Implementation of a Force Controller Based On Fuzzy Rule Emulate Networks for Soft Contact with an Object with Unknown Mechanical Properties

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ABSTRACT

In this article, a novel force control system for soft contact with an object of unknown mechanical properties is proposed by using an ultrasonic sensor implemented in a 3 DOF manipulator robotic system. The emphasis is on the development of a control system to allow soft contact with an object of nonlinear elastic contact properties. In this work a Multi-input Fuzzy Rules Emulate Network (MiFREN) scheme controller with adaptation is developed to regulate the contact force. We propose the use of an ultrasonic sensor in conjunction with a signal conditioning for force based on a parallel-distributed-model as well as the Hertzian model, and considering the transmission and reflection of ultrasonic wave properties. The IF-THEN rules for the MiFREN control are defined taking into account the human knowledge of a physical system and a stability analysis is developed by the Lyapunov method. The experimental results demonstrate that the system is able to find a stable first contact force and moreover the proposed controller is capable of controlling the contact force for both regulation and tracking tasks.

1. INTRODUCTION

In modern automatic systems, the control of an applied contact force value on an object is an important starting point for dexterous manipulation (i.e. industrial robots, manufacturing processes, handling of objects, etc.). Current manipulator systems equipped with sensors automatically make decisions to avoid collisions with the surroundings. Collisions could generate a detrimental impulse signal which could destabilize the control system [1]. To avoid instability, the interaction with the environment should be considered in the algorithm by a direct exploration of the object. Most of the current robotic systems have been designed to operate in environments with known properties; the development of exploration schemes in an environment with unknown characteristics is still under study. Many industrial processes such as: control of surface frosted processes, control of the heat treatments, hardness profiles and residual stresses (produced during the manufacturing process or cold forming processes such as peening) exhibit variation in surface, thus, affecting manipulation conditions where deterministic manipulation schemes are limited.

Manipulation and exploration operations are inherently coupled, therefore the information of object properties improves manipulation control. In cases where complete information of object properties is not known, a learning exploration scheme need to be considered. Thus, the first step toward a successful manipulability is the determination of the contact features [2].

The goal of this paper is the implementation of a force sensor based on the relation between the contact force and ultrasonic signal. To accomplish this, a control scheme is implemented to solve the transition problem between the free movement and the restricted movement. Once the force was controlled, mechanical properties were incorporated using acoustic propagation theory and mechanical contact models [2, 3].

The controlled plant is operated by an adaptive controller based on a multi-input fuzzy rule emulated network (MiFREN) [4] with the ultrasonic and force feedback signals. Positioning of the probe is carried out by using a 3 DOF manipulator robotic system.

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This paper is organized as follow: first, the theoretical basis of ultrasonic sensing and contact mechanic, as well as the scheme control MiFREN are described; second, the adaptation algorithm and the stability analysis are discussed; finally, the experimental setup and results are presented.

2. THEORETICAL BASIS FORMULATION OF THE CONTACT TEST

In this section the basic theory of the transmission and reflection waves and the proposed soft contact model are discussed. The correlation between the force signal and the ultrasonic signal is obtained using the area of contact found from the contact mechanics theory.

2.1. ULTRASONIC WAVES PROPAGATION

The contact sensor (hemispherical probe) includes an ultrasonic transducer which uses the transmission and reflection ultrasonic to determine the contact between the probe and the objects. A force sensor is attached to the test object (Figure 1a).The ultrasonic wave is reflected and the amplitude is decremented at different applied forces due the contact area (Figure 1b). The reflection coefficient at the interface between two media can be expressed by

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \tag{1}$$

where Z_1 and Z_2 are the characteristic acoustic impedance of the two media.

2.2. CONTACT MECHANICS

A parallel-distributed model to determine the contact area produced by a soft fingertip pressed against a flat surface which can be incorporated in the force control scheme was proposed in ref. [2, 3]. This model provides a description of the force-displacement relationship for nonlinear elastic material.

