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Towards a real-time control of robotic ultrasound using haptic force feedback

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Abstract: Ultrasound is a widely used imaging technique and is appreciated for its non-invasiveness, absence of radiation, widespread availability, and compact equipment. Ergonomic difficulties in manual handling of the probe could be enhanced by a robotic controlled ultrasound. The paper addresses the development of such a system which enables remote operation of a ultrasound probe and includes haptic force feedback as well as video conferencing components for visual feedback. The development process followed a user-centered approach by investigating needs of potential end-users. Preliminary results demonstrated the functionality of the developed system for generating medical image data under laboratory conditions.

Keywords: human-robot interaction, robotic ultrasound, tele-operation, medical robotics

1 Introduction

Robotics are increasingly present in clinical routine. Among hospital, care and assistive robots, tele-operated robotic systems are experiencing tremendous growth. These robots are controlled across varying distance using wired or wireless connection [1]. To prevent damage to the treated patient, visual as well as haptic feedback provided to the physician are of paramount importance. The combination of ultrasound (US) and robotics enables remote control of a US probe and thereby allows for the examination of a specific anatomical region of interest. Anatomical areas where recently developed systems have been applied during in vivo evaluations are primarily the heart, abdominal organs, and vascular structures [2]. However, these systems concentrate on application for diagnostic purposes.

The scope of this work covers the description of the development process of a prototypical tele-operated system for medical US. The development process follows a user-centered approach by investigating needs of end-users. The system incorporates features of a 6 degrees of freedom (DOF) control of a robotic US probe, haptic force feedback and video conferencing components provided to the user. Moreover, graphical user interfaces (GUIs) were developed to make the system more user-friendly. The resulting prototype was evaluated under laboratory conditions using a phantom.

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1.1 Motivation

Both patients and physicians can benefit from a tele-operated US system. Due to the remote system control, no physical presence of the physician is required at the examination site, reducing costs for potential travel. This is especially relevant for patients living in isolated areas with limited access to medical facilities and experts. The usage of such systems could also be useful in the examination of patients with infectious diseases . Moreover, the physical strain on physicians involved in manual handling of the US probe [4] could be reduced, improving ergonomics while taking advantage of the benefits of the robot.

1.2 Related Work

Recent systems for robotic US developed in research are presented in a review paper by Haxthausen et al. [2]. The system of Tsumura et al. [3] proposes a tele-operated lung US system that comprises a 3-DOF gantry style positioning unit and a joystick gaming controller. Three cameras and monitors displaying the US image provide visual feedback to the physician. However, this system lacks haptic force feedback. Another work by Sandoval et al. [4] enables haptic feedback via a 6-DOF input device but does not include video conferencing components. Modulation of the contact force of a robotic US probe for abdominal organ examination was implemented by Raina et al. [5] using a slider on a GUI. Giuliani et al. [6] followed a user-centered approach and involved physicians throughout the development phase of a remotely controlled robot for echocardiography examinations. Feedback was given on the user interface and the hardware used and was incorporated into the further development process. The system we developed addresses the shortcomings of the systems described and additionally incorporates a user-centered development process.

Clinically tested tele-US systems worth mentioning are *MELODY* (Société AdEchoTech, Naveil, France), *MGIUS-R3* (MGI Tech Co., Shenzhen, China), *Medirob Tele* (Medirob AB, Skelleftea, Sweden) and *ROSE* (Sensing Future, University of Coimbra and the Instituto Pedro Nunes, Portugal). All systems comprise a robot with at least 3-DOF and an input device that enables haptic feedback.

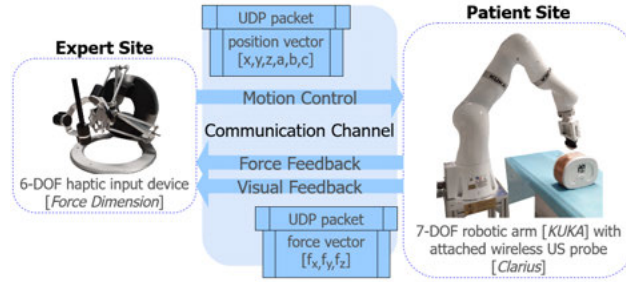

Fig. 1: System setup of the tele-US system depicting the used hardware at the expert and patient site as well as the communication of required data.

