Development of an Estimated Force Feedback Controller Based on Hertzian Contact and Ultrasound

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Abstract—In this paper, the design of a novel force controller which combines a neuro-fuzzy algorithm and a new contact ultrasonic probe is proposed. The fuzzy rules emulated network (FREN) has a control algorithm structure based on fuzzy IF-THEN rules. The force sensor is integrated in a Cartesian robotic system with the FREN force control. The contact probe is equipped with a 1 MHz frequency ultrasonic transducer. The probe is constructed by a semi-spherical head and an ultrasonic transducer located at the top of the head. The contact between the probe and the medium is modeled by Hertz theory. The experimental results showed that the proposed system exhibits high sensitivity for touching contact, instantaneous contact and reaction force estimation. To test the system, experiments were conducted in elastic and elastic-plastic materials. The results indicate that the proposed system is able to effectively control the contact force.

Keywords: Contact; Force control; Neuro-Fuzzy control; Ultrasonic technique

I. INTRODUCTION

In modern automatic systems (e.g., industrial robots, manufacturing processes, service robots, grasping materials and others) it is important that they be equipped with sensors to perceive the work environments for subsequent decisions by using algorithms and control laws. When it is necessary to handle materials with low yielding stress, sensors with high sensitivity are required for measuring contact force [1, 11, 12 and 13]. Recently, the integration between fuzzy logic and neural network known as a neuro-fuzzy or the fuzzy neural network (FNN) has drawn attention of many researchers in the field of control engineering [2-7]. Combining a learning ability of neural network and human-like reasoning of fuzzy logic makes FNN a very flexible intelligent control technique for many applications [8]. An adaptive controller inspired by the similar principle of FNN was proposed by Treesatayapun [9] called fuzzy rules emulated network (FREN); this structure is simple and allows the initial setting of network parameters to be intuitively selected.

FREN does not require knowing the mathematical model between the force and the ultrasonic reflection which is quite difficult to obtain; thus by follow the IF-THEN rules similar to human sense, the force and velocity is controlled.

In this work, a novel force feedback FREN controller and a new probe for contact and measuring force are presented. The objectives of the paper are: first to design a force control based on fuzzy rules, second to demonstrate the applicability of the simple structure FREN for controlling the force contact interaction, and third to present a new type of probe based on Hertzian contact and ultrasound for measuring contact force and detection of instantaneous contact.

II. FORCE FEEDBACK FREN CONTROLLER

A general fuzzy inference system can be represented by IF-THEN rules. For each force-input there is a corresponding velocity-output, these rules may be written as

\[ \text{RULE } i: \text{ IF } e_f \text{ IS } A_i \text{ THEN } v_i = f_i(e_f) \]

where \( e_f \) denotes the force error input of the fuzzy system. This rule indicates that if \( e_f \) belongs to the fuzzy set \( A_i \) with the membership value of \( \mu_{A_i} \) then the fuzzy value of the output of this rule, denoted by \( v_i \), is equal to \( f_i(\mu_{A_i}) \). After all rules have been processed, the velocity output \( V \) is calculated using a defuzzification scheme.

The force feedback FREN control is derived based on these fuzzy rules, its structure can be decomposed into four layers as shown in Fig. 1. The function of each layer is as follows:

Layer 1: The input \( e_f \) of this layer is sent to each node in the next layer directly, thus there is no computation in this layer.

Layer 2: This is called the input membership function (MF) layer. Each node in this layer contains a membership function corresponding to one linguistic level (e.g. negative, positive, nearly zero, etc.).

The output at the \( i \)-th node is calculated by

\[ A_i = \mu_i(e_f) \]  \hspace{1cm} (1)

where \( \mu_i(\cdot) \) denotes a MF of \( i \)-th node \( (i = 1, 2, \ldots, N) \), examples of MF are given in Fig. 2.

Layer 3: This layer may be considered as defuzzification step. It is called the linear consequence (LC) layer. There are also \( N \) nodes in this layer. The output at the \( i \)-th node in this layer can be calculated by

\[ v_i = (h_i - k_i)A_i + k_i \]  \hspace{1cm} (2)
where $h_i$ and $k_i$ are parameters of $i$th node, examples of LC are shown in Fig. 3.

$$\text{Figure 1. The structure of force feedback FREN controller.}$$

$$\text{Figure 2. Examples of membership function.}$$

Layer 4: The structure of this layer is similar to the output layer of an artificial neural network. The output velocity of the actuator $V$ of the force feedback FREN, is calculated in this layer as

$$V = \sum_{i=1}^{N} V_i. \tag{3}$$

When using the proposed force feedback FREN controller, the structure of the control system becomes what is shown in Fig. 4. The control receives the force error signal $e_f(k)$ and computes the nominal control signal $V(k)$ as the actuator velocity.