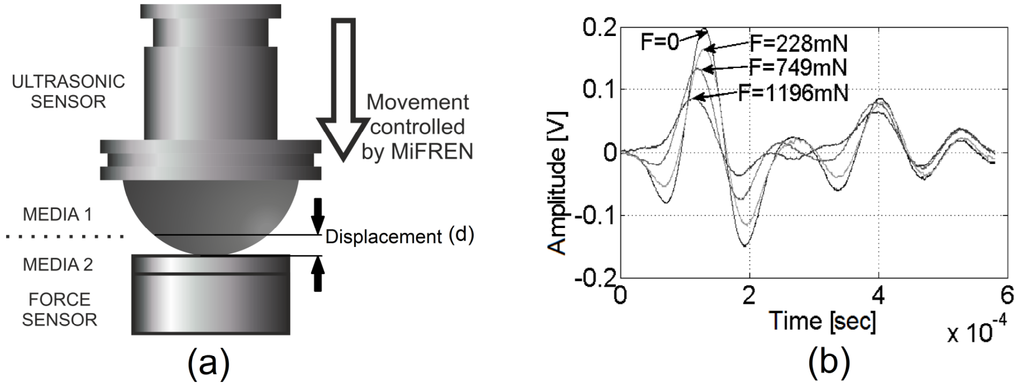


Figure 1. (a) Schematic of the proposed ultrasonic force sensor pressed against a MINI40 force/torque sensor; (b) Typical ultrasonic signals at various force values (F).

3. CONTROL DESIGN FOR FORCE-ULTRASONIC FEEDBACK BASED ON MIFREN WITH ADAPTATION

A control algorithm capable of finding stability before and after the collision for the proposed automatic system is presented. The MiFREN controlled is able to guarantee the system performance without knowing the mathematical model; in addition, in this scheme more than one feedback inputs are allowed. Recently, Navarro [5] used a modified controller MiFREN to control a gripper using the force and ultrasonic feedback signals. In this work, the system stability after collision using only the force sensor with two inputs defined by $e_f(k) = F_d(k) - F(k)$ and $e_f(k+1)$ and a control signal $u(k)$ acting directly on the DC motors is presented. The control signal establishes the output voltage as show in the block diagram of the system (Figure 2). The $F_d(k)$ corresponds to the reference value of desired force. The force signal is used to determine the two control input errors $e_f(k)$ and $e_f(k-1)$; $F(k)$ corresponds to the system output; $u(k)$ is the control signal linked directly to the DC motor voltage.

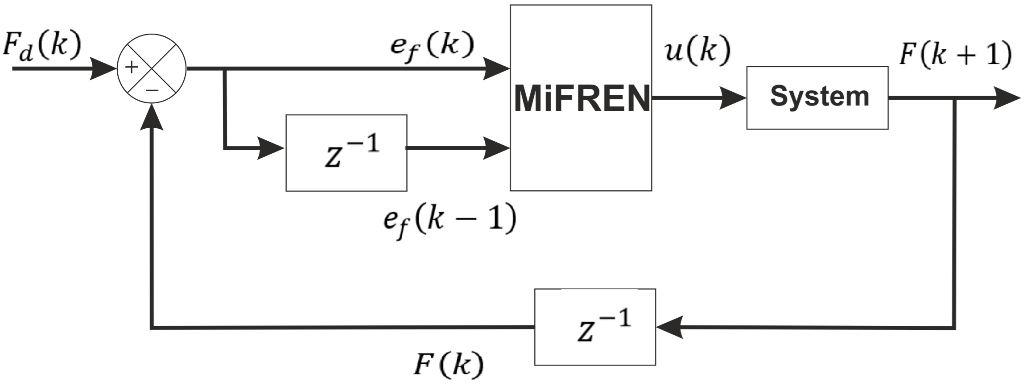


Figure 2. Close-loop system configuration based on MiFREN.