2 Methodology

The methods of this project include a requirement analysis. Results of this analysis contributed to the specification of requirements for the prototype setup of the robotic system. A bilateral tele-operated system between a robot and an input device was developed in order to enable the transmission of position and force data in real-time. To enable a user-friendly control, GUIs were devised.

2.1 Requirement Analysis

The application of a user-centered approach requires exploration of the needs of potential end users. Therefore, an online survey was created and distributed among radiologists of the Magdeburg university hospital. The survey included 16 questions in three categories:

1. Use-case Specification
2. General System Requirements
3. Personal Information

The questions in the first category were aimed at determining conceivable use-cases of a tele-operated US system. Another objective of this category was to specify the potential anatomical structures to be scanned. The second category was intended to collect information on general system requirements, which should provide information about the degree of importance of the following aspects:

- haptic force feedback
- a videostream showing the entire patient / anatomical region of interest / body parts outside the anatomical region of interest
- a videostram showing 360° of the patient site
- control of the camera angle
- audio stream for communication with the patient
- full control of the US probe

In addition, the second category included questions about the preferred shape of the input device and the number of video monitors at the expert site.

Questions from the third category had the purpose of assessing the participants' level of practical experience in performing US and their current professional position.

2.2 Bilateral Teleoperative System

The developed robotic US system consists of a patient side that includes a 7-DOF robotic arm of type *KUKA LBR iiwa 14 R820* and a wireless *Clarius US scanner HD C3* which is attached to the robot flange with a custom-designed adapter. The robotic arm is controlled by a user who is located at the expert site. This in turn includes the 6-DOF haptic input device *Omega.6* by the company *Force Dimension* (see Fig. 1).

2.2.1 System Setup

Two control units are used at each site of the system. At the patient site, the supplied control unit of the KUKA robot is used. Both sites communicate via direct ethernet connection using a user datagram protocol (UDP) as communication protocol in order to meet the real time requirements. For this reason, the operation of the robotic US can only be realized at close proximity to the expert site.
A UDP packet with position (x,y,z) and orientation (a,b,c) parameters of the input device is transmitted to the robot controller, whereas the UDP packet containing the force vector (f_x, f_y, f_z) is transferred in the opposite direction (see Fig. 1).
To align the spatial movement directions and to ensure ease of use, an intutitive transformation between the coordinate frame of the input device and the coordinate frame of the robot base was calculated. . The Cartesian position data which is sent to the robot contains position parameters in meters and rotational parameters in radians.
The initial position of the US probe is specified in the application data of the robot program. The communication between the hardware of the expert and patient site starts after the US

probe moves to this initial position, which was specified as a position a few centimeters above the surface to be scanned. Position commands which are send to the the robot refer to this initial position.

2.2.2 Motion Control & Haptic Feedback

To enable motion control, the supplied *KUKA* software *Sunrise.Servoing* was used for the processing of external sensor data provided by the input device. A motion scaling was implemented that maps the translational movement of the input device with a scaling factor of 1 to the robot movement and the rotational movement with a scaling factor of 0.5, meaning that the rotation is executed on the robot with halved values. The resulting rotational workspace is sufficient for the usage of the US probe. By applying the motion scaling, the accuracy of the motion control is increased.
Force control within the tele-operated system is of crucial importance on one hand due to the influence on the diagnostic outcome, and on the other hand due to the potential danger of harming the patient. As the robot is able to detect acting forces on its end-effector due to joint torque sensors, external forces at the tip of the US probe can be estimated. However, these force values, cannot be used directly by the *Omega.6* actuators to provide adequate translational haptic feedback because the device can only provide feedback on forces up to 12 N. In addition, there exist safety concerns when high forces are applied to surfaces and specifically patients. For this reason, the received forces are scaled down using a force mapping function according to:

$$F_{omega} = \begin{cases} 0 & \text{if } F_{robot} < F_{min} \\ K * (F_{robot} - F_{min}) & \text{otherwise} \end{cases} \quad (1)$$