III. EXPERIMENTS

A. Force Probe Based on Hertzian Contact and Ultrasound

In Fig. 5 the probe for contact measurements is described. This is built from a solid semi-spherical head which is sonified from the top by an ultrasonic transducer. The ultrasonic transducer, with a central frequency $f$ of 1 MHz and a piezoelectric element of 19mm diameter $d$, is used to generate a pulse inside the semi-sphere. The probe shape allows analyzing the contact with the test surface by using Hertz theory [1].

$$\text{Figure 3. Examples of linear consequence.}$$

$$\text{Figure 4. Control system using force feedback FREN controller.}$$

The semi-sphere probe is made of Plexiglas and its design was based on calculations of ultrasonic propagation parameters inside the probe such as near field $NF$ and beam divergence angle $\Phi$. These parameters were calculated [10] by

$$\lambda = \frac{C}{f} \tag{4}$$

$$\Phi = 2 \sin^{-1} \left[ \frac{(1.2 \times 10^{-3}) C}{f d} \right] \tag{5}$$

$$NF = \frac{d^2 - \lambda^2}{4 \lambda} \tag{6}$$

where $\lambda$ denotes the wavelength and $C$ the acoustic wave velocity. The corresponding constant values for Plexiglas are: $NF=32.37\text{mm}$, $\Phi=19.85^\circ$ and the wavelength $\lambda=2.73\text{mm}$. In Fig. 5 the assembled probed is shown. An ultra thin force sensor (0.203mm) integrated on the probe is used. Hertz theory [14] allows estimation of contact force and elastic properties of the test surface. The probe could be useful for measuring of
force and estimation of mechanical properties in materials with low yielding stress.

![Figure 5. Force probe based on Hertzian contact and ultrasound.](image)

The spherical shape of the probe transmits energy through the contact surface. If the interface is Plexiglas-air, all the energy is reflected and if the spherical probe makes contact with the material, part of the energy is transmitted and part is reflected. Due to this phenomenon it is possible to detect instant contact. During the design of the probe, signal response from two spheres made of different materials (Plexiglas and aluminum) was studied. A time domain signal response on the aluminum sphere and Plexiglas are shown in Fig. 6 and Fig. 7, respectively. It is clear that more information about echo-pulses patterns is found by using the Plexiglas sphere; thus, amplitude variation can be monitored more easily. The noticeable difference between the signals is mainly due to the larger wave velocity in aluminum ($C_{al} = 6320 \text{ m/s}$) 2.3 times than in the Plexiglas. This could cause the first pulses to overlap with the initial pulse, making the signal analysis more difficult.

![Figure 6. Signal using an aluminum sphere.](image)

B. System and Experiments Procedure

Experiments were carried out by using a 1 MHz transducer to transmit ultrasonic energy through the Plexiglas spherical surface. The probe operating at that frequency shows high sensitivity of the ultrasonic technique for touching contact, and signal analysis.

One of the characteristics of using ultrasound is the high contact sensitivity over the spherical surface which allows detecting the initial contact point (Fig. 8). Sensitivity of probe occurs when it comes into contact with a surface (slight amplitude decreasing on the ultrasonic signal). This is caused by the energy transmission through the contact point. In the absence of contact, the interface is Plexiglas-air where nominally all the energy (99.995%) from the interface is reflected back to the transducer.

![Figure 8. (a) First contact point when $\delta \to 0$, (b) displacement in the normal direction where $\delta_1 < \delta_2$.](image)

The probe is integrated in a Cartesian robotic system; the drivers and user interface were developed in LabVIEW, this includes positioning the force probe, to control sending and receiving of ultrasonic pulses by using PCI Local Bus compliant device (PDA14), and performing the required signal processing. The applied force and the ultrasonic signal were controlled by the intelligent control based on force feedback FREN. Once the reflected pulse is received by the PDA14 and passed to the PC, signal processing including a fast Fourier transform (FFT) is carried out to obtain the amplitude frequency spectrum of the test pulse. Incident ultrasonic signal is normalized by the spectrum of the noncontact region.
In Fig. 9 the experimental methodology is summarized, the main steps are:

1) The onset of contact point is detected between the probe and the test surface by analyzing the amplitude variation of the signal on the frequency domain.