3.1. *FUZZY LOGIC CONTROLLER DESIGN*

The control algorithm based on MiFREN is constructed of a fuzzy logic system with n-inputs each with r fuzzy states, r^n IF-THEN rules. The experiment in section 4 shows the control implementation for $r = 5$ and $n = 2$ inputs ($e_f(k)$ and $e_f(k-1)$). The rules structure of the inference system has the form

i^{th} Rule: if (e_1 IS A_{i_1}) AND (e_2 IS A_{i_2})…AND (e_n IS A_{i_n}) THEN $O_i(k) = B_i(k)$,

where, i is the rule number, e_n is the n^{th} control input, A_i denotes the i^{th} fuzzy set, and O_i is the output value corresponding to the rule that belongs to the fuzzy set of B_i, in this case it is directly linked to the system's DC motors voltage.

The fuzzy inference system is calculated as

$$\varphi_i = \varphi_{i_1 \ldots i_2} = \prod_{j=1}^{n} \mu A_{i_j} \pi , \qquad (2)$$

where, $i = [1,...,r]$. The output for each i^{th} is calculated as

$$O_i(k) = \beta_i(k)\varphi_i , \qquad (3)$$

where $\beta_i(k)$ is the ith linear consequence parameter. The output control signal $u(k)$ and is calculated as

$$u(k) = \sum_{1}^{r^n} O_i(k) . \qquad (4)$$

3.2. ADAPTATION ALGORITHM

An adaptation algorithm of the control's parameters. The adaptation's parameters are useful for the system stability before and after a collision. The adaptation algorithm analysis is verified with two control inputs ($n = 2$) obtained from the same signal. The block diagram considering the proposed adaptation algorithm is shown in Figure 3. The gradient descent method is used to adjust the lineal consequence (LC) parameters β_i for $i = [1,\dots,r^n]$. A cost function is defined as

$$E(k+1) = \frac{1}{2} e_f(k+1)^2 = \frac{1}{2}[F_d(k+1) - F(k+1)]^2 , \tag{5}$$

where $F_d(k+1)$ and $F(k+1)$ are the reference value and system output respectively (see Figure 2). The β_i parameters can be adjusted by

$$\beta_i(k+1) = \beta_i(k) - \eta_i(k) \frac{\partial E(k+1)}{\partial \beta_i(k)} , \tag{6}$$

where $\eta_i(k)$ is the learning rate based on to the gradient technique, this parameter determines the stability and convergence of the system, i.e., a small learning rate provides satisfied system stability but the convergence rate could be slow, contrary to this, higher learning affords a faster convergence. In this paper, the learning rate is considered as a time varying parameter to guarantee the closed loop performance. The differential term from equation (6) can be expressed as

$$\frac{\partial E(k+1)}{\partial \beta_i(k)} = \frac{\partial E(k+1)}{\partial e_f(k+1)} \frac{\partial e_f(k+1)}{\partial F(k+1)} \frac{\partial F(k+1)}{\partial u(k)} \frac{\partial u(k)}{\partial \beta_i(k)} . \tag{7}$$

Equation (7) can be rewritten as

$$\frac{\partial E(k+1)}{\partial \beta_i(k)} = [e(k+1)][-1][y_P(k)][\varphi_i(k)] , \tag{8}$$

where $y_P(k)$ is $\partial y(k+1) / \partial u(k)$. By substituting equation (8) into equation (6), the linear consequence is given by