The values of K and F_{min} define a scale coefficient and a force threshold, respectively. F_{min} is required in order to cope with measurement errors of the robot, such as non-zero values in case of collision-free movements. A simple thresholding approach was chosen to tackle the sensor problem instead of a software filter as proposed by various research works, for the sake of simplicity. However, this approach needs to be improved in the future by a more advanced solution (e.g. Kalman filter).
The values of K and F_{min} were experimentally obtained, which are subjective in nature because they rely on the subjective perception of the forces by the experimenter. A maximum force threshold of 30 N was implemented to prevent phantom damage. This force is below the threshold for safe human-robot collaboration, which was identified using a statistical model that takes into account the shape of the US probe and the body region to which the force is applied [7]. K was selected to map the maximum force of 30 N applied to the robot end-effector to the maximum force of 12 N at the input device.
Gravity compensation of the input device is always active if acting forces on the US probe are zero or rather if the probe it not in contact with a surface.

2.2.3 Graphical User Interfaces

To facilitate customization of the control and visual feedback to the user, two GUIs were created.

2.2.3.1 Control User Interface

The control GUI contains the following features:
- ability of starting/ending the tele-operation
- ability of adjusting control settings like control mode (choice between full control, translation or rotation), haptic feedback (turn on/off), and robot motion velocity (choice between five different levels)
- real-time monitoring of position and orientation of the US probe
- real-time monitoring of contact forces acting on the tip of the US probe
- user manual

Additionally, the presence of a stop button allows the user to end the tele-operation. After selection, the robot is moved to the initial position.

2.2.3.2 Camera View User Interface

Another GUI is provided to the user to facilitate switching between different camera views. The program is capable of detecting video capture devices and display video streams. There are three possible view modes :
- *Mode 1* - camera 1 view (full screen)
- *Mode 2* - camera 2 view (full screen)
- *Mode 3* - shared camera view (half screen each)

Different positions and angles of camera 1 and camera 2 are meant to address the lack of image depth information during tele-operation. By switching between different modes, the individually preferred visual feedback can be chosen by the user. Depending on the camera positions, *Mode 1* can be used for coarse positioning , whereas *Mode 2* can be used for fine positioning. Additionally, a control button enables the user to display the camera settings.

3 Results and Discussion

A total of 5 surveys have been answered by radiologists with practical experiences in conducting US of <1 year (40%) and >3 years (60%). Despite the low response rate, some trends have been detected. In general, the participants characterized a tele-operated US system as a contingent part of telemedicine, especially when examining abdominal anatomies. Respondents stressed the importance of haptic feedback, full control of the US probe (both translational and rotational), two monitors for video streaming from the patient site, low latency, and an input device in the shape of an US probe. On the other hand, the use of a 360-degree camera was not assessed as beneficial. The final system consists of a monitor displaying the live US image and another monitor displaying the video streams of the patient site provided by two RGB cameras. The master control unit runs the GUIs which were described in the previous section.

The system has been tested under laboratory conditions using a tissue mimicking US phantom by *CIRS Inc*. Two users have given qualitative feedback after testing the tele-operation. It was possible to obtain US images of phantom structures by remotely controlling the US probe with the haptic input device. Users reported that force feedback appears to be inaccurate at smaller forces (e.g., when touching a soft tissue surface). However, they rated the system's response as highly dynamic without noticeable delay.

We are aware that our research has limitations. The low response rate to the online survey limits the conclusiveness of the analyzed trends. Therefore, further data collection involving opinions of physicians from other facilities is required. An initial qualitative system assessment has been conducted. However, performance and usability evaluations should follow to ensure stability and transparency of the system and to increase the effectiveness with which the system is used in practice according to its application context. Moreover, an individual risk assessment is required to ensure safe human-robot collaboration. In this context, it would be conceivable to test the system on human volunteers in the future. In extension, it would be worth considering to explore further possibilities of human-robot interaction, e.g. multimodal interaction, as already suggested in a work by Hatscher et al [8].

4 Conclusion

A closed-loop tele-operated robotic US system with haptic force feedback has been designed and implemented. The development stages of the system followed a user-centered approach. Compared to other current robotic tele-US systems in research [3–6], our system has similar or advanced features. The application could enable physicians to perform US examinations without noticeable muscle fatigue, thus improving ergonomic conditions. In the future, further safety features will be added and the system will be evaluated for its performance and usability.

Author Statement

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