback to the controller, which controls the DC motor actuators accordingly. A position proportional-integral-derivative (PID) controller technique has been applied for one of the manipulators and a PID force control technique is applied to the other. Simulations and experimental tests have been conducted on models and the controller has been implemented on the real plant. Both simulation and test results prove that the implemented control technique has successfully provided the desired position and force to hold the deformable object with maximum experimental errors of 0.34mm and 50mN respectively.

1. Introduction

This paper focuses on the implementation of a control algorithm to handle deformable objects using cooperative manipulators. Deformable objects are objects whose shape change when force is applied [1]. The difficulty of manipulating deformable object is mainly due to the its nonlinear elasticity, friction and parameter variations [2]. Consequently, the manipulation of deformable objects is less researched because of mechanical reasons. On top of that, the modeling cost of deformable objects is high [3].

Despite all the challenges, the research of manipulating deformable object is still of interest due to their significant applications. Deformable objects can be found in petty everyday stuff, such as when folding a bed sheet [4], tying knots, flattening towels and erasing a whiteboard [5]. Handling deformable objects is also important on an industrial level, such as in food processing and recycling [6] [7]. Other significant applications include medical applications [8].

Due to the increase in demand in robots that imitate human arms and hands, the study of cooperative manipulators has been popular [9]. They are also a preferred choice for handling deformable objects [10]. For large objects and objects of heavy payload, such as vehicle chases, cooperative manipulators can be used to share the load and gain stiffness [11].

For the handling strategies of deformable objects, the study in [3] utilizes FEM, which is time-consuming. Thus, a powerful processor is required. The method in [4] is not equipped to handle 3-D deformable objects. In [12], the manipulators have to move slowly due to the online visual estimation

method. The general demonstration-based method in [5] faces the challenge of the difficulty of getting the robot to perform the demonstrations. Therefore, the goal of this study to design and implement a controller that is not computationally heavy that at the same time, is capable of holding deformable objects despite unknown stiffness and position. Also of concern are the force and position reaching their desired values without exceeding a time threshold. The difficulty in handling deformable objects is due to the fact that they are challenging to model and simulate. Handling deformable objects requires the robot to exert a particular amount of force to hold the object at the desired position. In [7], dual-motor drive gripper with parallel fingers is designed and parallel position-force algorithm is used.

In this paper, stiffness and the position of the deformable object to be held are unknown. In this sense, a deformable object is one whose shape changes due to an applied force such as paper cup, food and bag filled with sand. At this stage of study, this work focuses on the PID control strategy for cooperative manipulators in holding the deformable objects. The prototype is made of two 1-DOF cooperative manipulators, each powered by a DC motor. This paper focuses on deformable objects such as rings, sponges, paper cups and rubber balls instead of deformable objects of infinite degrees of freedom such as fabric and knots [2].

The rest of the paper is organized as follows: section 2 shows the mechanical design and electrical diagram. Section 3 details the derivation of mathematical models. Section 4 is dedicated to the simulation studies, while section 5 focuses on experimental studies. The conclusion is presented in section 6.

2. Mechanical Design

The scope of this paper is to design a controller that is capable of holding a deformable object in place by exerting desirable amounts of force at two 1-DOF cooperative manipulators. The force is translated from a DC motor to the manipulator through a rack-and-pinion configuration.

To achieve that goal, the system will comprise of an Arduino Mega 2560 microcontroller to interface the control algorithm running on MATLAB'S Simulink with the hardware, DC motors as actuators, a force sensor and an encoder to provide feedback to the controller and rack-and-pinion sets to translate torque generated by the motors into force, in addition to the structure holding these components together. One of the manipulators is assigned as the 'master' and the other is set as the 'slave'. Figure 1 shows the prototype of the master and slave manipulators.