$$\beta_i(k+1) = \beta_i(k) + \eta_i(k)[e(k+1) y_P(k) \varphi_i(k)] . \tag{9}$$

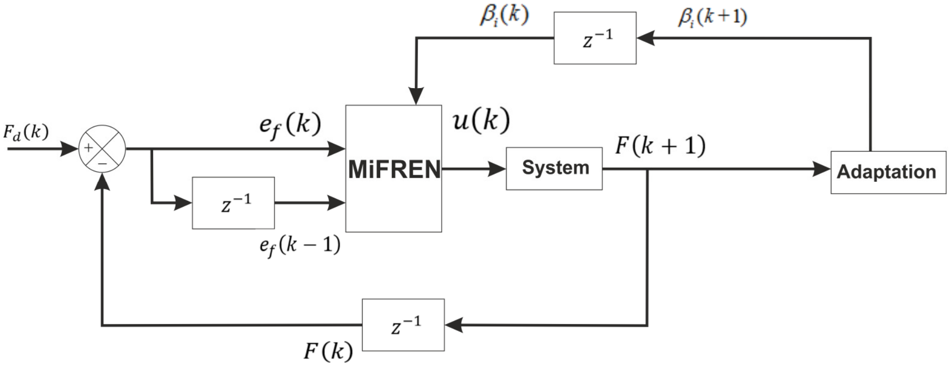


Figure 3. Plant of MiFREN control with adaptation algorithm.

3.3. STABILITY ANALYSIS

A stability analysis that includes the parameters of the learning rate is calculated by the Lyapunov stability method. The Lyapunov candidate function is

$$V(k) = \frac{1}{2}\left(F_d(k) - F(k)\right)^2 = \frac{1}{2}Z(k)^2, \tag{10}$$

with $Z(k) = F_d(k) - F(k) = e(k)$. This equation meets the characteristics of the Lyapunov function which is differentiable and defined positive. From equation (10) the change $\Delta V(k)$ is given by

$$\Delta V(k) = \frac{1}{2}\left(Z^2(k+1) - Z^2(k)\right) = \Delta Z(k)\left(Z(k) + \frac{1}{2}\Delta Z(k)\right), \tag{11}$$

where $\Delta Z(k)$ can be approximated as

$$\begin{aligned} \Delta Z(k) &= \frac{\Delta Z(k)}{\Delta \beta_i(k)}\Delta\beta_i(k) \approx \frac{\partial Z(k)}{\partial \beta_i(k)}\Delta\beta_i(k) \\ &= \frac{\partial Z(k)}{\partial F(k)}\frac{\partial F(k)}{\partial u(k)}\frac{\partial u(k)}{\partial \beta_i(k)}\Delta\beta_i(k) = -y_P(k)\varphi(k)\Delta\beta_i(k). \end{aligned} \tag{12}$$

Using equation (9) and equation (12) the change of Lyapunov function $\Delta V(k)$ (equation (11)) can be written as

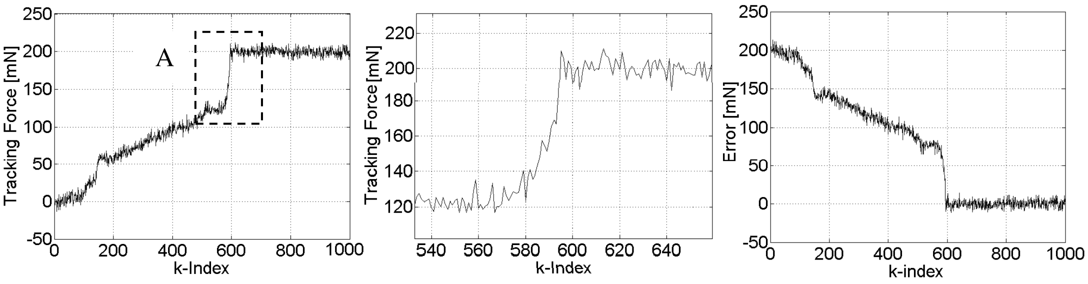
$$\Delta V(k) = -\eta_i\left[Z(k)\,y_P(k)\varphi(k)\right]^2\left[1 - \frac{1}{2}\eta_i\left[y_P(k)\varphi(k)\right]^2\right]. \tag{13}$$

According to the Lyapunov criteria ΔV should be less than zero to guarantee stability in the system, thus

