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Closed-loop model identification of cooperative manipulators holding deformable objects

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Abstract. This paper presents system identification to obtain the closed-loop models of a couple of cooperative manipulators in a system, which function to hold deformable objects. The system works using the master-slave principle. In other words, one of the manipulators is position-controlled through encoder feedback, while a force sensor gives feedback to the other force-controlled manipulator. Using the closed-loop input and output data, the closed-loop models, which are useful for model-based control design, are estimated. The criteria for model validation are a 95% fit between the measured and simulated output of the estimated models and residual analysis. The results show that for both position and force control respectively, the fits are 95.73% and 95.88%.

1. Introduction

System Identification is a methodology for constructing mathematical models of a system from its measured inputs and outputs. This method uses grey box or black box models on the model spectrum, which are less reliant on first principles like white box models [1]. System Identification has been used in many applications, and is mainly for obtaining the mathematical model of a system of interest for control design purpose. There are many different techniques in system identification, however, in general, one can classify them into two main approaches based on the domain; time-domain approaches, which use the time series data of the input-output of the system and frequency-domain approaches, which use the frequency response of the system and/or the corresponding spectral plots.

The typical procedure in system identification involves determination of model structure, parameter estimation and validation. In such case, statistical approach or artificial intelligence techniques can be used for obtaining the mathematical model based on the experimental data, such as ARX, ARMAX, artificial neural networks (ANN), Box-Jenkins, and many other techniques.

In terms of applications, system identification has been used widely. In this paper, as the system of interest has some similarity to link manipulators, one can find many applications of system identification, for examples, in modelling of single-link and two-link flexible manipulators in [2]-[5], the actuation subsystems of a heavy-duty electrohydraulic harvester manipulator in [6] and of a two-link pneumatic artificial muscle manipulator using genetic algorithm in [7].

In this paper, the system of interest is a pair of cooperative manipulators used to hold a deformable object despite the unknown stiffness and position of the deformable object without causing permanent visual deformation. Deformable objects are objects whose shape changes due to an applied external force, for examples, paper cups, tomatoes, and a bag of sand. The difficulty of manipulating deformable object is mainly due to the its nonlinear elasticity, friction and parameter variations [8]. Ability to hold deformable objects is important in robotics technology. The applications can be found in in industrial fields such as the food industry and recycling industry [9], as well as the medical field [10].

This paper presents closed-loop system identification of the cooperative manipulators for holding deformable objects that is proposed in [11]. The system consists of a master and slave system. The paper is organized as follows. Section 2 presents the methodology used including the description of the designed system. Section 3 presents the mathematical models of the master and slave manipulators as the results of the system identification described in Section 2. Finally, Section 4 concludes the paper.

2. Methodology

The system identification is performed on a closed-loop system, i.e. the manipulators together with the controllers, in order to obtain the input-output data through experiments. Tomatoes were used as the deformable objects. The mathematical models will be presented in form of transfer functions for the master and slave systems as will be explained in more details in the end of this section.

2.1. System Description

Figure 1 shows the prototype of the system. It is made of two 1-degree of freedom (DOF) cooperative manipulators; each is powered by a DC motor. One of the manipulators ('master') is position-controlled with encoder feedback where the input is the desired position and the output is the actual position, while the other ('slave') is force-controlled which tracks the desired force and uses a force sensor as the feedback [11].

