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Vibrational Feedback for a Teleoperated Continuum Robot with Non-contact Endoscope Localization

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Abstract: Limited or absent haptic feedback is reported as a factor hindering the continued adoption of surgical robots. This article presents a proof of concept for vibrotactile feedback integrated into a continuum robot to explore whether such feedback improves spatial perception in surgical settings. The robot is equipped with a capacitive sensor for non-contact endoscope localization, enabling spatial awareness of the robot's tool center point (TCP) within the surgical environment. The data from the sensor is processed and transmitted to a bracelet worn by the user, which generates vibrotactile feedback. The bracelet contains four vibration motors providing tactile cues for navigation and positioning of the robot's TCP. All subsystems are integrated into a unified system to deliver vibrotactile feedback to the user. When the user maneuvers the TCP of the robot near an object, they receive vibrotactile feedback via the bracelet. Thereby, the intensity of vibration increases as the TCP approaches the object, and the direction of the obstacle is mapped on the bracelet. Initial functional tests were performed and prove the functionality of the proposed system.

Keywords: vibrotactile feedback, continuum robot, capacitive sensor, minimally invasive, surgical instruments

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Fig. 1: A user controls the continuum robot (a) utilizing its capacitive proximity sensor (b) positioned at the TCP, while receiving vibrational feedback via the bracelet (c) placed on the upper arm.

1 Introduction

The integration of haptic feedback systems in surgical robots can enhance the users's perception to increase accuracy and safety in surgical tasks [1]. Various haptic feedback systems have been developed for robot-assisted surgery. Vibrotactile feedback, a specific type of haptic feedback, has demonstrated its ability to enhance task performance in various applications [2]. Schoonmaker et al. [2] proposed vibrotactile force feedback for minimally invasive surgery. They showed that vibrotactile force feedback can improve the perception of force, e.g., to recognize physical tissue characteristics, such as softness.

Most research in the field of feedback systems for robotic surgery focuses on where the robot is in direct contact with the tissue, i.e., force or contact sensing. Navigation through cavities, where unintended contact with the tissue is to be avoided, motivates the need for feedback systems with non-contact localization. This comes into play in surgical procedures where visual feedback alone is not sufficient. Research indicates that haptic feedback improves the performance of surgeons across diverse applications, such as microneedle positioning, telerobotic catheter insertion, suturing simulation, cardiothoracic procedures, and cell injection [10]. Vibrational feedback via a waist belt [3, 4] and tactile feedback via a bracelet has been shown to be effective for navigation tasks [5, 9, 11].

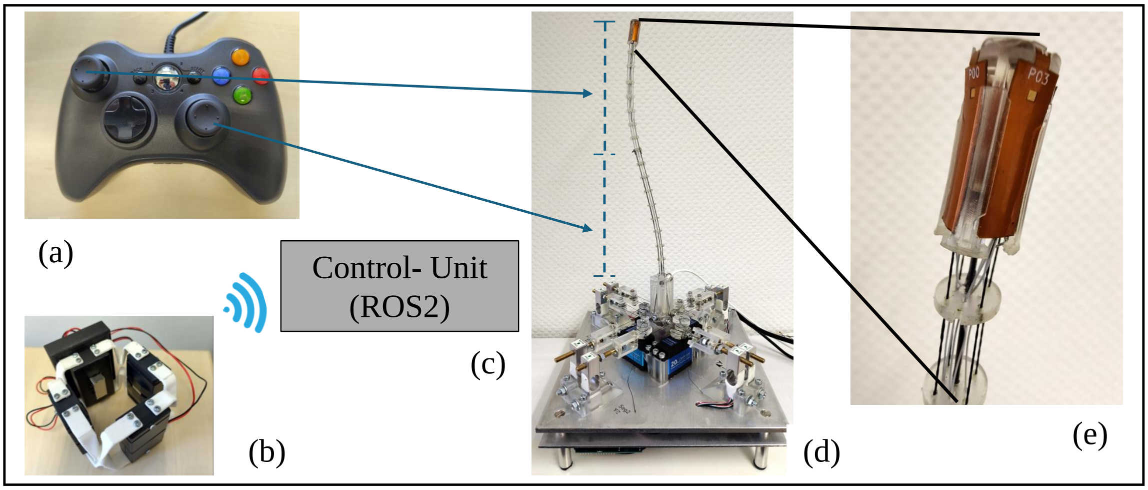

Fig. 2: This figure shows the overall setup with the continuum robot (d), the capacitive proximity sensor (e) placed on the robot's TCP, the Xbox 360 controller (a) with two joysticks to control the upper and lower segments of the robot individually. The bracelet (b) provides the vibrational feedback and communicates via WIFI with the control unit (c), that combines all subsystems running on ROS2.

