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ORIENTATION CONTROL OF AN ULTRASONIC SOFT CONTACT PROBE BASED ON NEURO-FUZZY NETWORKS

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ABSTRACT

Force and orientation control of an ultrasonic probe for medical application is performed free-hand by the practitioner. This operation requires a careful adjusting of the probe force and orientation until the target region is located. In this work, an adaptive control based on neuro-fuzzy networks is proposed to address the challenge of force and orientation control with a six degrees of freedom (6DOF) manipulator. Minimum force error and maximum ultrasonic energy are seek to adapt the control parameters in the algorithm. Test of stability control and numerical analysis were performed. The control was experimentally tested on a soft material (tissue mimicking phantom). The experimental results show that the proposed robotic system exhibits high sensitivity to initial contact, in and out of the normal orientation on sample with limited information of its surface topology and orientation.

Keywords: Ultrasonic probe, soft contact, force control, orientation control.

1. INTRODUCTION

Most ultrasound imaging is performed free-hand where the practitioner holds the probe in contact with the body, adjusting the probe orientation and force until the target region is located. In medical ultrasound, the force exerted by the probe on the tissue is often minimized to view the tissue anatomically correct or in an undeformed state.

In ultrasound elastography, the applied load can influence the measured tissue deformations and may allow determination of elastic modulus. The compressive force must be minimized (or quantified) to determine the effective stiffness of the target region, e.g., a tumor, and its surrounding tissue [1]. In reference [2], an approach to track and explore stiff tissues within 3-D ultrasound volumes acquired by a medical 3-D ultrasound probe mounted on a 6DOF robotic arm is presented. There, force and positioning to perform automatic palpation and centering of the target was controlled. However, the orientation control was tele-operated by a human using a haptic device. In reference [3] a free-model force control strategy was presented for autonomous dry contact ultrasonic inspection of object with different rough surfaces. The main objectives of this work are: I) to present a novel adaptive model-free orientation control based on neuro-fuzzy networks and ultrasonic signal power for its applicability on soft contact; II) to provide a strategy for the control and monitoring of orientation and applied forces of an ultrasonic probe on soft materials for exploration tasks. and III) to set the bases for autonomous exploration by an ultrasonic robotic system.

2. MATERIALS AND METHODS

The robotic system to simultaneously achieve force and orientation control using a force sensor and an ultrasonic probe is presented in figure 1. The proposed control plant is integrated by a 6-DoF robot KUKA KRC1 manipulator, a costumed made ultrasonic probe attached to a force sensor ATI Mini-40 FT connected to a National Instrument NI DAQ PCI-6221 board and the test tissue phantom. The described plant is considered as a class of unknown nonlinear discrete-time system. In this work, the inverse kinematics controller of KUKA robot is used, which allow us to control the manipulator by a set of six positioning parameters, that is, three parameters X, Y and Z corresponding to the tool task space configuration cartesian coordinates of the robot, and A, B and C parameters, related to the tool orientation. The proposed controller is designed to provide the control signals u_B and u_C to set the orientation values and the control signal u_Z to set the vertical displacement required to reach and keep a desired contact force of the probe. The measurable parameters of the system are the ultrasonic signal power P, and the applied forces F_x, F_y and F_z, which act as the feedback signals to the proposed controller, designed for discrete time systems with unknown mathematical model.

2.1 Ultrasonic Probe and Tissue Phantom

An ultrasonic contact probe was built with a 10 MHz ultrasonic transducer and a semi-spherical soft head made of elastomer material and filled with water. The probe is attached to a force sensor and adapted to the robotic manipulator. The acquisition of US data was implemented using a USB communication with a Tektronix DPO 3012 oscilloscope. We used a workstation (Intel (R) CPU @2.67 GHz) that performs all the control law computation and communication with the robot from MATLAB R2018a platform.

According to the modality, certain physical properties are of critical importance when constructing a tissue-mimicking phantom. In the case of US inspection, important phantom properties are the material's speed of sound, acoustic attenuation coefficient, and acoustic backscatter coefficient. In soft tissue, the average speed of sound is 1540 m/s [4]. In this work, a tissue mimicking phantom was built based on [5] and [6] works, by combining type-A, 300-Bloom gelatin derived

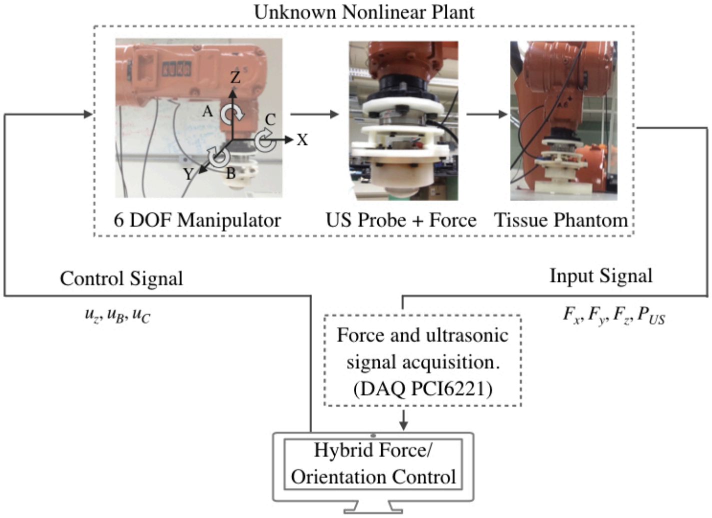

FIGURE 1: Ultrasonic Robot-Assisted System Scheme.