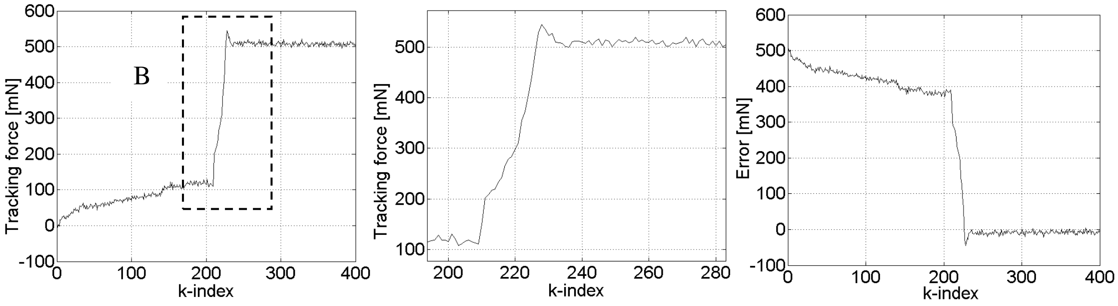
$$0 < \eta_i < \frac{2}{\left(y_P(k)\varphi(k)\right)^2 + \varepsilon}, \tag{14}$$

The constant ε, to avoid divisions by zero is defined as a positive small value; here, a value of $\varepsilon = .001$ is used. The learning rate value must be regulated carefully, a big value could significantly impact in the stability of the system; on the other hand a small value could reduce the adaptation performance.

The implemented control is used to determine the contact force applied on the object. A first test for system performance is shown in Figure 4. An initial separation of 1 mm separation between the object and the soft fingertip is used. It is found that the control is able to avoid the overshoot due to collision (Figure 4a,b center).



(a)



(b)

Figure 4. (Left to right) Tracking force performance; graph amplified of A and B; error graph for two forces (a) $F_d = 200mN$ and (b) $F_d = 500mN$

The tracking force performance plotted in Figure 6 shows a gap in stabilization time when regulation results at $F_d = 200mN$ and $F_d = 500mN$ are represented. The effort system difference between these two performed tests is described by a rule design consequence (section 3.1), given by:

IF feedback force error IS small negative THEN DC motor voltage IS small negative

IF feedback force error IS big negative THEN DC motor voltage IS big negative

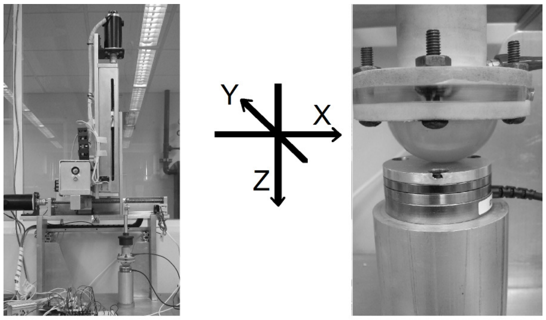
IF feedback force error IS small positive THEN DC motor voltage IS small positive

IF feedback force error IS big positive THEN DC motor voltage IS big positive

4. EXPERIMENTAL SETUP AND RESULTS

The experimental platform consists of a 3 DOF XYZ – axis manipulator robotic system (Figure 5) controlled by the MiFREN control scheme (Figure 2). In this scheme, the control signal is linked directly to the motor voltage. The system uses the proposed control scheme to place the end effector in a force range with no plastic deformation of the soft fingertip to obtain the force/displacement and force/Ultrasonic signal relationship (see Figure 1).

A hemispherical soft silicone fingertip is used as end effector, with radius (R) of 20 mm and Young modulus (E) of 0.173MPa. A piezoelectric transducer with a frequency of 1 MHz attached to the soft fingertip generates the ultrasonic signal that is used to determine the Force/Ultrasonic signal relationship. The transducer is connected to a pulser/receiver device. A Lecroy WaveJet 300A oscilloscope gathers and transmit the data obtained from the piezoelectric to the PC through USB port. An F/T Mini40 sensor reads the contact force and the value is sent to the PC through a National Instruments data acquisition card. The used servomotor has a terminal voltage of 60VDC, and a continuous torque .353N.m. This motor includes an AMT102 incremental encoder which has 1024 pulse per revolution (PPR) of output resolution, the pulses count is converted into an analog signal through a DAC0808, with 0-8VDC range and send to a PC. Each robot's axis has a lead screw with a pitch of 4.85mm. To calibrate the received voltage in the encoder of the Z-axis displacement each pulse in the encoder has a value of 8/255 VDC.