An electrical diagram of the connections of a dual-channel motor driver shield stacked on top of the microcontroller is presented in figure 2. The motors used are brushed DC motors with magnetic quadrature encoder for linear position feedback. For force feedback, the Honeywell FSS1500NST is used due to its low repeatability error of about $1.5mV$ at $300g$ compared to other types of force sensors, such as FSR.

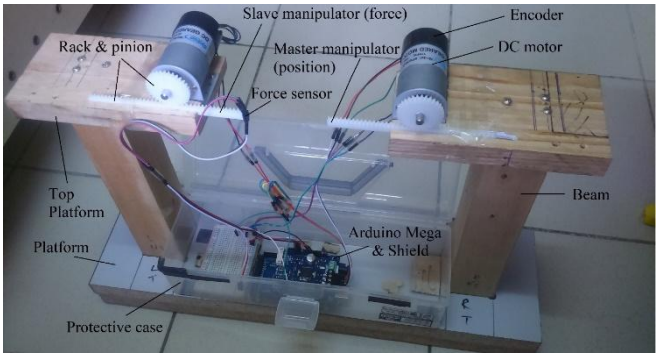

Figure 1. Prototype of the manipulators.

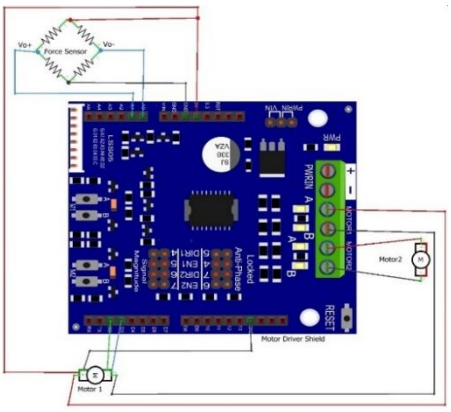

Figure 2. Electrical diagram.

3. Mathematical Modelling

In this section, the relationship between the output voltage of the force sensor and the corresponding force as well as model mathematical models of the plant and controller are presented.

3.1. Force Sensor Calibration

The force sensor is calibrated by taking readings incremental masses up to $500g$. No higher masses were sampled because no higher equivalent normal force is to be exerted on the manipulator. Figure 3 plots the relationship between the mass and voltage. When the relationship is linearized using line of best fit and converted, the force sensitivity amounts to $0.7007N/V$.

3.2. Manipulators

The plant is a 1-DOF manipulator and its free-body diagram is shown in figure 4, where f_{fr} is the friction force and f is the force exerted on the slave manipulator by the motor torque. Therefore, its model can be derived using a force equation:

$$\sum F = ma;\ f - f_e - f_{fr} - b\dot{x}_e = m\ddot{x}_e \tag{1}$$

where m is the mass of the manipulator in kg, b is the damping friction coefficient, f is the force from the actuator in N, f_e is the force exerted on the environment in N, f_{fr} is the friction force in N, and x_e is the position in m, $\dot{x}_e$ and $\ddot{x}_e$ are its first and second derivatives, respectively. For the master manipulator, the term f_e is taken out from (1) since the position control strategy will be applied to this manipulator. If x_e is constant, $\dot{x}_e = \ddot{x}_e = 0$.

The pressure angle of the rack and pinion is $20°$ and the module is 1. The pitch diameter of the pinion is given by

$$P_d = zm \tag{2}$$

where z is the number of teeth and m is the module. The pinion is of module 1 and has 32 teeth.

One rotation of the pinion will displace the rack by I, which is given by

$$I = \pi P_d \tag{3}$$

The relationship between the exerted torque by the motor and the force is

$$T = fr\sin\theta \tag{4}$$

where r is the distance from the axis of rotation to the point of application of the force in m, and θ is the angle between the force applied and the axis of rotation in degrees, which is 0°, as shown in figure 4. Thus, (4) becomes

$$T = fr \tag{5}$$

3.3. PID controller

A proportional-integral-derivative controller is used for both position control on the master manipulator and force control on the slave manipulator. The PID equation is

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} \tag{6}$$

where K_p, K_i and K_d are the proportional, integral and derivative gains, respectively, and $u(t)$ is the control input to the manipulator, which in this work is the force, f.