from acid-cured porcine skin (G2500, Sigma-Aldrich Corp.) with ultrapure deionized water. The gelatin was contained on a petri box of $95mm$ of diameter and $15mm$ of high. At this first stage, the sample is an homogeneous material without any discontinuity inside. Thus, the ultrasonic echo to be analyzed is the one coming from the soft material interface.

2.2 Force and Orientation Control Algorithm

The force control algorithm is intended to reach and keep a desired contact force that allows US signal measurements and prevent damage to the soft material. The force exerted in Z axis F_z is the only monitored parameter to control the force contact by using the conventional version of an adaptive Fuzzy Rule Emulated Network (FREN) structure. The force contact is controlled by minimizing the error between the desired contact force and the current force measurement.

The orientation control algorithm is intended to reach the normal position of an US probe over a test surface from whatever initial position. By knowing that the maximum ultrasonic power (P) value, estimated in equation (1), can be achieved at the normal position of the probe with respect to the object surface, the algorithm is designed as a modified version of FREN that seeks the maximum power value of the gathered signals The initial positive or negative values of the forces F_x and F_y are considered to determine the initial direction for the control parameters.

$$P = \lim_{N\to\infty} \left(\frac{1}{2N+1} \sum_{n=-N}^{N} |x(n)|^2\right), \qquad (1)$$

where $x(n)$ is the amplitude value in volts $[V]$ and N is the number of points that conform the acquired signal. The distribution of energy around the central axis of the probe is expected to be symmetric following a Gaussian distribution (see figure 3), where the maximum value is located at the normal position relative to the tangent of the surface and decreasing monotonically as a function of the orientation parameters B and C.

2.3 Fuzzy-Rule Emulated Network Structure

The architecture of a conventional FREN is illustrated in figure 2. A characteristic of FREN is that human knowledge regarding to the controlled plant can be generalized within IF-THEN rules. Here is given a brief description of FREN's architecture, for a detailed and implemented version see [7]. FREN is composed by four layers:

Layer 1: The error measurement $e(k)$ is the input of this layer which is sent to each node in the next layer directly. Thus, there is no computation in this layer.

Layer 2: This is called input membership function layer. Each node in this layer contains a membership function corresponding to one linguistic variable (e.g. negative, positive, zero, etc.). The output at the ith node of this layer is calculated by

$$f(k) = \mu_i(e(k)), \qquad (2)$$

where μ_i denotes the membership function at the ith node ($i = 1,2,...,N$).

Layer 3: This layer may be considered as a defuzzification step. It is called the linear consequence (LC) layer, where the initial parameters β_i are intuitively selected and conventionally, by the steepest descendent technique can be adaptive at each iteration.

Layer 4: This is the output of the artificial neural network and is calculated as:

$$o(k) = \sum_{i=1}^{N} \beta_i \cdot \mu_i(e(k) \qquad (3)$$

where N represents the number of linguistic variables.

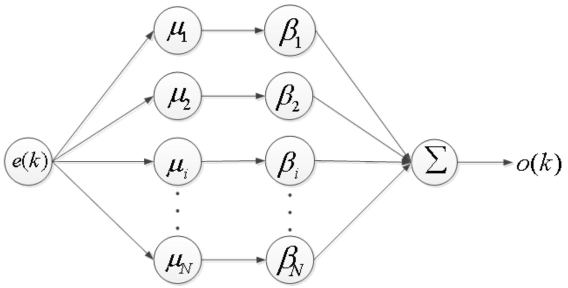

FIGURE 2: Fuzzy-Rule Emulated Network (FREN) Structure.

3. RESULTS AND DISCUSSION

3.1 Numerical Analysis

The numerical analysis is developed to test the proposed orientation controller based on neural networks, considering the observed power distributions as function for the control. It was applied for one dimension and two dimensions cases. Both simulations reaches the maximum value in the first iterations as shown in figure 3.

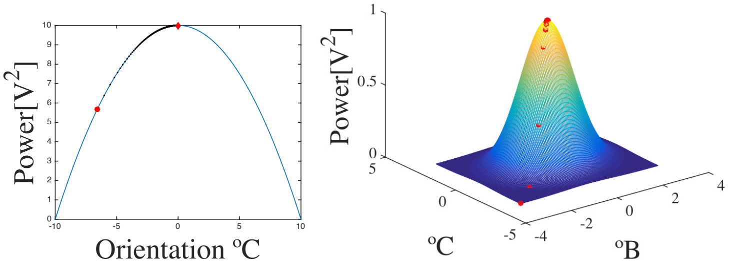

FIGURE 3: Numerical results for 1D and 2D simulations.