The results of the studies mentioned above suggest that vibrotactile feedback can improve spatial perception in robot-assisted minimally invasive surgery. To enable the possibility of assessing this hypothesis, this paper provides a proof of concept of a vibrotactile feedback system for a continuum robot that is designed for medical applications in the field of laparoscopic or gastroenterologic interventions.

The following section outlines the integration of subsystems. In section three initial functional tests are described, while section four presents a discussion and a conclusion and outlines future perspectives.

2 Implementation of Vibrotactile Feedback

This section describes the individual subsystems and their integration. The overall system consists of the following three subsystems: continuum robot, capacitive proximity sensor, and vibrotactile bracelet.

2.1 Continuum Robot

The robot, shown in Figure 2 (d), is a 4 degree of freedom tendon-driven continuum robot with two segments developed and proposed by Marzi et al. [6]. Each segment is actuated via two antagonistic tendon pairs. Whereby four servo motors drive the tendon pairs and are commanded by pulse width modulation. This approach makes the robot flexible. Controlled flexible tools and robots offer considerable advantages through enhanced agility, expanded operational range, and the ability to navigate around obstacles, resulting in notable benefits. The robot is controlled by the user using an Xbox 360 controller (Microsoft Corporation, USA). Each aforementioned segment can be activated individually via two joysticks implemented in the controller. In this process, the robot is moved to a desired position using forward kinematics, where the position of each joint is predetermined. The robot was designed for research purposes targeting surgical robot applications such as minimally invasive robotic interventions.

2.2 Capacitive Proximity Sensor

For the non-contact localization of the robot's TCP, a capacitive proximity sensor is used, which is depicted in Figure 2 (e). It was designed by Marzi et al. [7] and is based on a capacitive sensing method presented by Alagi et al. [12]. A capacitive proximity sensor operates by assessing the electrical field interaction between sensing electrodes and an object, which is quantified through capacitance measurement. The higher the interaction, i.e. the closer an object is to the electrode or the greater the surface area overlap between the electrode and an object, the higher the capacitance. Each electrode can reliably detect distances of approximately 30 mm or less. The sensor was originally developed to provide spatial data from a flexible endoscope.

2.3 Vibrotactile Bracelet

The vibrotactile bracelet provides the user with feedback on the robot's surroundings. The bracelet is depicted in Figure 2 (b). It is equipped with four linear resonant actuators (LRA) and can be expanded modularly to up to five LRAs. The LRAs can modulate vibration intensity by changing the amplitude rather than frequency. The operating frequency of the used LRAs is approximately 160 Hz, which is within the range of highest sensitivity of the mechanoreceptors on the skin that is between 150-300 Hz [8]. The particular type of LRA incorporated is the VL91022-160-320H (Vybronics Inc, New York, United States).

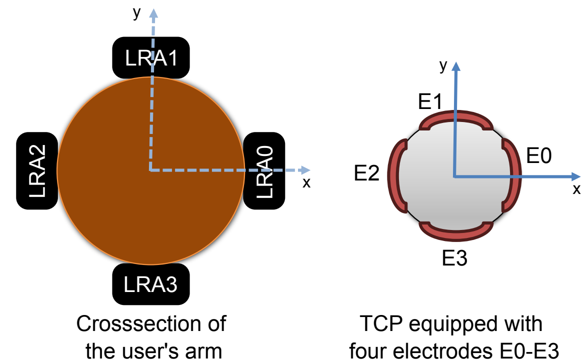

Fig. 3: The LRAs (LRA0-LRA3), which are attached to the user's upper arm (left), vibrate according to the measured distance of the electrodes (E0-E3) between TCP and obstacle (right). The numbering indicates corresponding directions and the dotted coordinate system the perceived directions.

2.4 Integration of Subsystems

The communication between the subsystems relies on the Robot Operating System 2 (ROS2) (see Figure 2). The capacitive proximity sensor consists of four electrodes that detect the approach of objects from four directions, positive and negative in X and Y directions of the TCP respectively. The sensor outputs a unitless 16 Bit value , which correlates to the measured capacitance. The implementation of vibrotactile feedback is as follows: The closer the TCP approaches an object, the stronger the corresponding LRA vibrates linearly. Four LRAs of the bracelet vibrate independently of each other, depending on which electrode detects proximity to an object. The orientation of the bracelet with respect to the TCP is depicted in Figure 3. The signals of the proximity sensor are processed to vibration intensity levels and sent to the haptic feedback bracelet to actuate the corresponding LRA. Since the direction to the measured capacitance behaves reciprocally, while the intensity of vibration is intended to vary linearly with proximity, a linearization around an operating point was implemented. The LRA takes a unitless value in a range of 128 - 255, which correlates with the vibrational intensity. The diagram in Figure 4 depicts the corresponding curves. The optimal reference point, which best represents the measured distance as vibrational intensity, was determined experimentally. Further adjustments are made to align the range of the outputs of the sensor with the input range of the LRAs. The overall system with its subcomponents is depicted in Figure 1.