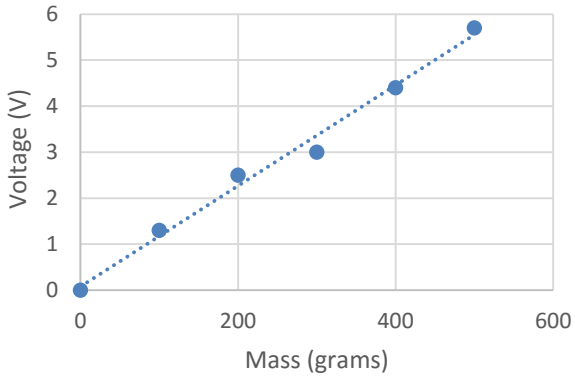

Figure 3. Mass-voltage relationship for the force sensor.

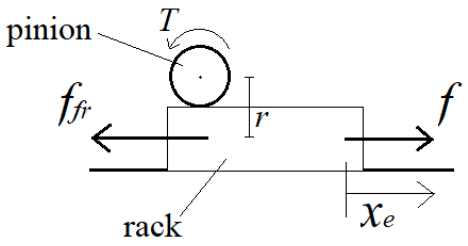

Figure 4. Free-body diagram of the manipulator.

Performing Laplace transform on (6) yields

$$U(s) = K_p + \frac{K_i}{s} + K_d s \tag{7}$$

The error $e(t)$ is the error for the master manipulator is

$$e(t) = e_x = x_d - x_e \tag{8}$$

where x_d is the desired position and x_e is the actual position. On the other hand, the error $e(t)$ is the error for the slave manipulator is

$$e(t) = e_f = f_d - f_e \tag{9}$$

in which f_d is the desired force and f_e is the actual force.

4. Simulation Studies

In this section, a few simulations are run to test the proposed technique. Figure 5 shows the simulation block diagram. The controller used in both cases is PID controller, as in section 3.3. The desired specifications for the controller in both cases are that the percentage overshoot (PO) should be less than 15%, the settling time (T_s) be less than 4 seconds and the steady state error (e_{ss}) be less than 5%. The simulation is run with the following values: b = 10, x_e varies between 0 and $2cm$, F_d = $3N$, k_e = $2N/cm$, m = $0.6kg$ and $f_{fr} = 0$ (due to smooth contact surface) into the model in (1). Figures 6 and 7 show the result for the master and slave manipulators, respectively. Figure 6 shows that the manipulator has successfully tracked the desired position, while figure 7 proves that the controller follows the desired force.

To meet the performance specifications above, for the master manipulator controller, the gains values have been manually set to K_p = 93.275, K_i = 139.139 and K_d = 7.212, and for the slave manipulator controller, K_p = 102.940, K_i = 162.104 and K_d = 5.077. Table 1 tabulates the performance of the force and position control simulation.

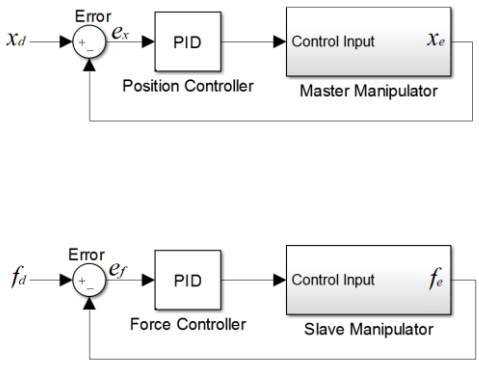

Figure 5. Simulation block diagram.