2) then, the origin “O” of XYZ coordinate system is located at the point where both the normal contact regarding to the surface and the instant contact are achieved.

3) finally, the system applies force to the touching surface, the force feedback FREN controller gets the force error from the probe, and the desired force is achieved.

where $q$ is the $(n \times 1)$ vector of generalized joint coordinates, $H(q)$ is the $(n \times n)$ inertia matrix, $g(q)$ is the $(n \times 1)$ vector of gravity forces, $V$ is the $(n \times 1)$ vector of joint control input to be designed, $f$ is the $(n \times 1)$ vector of generalized forces, and $J(q)$ is the geometric Jacobian square matrix.

The physical Cartesian robotic system is shown in Fig. 11a and the force probe is shown in Fig. 11b.

C. Cartesian robotic system

The Cartesian robotic system to be controlled by the force feedback FREN controller is shown in Fig. 10. The equation of the dynamic model (in the absence of friction forces) governing this system is given by

$$H(q)\ddot{q} + g(q) = V + \dot{J}(q)f,$$  \hspace{1cm} (7)
D. Experimental results

Experiments to measure the contact force response of the system by the force feedback FREN controller were carried out. Soft materials: synthetic elastometer and a tomato fruit were tested.

1) Synthetic elastometer

The force contact throughout the time is shown in Fig. 14. In this experiment, the desired force $f_d$ is set to 5 Newton and the system initiates on the zero position XYZ (i.e. [0,0,0]). The elastometer in contact is a synthetic material, highly flexible providing good surface contact, and it has high transmission efficiency with acoustic properties close to those of water. The surface elastic modulus is $E_{\text{Elastometer}}=3.72 \times 10^6 \text{ N/m}^2$.

It was found that the force feedback FREN controller converges in less than 35 seconds to the desired force into stable state (Fig. 14); this is due to the low velocity when the system is applying the contact force. The velocity response of the control system during the contact is shown in Fig. 15.

2) Tomato

The force contact throughout the time is shown in Fig. 17, and the surface elastic modulus is $E_{\text{Tomato}}=6.24 \times 10^5 \text{ N/m}^2$.

Due to manipulation of fragile objects precise contact interaction is required. It is necessary to use low velocities over the increasing contact force until the system reaches the desired position, and thus zero velocity. Fig. 16 shows the relation between the applied load and the ultrasonic amplitude. The signal amplitude decreases due to the contact force increase, then the contact area increase, and therefore more ultrasonic energy is transmitted through the touching material.
In both materials presented above, it can be seen that the Cartesian robotic system controlled by the force feedback FREN can reach the desired force by using this new type of force probe. Due to the difficulty for estimating force in soft materials like a tomato, the advantage of this kind of new probe structure allows measuring forces less than 1 Newton which is necessary in the manipulation of fragile objects. In addition by using the proposed controller, the system can reach the desired force smoothly by controlling contact force and velocity.

IV. CONCLUSIONS

In this paper, a novel force feedback FREN controller and its application by using a new probe based Hertzian contact and ultrasound was presented. The intelligent control follows a simple experimental methodology. With the proposed probe, the contact force on the interface and its relation with the ultrasonic reflection due to the transmission energy was estimated. By observing the amplitude variation of the ultrasonic signal, the proposed probe detects instant contact and applies a desired force on the touching surface. FREN is a convenient controller which does not require the exact mathematical relationship between the contact force and the ultrasonic amplitude. The proposed force feedback FREN controller has a simple structure based on human knowledge in the form of fuzzy rules, and the velocity is controlled in direct proportion with the force error. Experimental results demonstrate good agreement of the force control for reaching the desired force in elastic materials with low yielding stress. The force response rising time can be improved by changing the velocity and modifying the membership functions based on an adaptive scheme.

We are also currently investigating possible applications for this force ultrasonic based probe in agriculture, medicine, materials and robotic grasping, and the use of the force feedback FREN controller together with the probe in a more dexterous robotic system.

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