(a) (b)

Figure 5. (a) Robotic system manipulator; and (b) ultrasonic probe and force sensor.

Figure 6 shows the tracking force test to obtain the force–displacement relationship for a controlled load and unload force cycles in the range of 0 N to 10 N. Since the first contact point is unknown, the position of the end effector is placed near to the contact point in free movement. The system records the displacement and force values only when the force magnitude is not zero.

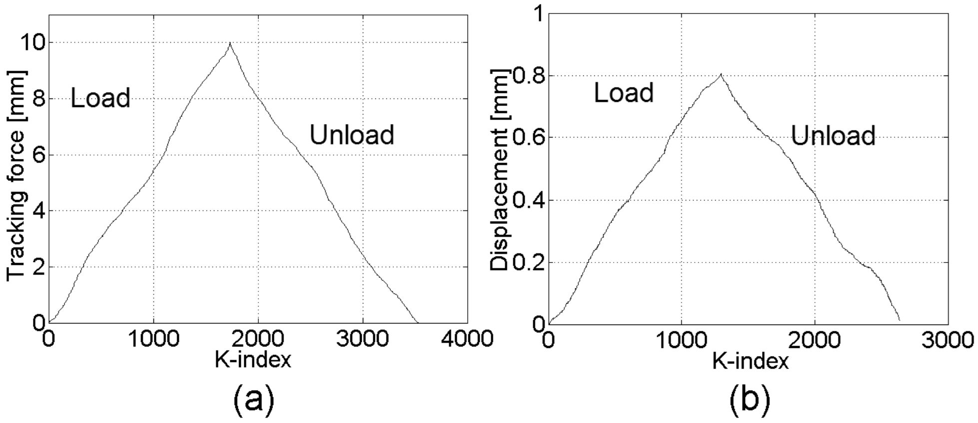


Figure 6. (a) Record force for load and unload cycles; (b) Corresponding displacement data for applied force.

According to contact mechanic theory, the displacement-force relationship of an ideal elastic semi-sphere in contact with an infinitely rigid plane can be approximated by the Hertzian model [6]

$$F = \left(\frac{16}{9} d^3 R E^2 \right)^{1/2}, \tag{15}$$

where F is the force, d is the displacement, R denotes the hemispherical soft fingertip radius and E is the young modulus. For nonlinear elastic materials Inoue & Hirai [2] proposed a new model based on Parallel-distributed model. The final formulation is simplified as

$$F = \pi E d^2. \tag{16}$$

According to Inoue & Hirai [2], this model can be incorporated much easier in the dynamics and kinematics of a manipulator. However, our preliminary results showed that the Hertzian model has better correlation in the range of forces studied in our experimental results (Figure 7).