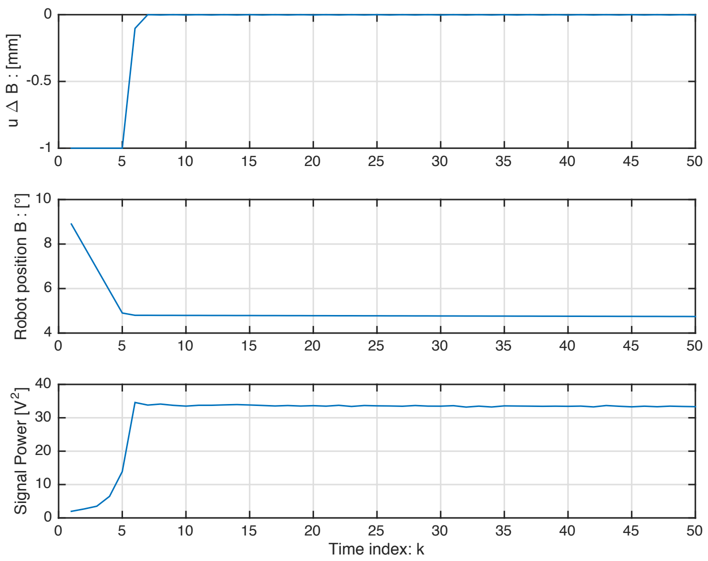

FIGURE 4: Experimental results for ºB control parameter.

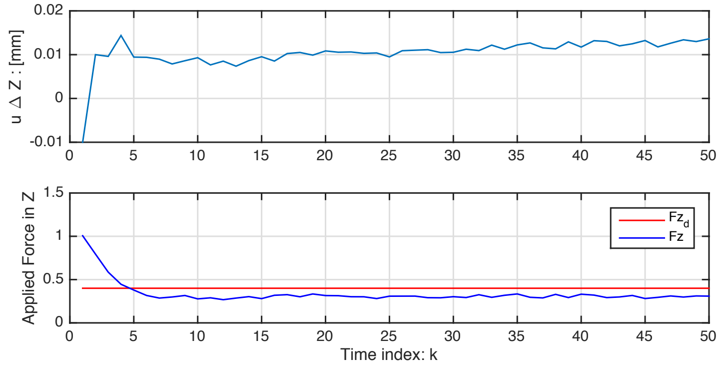

FIGURE 5: Experimental results for applied contact force in Z.

3.2 Experimental Results

Testing was carried out in the plant described in section 2. The objective of this experiment is to verify the performance of the proposed system in reaching the normal orientation of the ultrasonic probe when interacting with the soft material for US inspection tasks. The monitored parameters are the positive ultrasonic signal power and the exerted contact forces. Here are presented the results for 2D controller, where the two orientation parameters B and C were controlled to reach the normal position of the ultrasonic probe on the sample having a flat surface and the contact force was monitored and controlled to keep the desired contact force under a set threshold. Ultrasonic signals acquired at different orientations can be seen in figure 6. In figure 4, the control signal u_B in mm, the robot orientation in ºB and the signal power $[V^2]$ value from experimental results are shown. The control signal is stabilized at zero, once the maximum power values has been, indicating the normal position of the robot over the soft material. The normal position for the robot tool is at 4.9º in B and at 180º in C due to inherent robot configuration and calibration. In figure 5, the contact force behavior is shown. It was set a threshold of 0.4N to avoid damage in the soft material. The control signal sends the displacement required to maintain a contact force lower than the threshold after the normal position was reached.

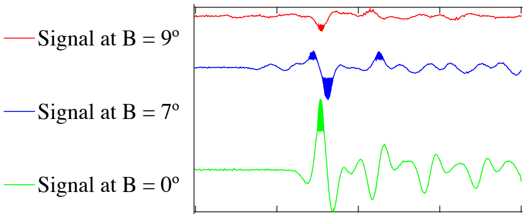

FIGURE 6: Acquired signals at different orientations.

4. CONCLUSION

In this work, a novel adaptive hybrid force/position control of an ultrasonic soft contact probe based on a neuro-fuzzy network controller has been presented. The proposed control, was implemented to control the orientation of a soft probe over a soft material to reach the normal position with respect to the surface of the sample. The exerted forces at the contact interface and the ultrasonic signal power were used as inputs for the proposed controller, which generates the three control signals, two for B and C robotic parameters to change the orientation and one for Z axis in order to keep a fixed contact force. The main importance of this work is its future applicability in autonomous ultrasonic inspection of soft materials, overcoming the prominent challenges for robotic-assisted inspection between soft materials, like the presence of multiple contact points, deformation of both materials and the possibility of damage occurrence due to high applied loads.

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