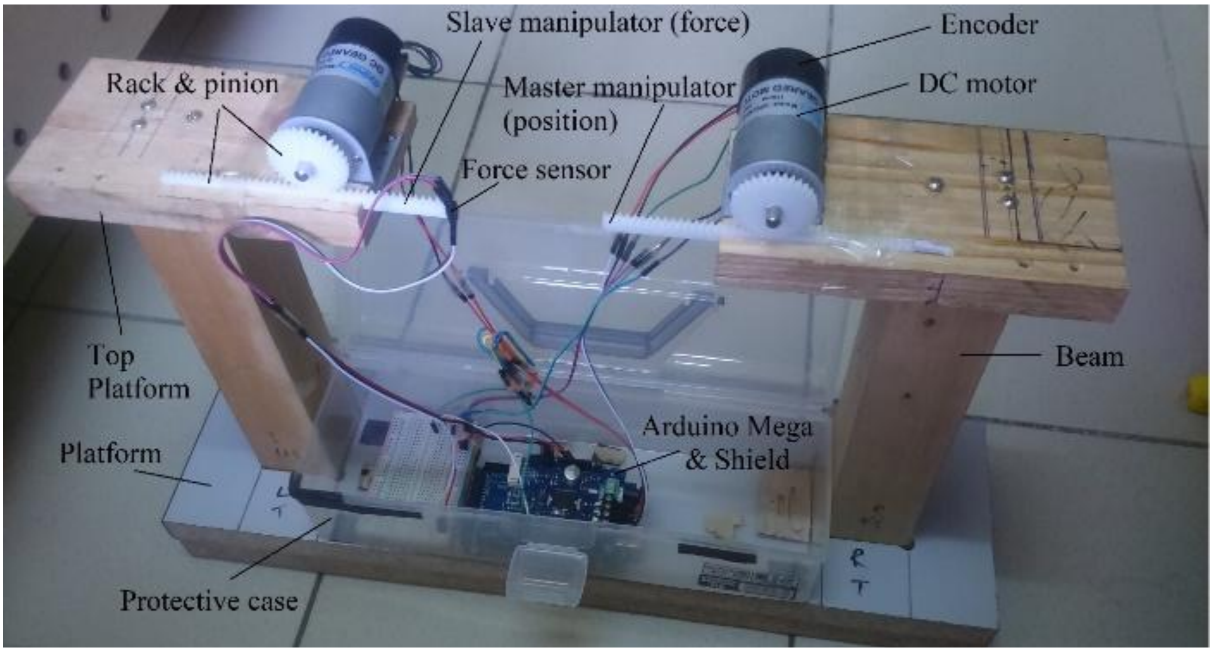

Figure 1. Manipulators prototype [11].

Proportional-Integral-Derivative (PID) controllers have been designed for the purpose of holding a deformable object in place by bringing the master manipulator to the desired position and exerting desirable amount of force at the slave manipulator. Thus, two sets of input and output data can be acquired. Figure 2 shows the block diagram of the system.

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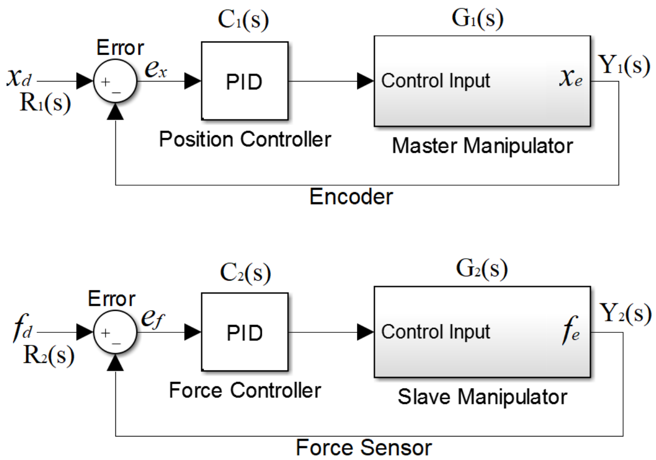

Figure 2. Block diagram of the system [11].

In [11], PID controllers are tuned to acquire the desired output as shown in Figure 3 and Figure 4, and while the controllers' parameters are known, the models of the master and slave manipulators are not mathematically identified. The PID gains for each controller are as follows. For the master (position) manipulator, Kp = 3100, Ki = 20 and Kd = 150, and for the slave (force), Kp = 800, Ki = 200 and Kd = 500. The tuning was performed through trial-and-error with the initial gains were obtained using the Ziegler-Nichols method.

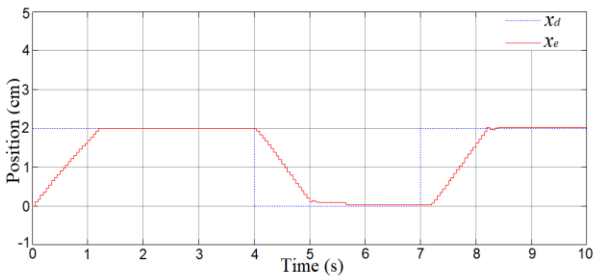

Figure 3. Position tracking of the master manipulation, where x_d and x_e are desired and actual positions, respectively [11].