3 Initial functional tests

Initial functional tests were conducted to validate system functionality. During these tests, a user manipulated the robot while nearing an obstacle with the TCP as shown in the pictures (a) and (b) of Figure 4. The blue curve in the diagram in Figure 4 shows the measured distance of the sensor to the object over time. Before ∼2.5 seconds, the TCP has a distance over 30 mm to the object (depicted in picture (a) of Figure 4), which results in measured values of ∼1300 of the corresponding electrode. After ∼2.5 seconds, the TCP approaches the object, as shown in picture (b) of Figure 4, which leads to an increase in the sensors' data to ∼1700. Due to the reciprocal behavior mentioned above, the increase is relatively steep. The approaching of the TCP to the object causes vibration feedback on the user's arm through the corresponding LRA. The values for the LRA resulting from the measured distance are shown in the red curve. Before ∼2.5 seconds, the values are ∼128, which corresponds to no vibration. After the approach (after ∼2.5 seconds), the values rise to ∼180, which is due to the reduction in the measured distance. The increase in the red curve at ∼2.5 seconds is linear due to the above-mentioned linearization. During the tests, the user approached the robot's TCP to various objects from different directions. During this process, the user not only relied on visual feedback but also paid attention to vibrational feedback. They noted an increase in intensity, as well as variations in direction.

4 Discussion and Conclusion

The subsystems continuum robot, capacitive proximity sensor and vibration bracelet were integrated into a unified system to deliver vibrotactile feedback to the user. As intended, the vibration intensity increases linearly depending on the measured distance, and the direction of an object approaching the TCP can be perceived via the bracelet. The proposed system offers a proof of concept for human-machine interaction within the domain of surgical robotics. It provides the possibility to

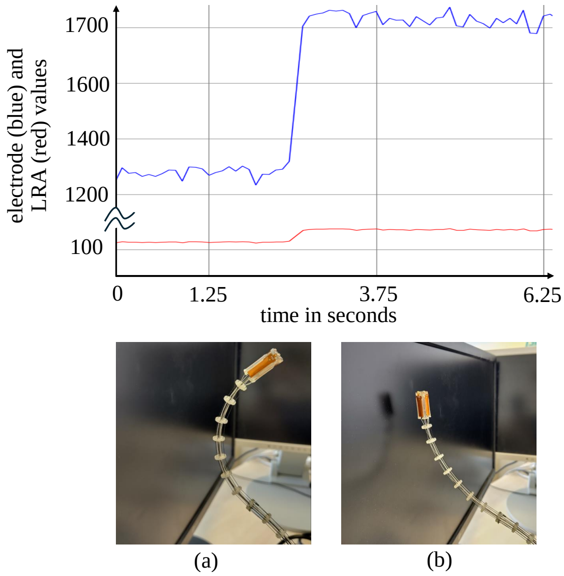

Fig. 4: The diagram shows the plotted values of one electrode in blue and the corresponding LRA values in red over time. Below the corresponding position of the TCP is depicted (from (a) to (b) the distance to the object decreases). Approaching the object results in a steep increase of the sensor curve and a linear increase of the LRA curve.

asses whether vibrotactile feedback enhances spatial comprehension of the user during surgical procedures and thereby enhancing safety, reliability, and intuitive operation. However, challenges remain, to enable a more intuitive human-machine communication. The current system exhibits a noticeable latency between the proximity of an object and the ensuing vibratory response. This inhibits the intuitive control of the robot, which is crucial for executing tasks in robotic surgery. Additionally, it remains uncertain whether the optimal placement for the bracelet's feedback is on the upper or lower arm. Furthermore, the used bracelet only represents the X-Y plane of the robot's TCP, and neglects the Z-direction. In scenarios where the TCP assumes a vertical orientation relative to the X-Y plane or the TCP rotates and encounters an obstacle, additional cognitive load is imposed on the user to correlate the perceived vibrations with the TCP's position and the nearby obstacle. Controlling the robot using two joysticks for each segment requires training and a comparable high cognitive load to position the TCP as desired.

In future iterations, there is potential to leverage distance sensing from the four electrodes to control all five LRAs, thus harnessing Phantom Tactile Sensation benefits as proposed by Seiler et al. [8]. They showed that two closely spaced actuators on the skin produce vibrations which are perceived as one single vibration in-between, allowing 32 cues to be distinguished. Investigating various input devices in future research by assessing user load could yield valuable insights. In a next step the applicability of the system within hollow cavities or tissues is planned to investigate.. Further tests and experiments are necessary to explore whether this system is suitable for use in minimally invasive surgery and whether it enhances safety, reliability, and a more intuitive human-machine communication. The proposed setup enables studies to thoroughly investigate the applicability and benefit of vibrotactile feedback for the control of robotic surgery system with proximity/localization sensing and thus to investigate possibilities to improve robot-assisted surgery.

Author Statement

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