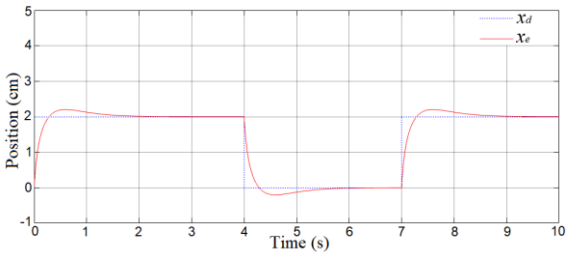

Figure 6. Position control simulation for master manipulator.

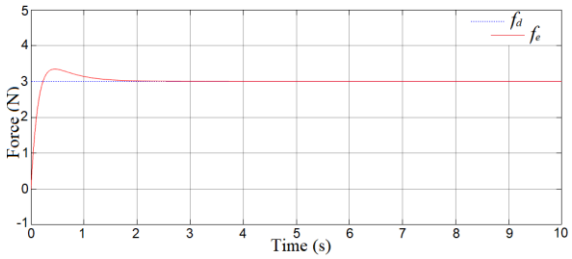

Figure 7. Force control simulation for slave manipulator.

5. Experimental Studies

The results of running the controller on the real plant are shown in figures 8 and 9; figure 8 shows the position tracking on the master manipulator while figure 9 shows the force tracking on the slave manipulator when grasping a tomato, as shown in figure 10. Due to the limited space between the two manipulators, the desired position tracked ranges between 0 and $2cm$. To avoid damaging the tomato, the desired force is set to $3N$.

The values of the gains of the controller have to be tuned manually. Ultimately, to achieve the result shown in figure 8, the values of the gains of the position controller are set to K_p = 3100, K_i = 20 and K_d = 150, and for the force controller in figure 9 the values are set to K_p = 800, K_i = 200 and K_d = 500. Table 1 tabulates the performance of the force and position control simulation.

The master manipulator deals with position, which is independent of the object being held. Figure 8 shows that the actual position of the master manipulator converges toward the desired values. Likewise, for force tracking on the slave manipulator is shown in figure 9. These results validate that the proposed technique is effective in controlling the cooperative manipulators in holding a deformable object.

The K_p, K_i, and K_d values in the implementation are fine-tuned manually since the parameters of the plant are quite different from the values assumed in the simulation. In tuning, having a relatively slower steady-state response is preferred to an overshoot to avoid the object from being squished or damaged.

From Table 1, it can be seen that are some discrepancies between the simulation and experimental results although both results meet the desired specifications. This is due to the unmolded dynamics and noise present in the experiment. It is suggested that a more accurate mathematical modelling to be developed so that the simulation resembles the actual experiment closely.

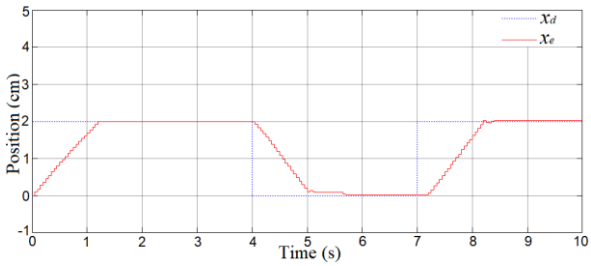

Figure 8. Position tracking of the master manipulation.

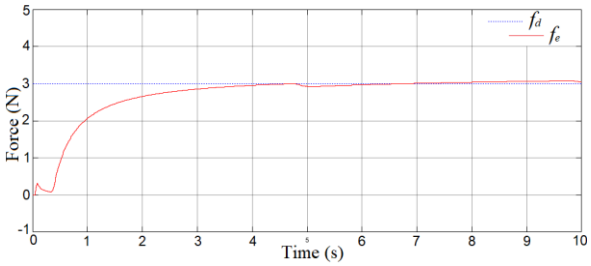

Figure 9. Force tracking of the slave manipulator, holding a tomato.