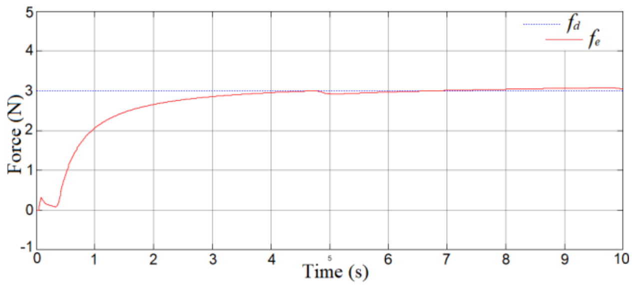

Figure 4. Force tracking of the slave manipulator, holding a tomato, where f_d and f_e are desired and actual forces, respectively [11].

2.2. Structure of Mathematical Models

This section discusses the models and parameters of the closed-loop transfer functions of the manipulators.

After acquiring data from the experiments, the model set is chosen (which in this case is transfer functions). Then, the criterion of fit is chosen; in this paper, a model with 95% fit against the validation data is considered a "good" model. Residual analysis test is also carried out to ascertain that the cross correlation function between the residuals and input is mainly within the confidence region, which also translates to the "goodness" of the model [12]. This process is repeated until the optimal tradeoff between model fidelity and model complexity is achieved, i.e. the least complex model that achieves at least a 95% fit. Performing identification in closed loop is useful for model-based control design [13].

MATLAB'S System Identification Toolbox [14], which provides convenient GUI menu, is used in the system identification process.

For the master manipulator, a sixth order transfer function with six poles and five zeros is chosen (equation (1)). The order was chosen by trial and error while observing the output response of the system.

$$\frac{Y_1(s)}{R_1(s)} = \frac{b_5 s^5 + b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s^1 + b_o}{a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s^1 + a_0} \quad (1)$$

where $R_1(s)$ and $Y_1(s)$ are the input and output of the system (desired and actual position), respectively, a_6 through a_0 are the denominator coefficients, and b_5 through b_0 are the numerator coefficients.

Similarly, for the slave manipulator, a fourth order transfer function with four poles and three zeros is selected as in equation (2).

$$\frac{Y_2(s)}{R_2(s)} = \frac{d_3 s^3 + d_2 s^2 + d_1 s^1 + d_o}{c_4 s^4 + c_3 s^3 + c_2 s^2 + c_1 s^1 + c_0} \quad (2)$$

where $R_2(s)$ and $Y_2(s)$ are the input and output of the system (desired and actual force), respectively, c_4 through c_0 are the denominator coefficients, and d_3 through d_0 are the numerator coefficients.

3. Results and Analysis

In this section, the validation of the closed-loop transfer function models obtained from model estimation is discussed.

Figure 5 shows the comparison between the measured output of the master manipulator and the simulated output of the model in (1). The fit between the measured and simulated output is 95.73%, which is above 95%, and therefore is considered satisfactory. The coefficients of (1) have been obtained from the estimation. Therefore, (1) now becomes

$$\frac{Y_1(s)}{R_1(s)} = \frac{0.2369 s^5 + 6.302 s^4 + 9.741 s^3 + 264.3 s^2 + 57.06 s^1 + 942.4}{s^6 + 5.395 s^5 + 56.18 s^4 + 169.3 s^3 + 471.8 s^2 + 634.7 s^1 + 957.5} \quad (3)$$

Likewise, Figure 6 compares the measured output of the slave manipulator to the model simulated output and the fit between them is 95.88%, well above 95%. From the estimation, the coefficients of (2) have been obtained. Therefore, (2) now becomes

$$\frac{Y_2(s)}{R_2(s)} = \frac{2.192 s^3 - 17.06 s^2 + 116.6 s^1 + 33.33}{s^4 + 9.501 s^3 + 103.1 s^2 + 172.6 s^1 + 31.91} \quad (4)$$

The higher order of the master manipulator model can be attributed to the complexity of its feedback mechanism that requires more pre-processing filters, which is the rotary encoder as opposed to the force sensor of the slave manipulator. Consequently, the master manipulator model will be more complex and burdensome for running simulations.