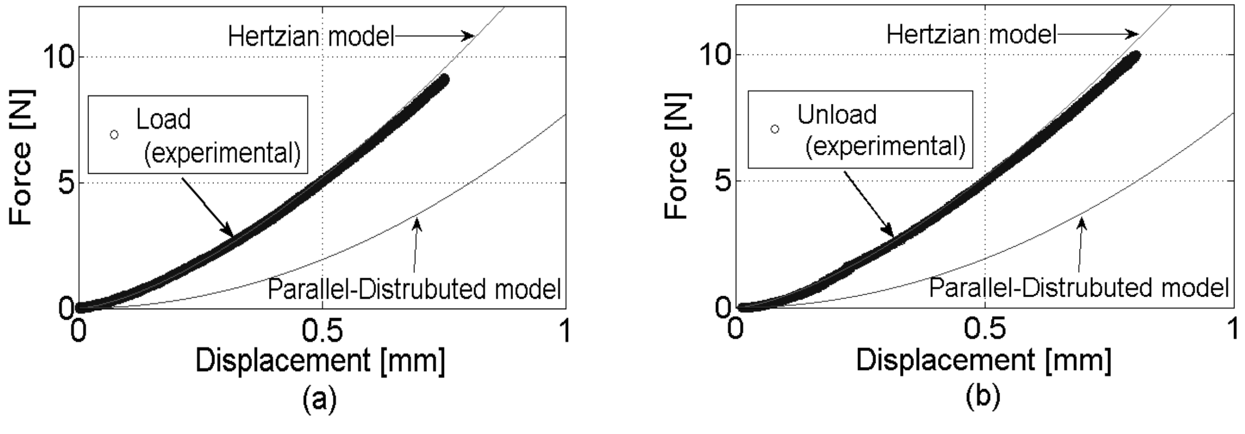


Figure 7. Comparison between test Hertzian and Parallel distributed model (a) loading; (b) unloading cycles.

The relation between the ultrasonic (using the peak to peak voltage, see Figure 1) and the force is shown in Figure 8. The operation range for the ultrasonic signal was set in the range of 0 to 7 N. A large sensitivity of the ultrasonic probe to load and unload cycle was observed. This sensitivity could be related to material property of the hemispherical silicon fingertip used in the experiments; however, further studies are needed to corroborate that.

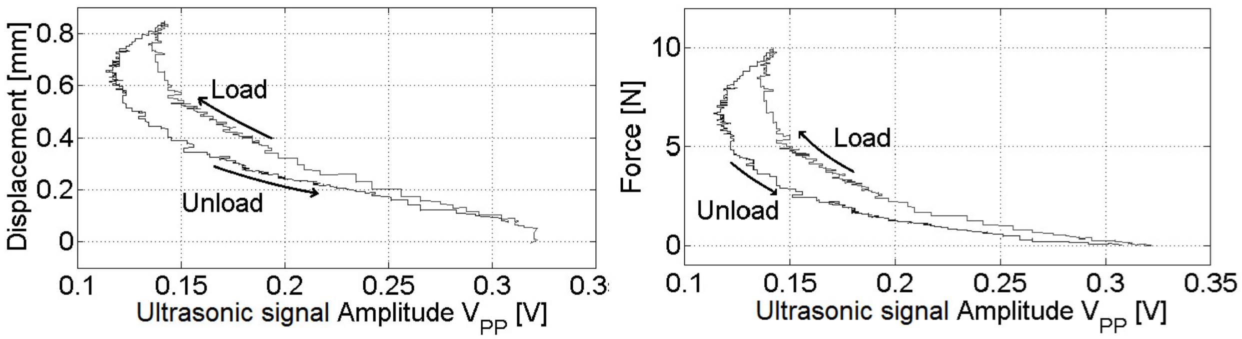


Figure 8. Ultrasonic (peak to peak voltage) and displacement signal relationship, and ultrasonic (peak to peak voltage) and force signal results.

5. CONCLUSIONS

In this work a new controller scheme MiFREN with the output control signal linked directly to the DC motors of the positioning system is implemented and tested in a 3 DOF robotic system. The system uses only force feedback signal to attain a desired force. The overshoot problem due to the collision in the transition phase is studied. A force control to reach a desired force without any knowledge of the mechanical properties of the contacting surface or of a mathematical model of the system dynamics is developed and implemented. A good correlation between the fingertip ultrasonic data and the applied force was found; the ultrasonic information can then be incorporated to the manipulator controller to provide knowledge about load and unload stages without need for a force sensor.

Future work includes the implementation of the developed force control scheme in a 6 DOF ABB robot manipulator to perform manufacturing operations in a partially unknown environment using multi-input feedback.

ACKNOWLEDGMENT

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