Table 1. Performance of force and position control comparison.

		e_{ss}	T_s (s)	PO (%)
Simulation	Position	0	0.261	10.484
	Force	0	0.207	12.366
Experiment	Position	$0.323mm$ (3.266%)	3.5	3.266
	Force	$48.387mN$ (4.839%)	1.707	0

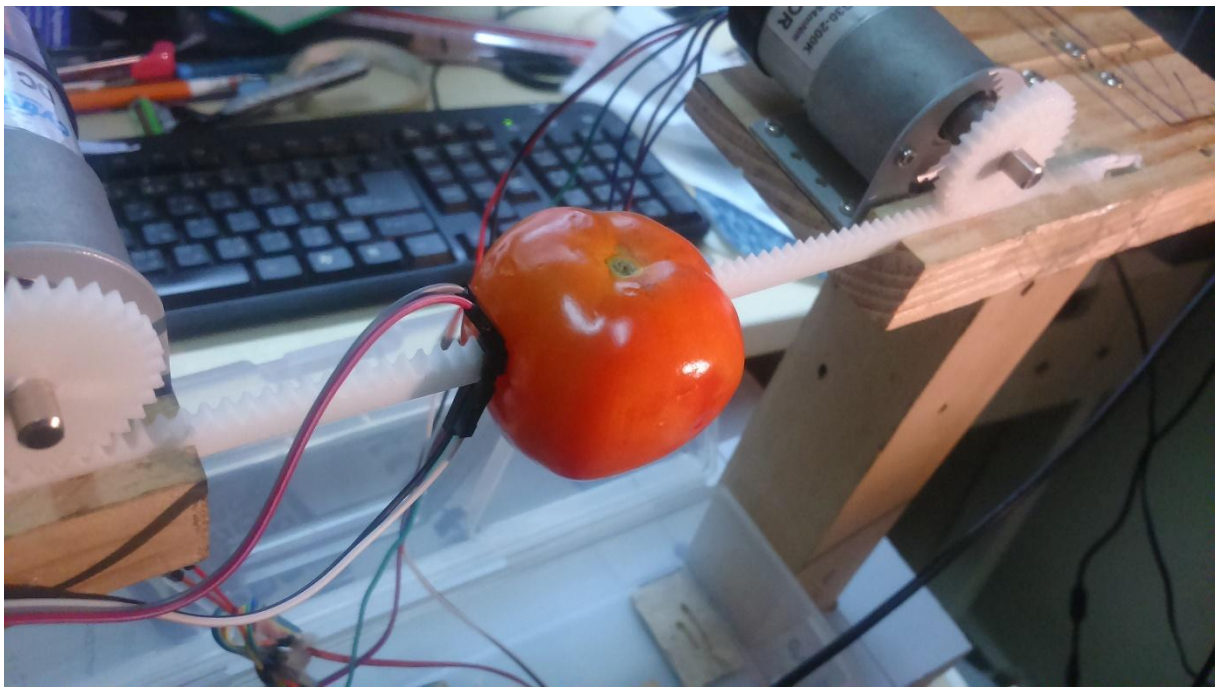

Figure 10. Manipulators holding a tomato.

6. Conclusion

The prototype of the cooperative manipulators has been developed and built, and the control system to control the manipulators has been evaluated and implemented successfully. Through simulation and experimental tests, the implemented control technique has successfully held the deformable object with maximum errors of 0.34mm for position, and 50mN for force. The significant difference between the simulation and experimental result indicates the inaccuracy of the initial modelling of the system.

The scope of this paper is limited to the action of holding a deformable object. Due to that focus, 1-DOF manipulators have been utilized in the study. To expand the tasks that the robot can do, the number of DOF can be increased; for example, to allow picking and placing the object. The deformable object to be held in this work is also limited. Currently, this paper regards only objects such as a plastic cup, cardboard boxes, fruits and vegetables. In the future, this study could be extended to handle more complex deformable objects such as fabrics. Moreover, more complex controllers, such as adaptive control could be implemented instead of the PID.

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