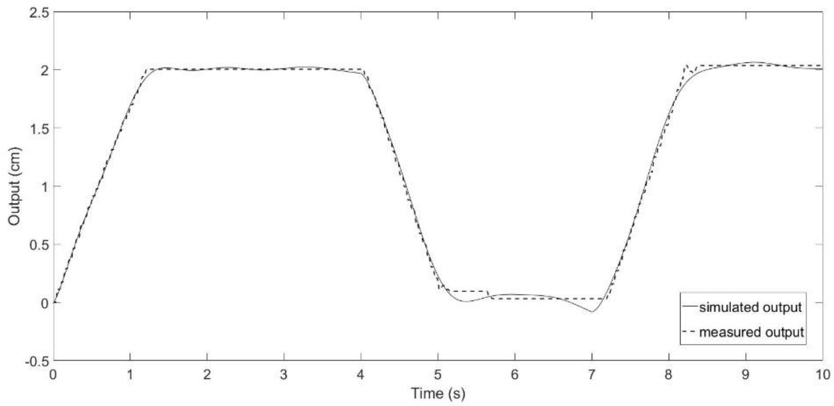

Figure 5. Measured and simulated model output of the master manipulator.

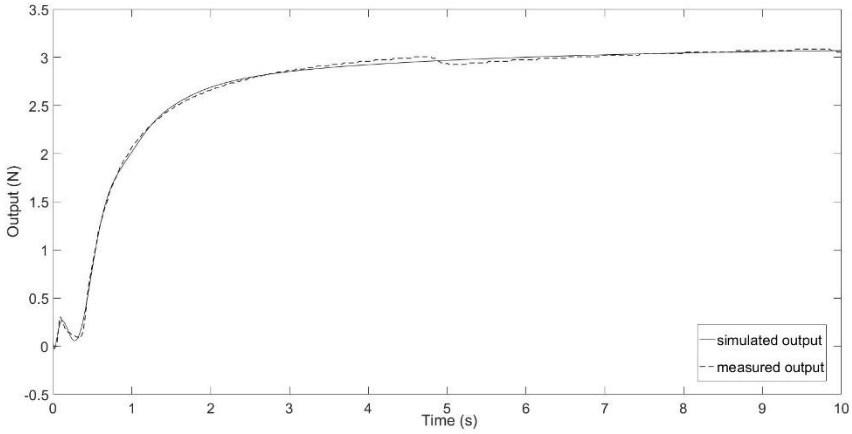

Figure 6. Measured and simulated model output of the slave manipulator.

Figures 7 and 8 show the cross-correlation between the input and the residuals for each input-output pair for the master and slave manipulators, respectively. In both cases the cross correlation function is between the confidence region (dashed lines). This shows that the residuals of the models are not correlated with and are independent from past inputs. Therefore, validating the “goodness” of the models.

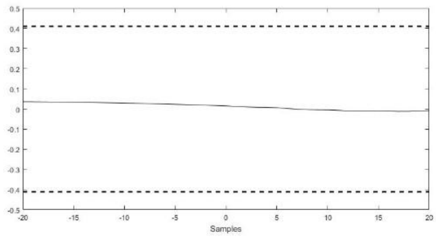

Figure 7. Cross correlation for $Y_1(s)$ and $R_1(s)$ residuals.

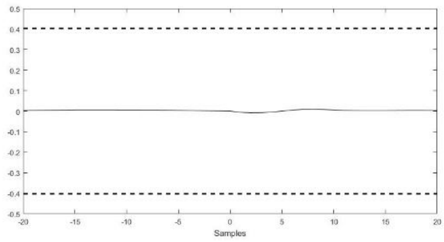

Figure 8. Cross correlation for $Y_2(s)$ and $R_2(s)$ residuals.

4. Conclusion

The closed-loop transfer function models of cooperative manipulators holding deformable objects have been estimated and validated using the system’s closed-loop input and output data. The fits between the measured and simulated output of the estimated models are 95.73% and 95.88% for the master and slave manipulators, respectively, above the 95% criterion for a “good” model. The obtained models are useful for model-based control design. The residual analysis also shows the cross correlation functions being within the confidence region for both cases.

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