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Control software with supporting features to enhance the quality of tactile feedback

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ABSTRACT

Tactile displays are devices for cutaneous stimulation to be integrated in haptic feedback systems e.g. in robot-assisted minimally invasive surgery. In general, there are severely limited in performance due to the necessary small size. In this work, we have developed a control software with the goal to allow simple hardware to present sensible tactile information to the user. For the development and evaluation of the software including various features to improve tactile feedback, a tactile display with twelve servo-driven pins was used. With the pins moving upwards and downwards, height maps can be presented to the user's finger. The feedback system runs at a frequency of 50 Hz which generates the sensation of a fluid movement. The supporting features include a simulation of shear forces which give the user information on the movement direction of the sensor. A smoothing algorithm was implemented to prevent jerky pin movements. High effort was put in the generation of well distinguishable vibration patterns. These serve to enhance the presentation of the height maps or even allow a second layer of information.

In an evaluation series, the control software and the support functions were extensively tested. The users were capable of distinguishing differences in height as low as 0.05 mm or differences in width smaller than the pin spacing. The task to find an invisible object only with the help of different vibration patterns was solved with great success. In a practical test, the users had to pursuit invisible paths standing out from the surroundings for 1 mm and less using the mouse relying only on tactile feedback. The users showed very good performance here with each user finishing every part of the test. This leads to the conclusion that our control software is an appropriate mean to create sensible tactile feedback even with limited hardware.

1. Introduction

Haptic perception is besides sight and hearing the most important sense when it comes to interaction with the environment. It allows humans to execute tasks with their limbs and hands without optical movement control and to identify objects' properties like shape or surface structure by touch. But if direct touch is not possible or limited and delicate interaction is required, artificial haptic feedback comes into play. This applies to scenarios in virtual environments and especially in teleoperation. The concept behind the latter is that humans can control a robot or other devices from a (safe) distance in a master–slave-setup. Such a scenario is of interest e.g. for dismantling of radioactive waste, disarming of explosives or in hostile environments like deep sea or space.

Another field of application for teleoperation that gained interest in the recent decade is laparoscopic or minimally invasive surgery. This operation technique serves to minimize the trauma for the patient by performing surgery via rod-shaped instruments inside the abdomen. The reduced trauma leads to less scarring and to shorter recovery times. Yet, for the surgeon, laparoscopic surgery means higher stress: The movement of the instruments inside the body is scaled and mirrored on the trocar point (the so-called fulcrum-effect), the endoscopic view handicaps the hand-eye coordination as well as depth perception and the non-ergonomic posture during operation leads to faster fatigue [1]. These disadvantages can be overcome with teleoperation systems [2–4], with Intuitive Surgical's da Vinci platform being the only one that is currently used in clinics worldwide [5]. The fulcrum-effect is compensated, the tremor of the surgeon is filtered and the console is ergonomically designed. Additionally, a stereo

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endoscope combined with a 3D-screen allows better perception of depth. Altogether, this leads to higher dexterity and less mental and physical fatigue of the surgeon during operation [6].

One major disadvantage of laparoscopic surgery is the partial loss (or in case of teleoperation complete loss) of haptic feedback. In open surgery, surgeons can manipulate the tissue with their gloved hands. This allows them to search for hard inclusions inside the tissue (e.g. tumors) and find pulsating blood vessels below the surface before cutting the tissue. The instruments (scissors, scalpel, needles for suturing) can be handled intuitively and with appropriate force so that the surgeons can focus on their actual task.

There are different possibilities to compensate the lack of haptic feedback. Heavy training allows to overcome the non-intuitive handling of instruments and helps to get a feel for the impaired vision. Pre-operative imaging technologies (computer tomography, magnetic resonance imaging) help locating the areas to be dissected. Laparoscopic ultrasound has proven to be a good mean to detect differences in mechanical properties which is helpful for intra-operative localization of tumors or blood vessels. However, the outcome highly depends on the surgeon's experience. The ultrasound transducer has to be handled properly in order to have suitable contact with the tissue and needs exact placement and orientation. Furthermore, the surgeon now has to keep track of additional visual information besides the endoscopic image. For these reasons laparoscopic ultrasound is not yet widely used [7] and not considered an optimal solution [8].

Instead of compensating the loss, the more obvious approach is to restore haptic feedback. It has been demonstrated that haptic feedback can enhance performance and counter the cognitive load during laparoscopic surgery [9]. Furthermore, unexperienced surgeons profit from haptic feedback in laparoscopy while learning surgical tasks such as knot tying [10]. During surgery, tactile feedback can help to reduce grasp forces in order to prevent tissue damage [11]. However, the optical feedback of tactile data alone seems to be insufficient, at least in recognition tasks [12]. Furthermore, the haptic perception is very subjective and differs from user to user. This has to be taken into account when it comes to processing of the tactile data.

Current research focuses on very different aspects of haptic feedback [1,6,13]. Haptic feedback systems are challenging because they are mechanically complex. Sensors to record forces or tactile data have to be integrated into instruments without compromising their actual functions but progress has been made in recent years [14,15,11]. Furthermore, input devices with force feedback are already commercially available (e.g. force dimension omega/sigma, Geomagic Phantom). In contrast, devices for cutaneous feedback are still in development. These so called tactile displays stimulate the mechanoreceptors inside the skin, preferably at the finger. The four different types of receptors respond to different stimuli: static, dynamic and shear forces and vibrations in the range of 0.1 to 1 kHz.

Most tactile displays are limited to generate static and dynamic forces and vibrations below 50 Hz. They are constructed as so-called pin-arrays. The pins' heights can be adjusted individually in order to form a specific pattern. They can be operated by motors [16], by dielectric elastomers [17], piezoelectrically [18] or pneumatically [19]. Nevertheless, there are also approaches for tactile feedback via shear forces (location-dependant friction [20] or mechanical skin stretch [21]). Feedback via vibration is already established in mobile devices with touch screens, but in the currently rather low stage of development this is not applicable for surgical input devices.

Another approach are electrotactile displays [22]. They are made of an array of small electrodes which are placed on the skin. An electrical potential between the electrodes induces a small current inside the skin. This current can trigger signals in the nerve fibers of the mechanoreceptors, which gives the user the illusion of touching a real object. The main challenge here is to find and stimulate the proper nerve fibers, as there is a dense network of nerve fibers inside the finger's skin.

Present tactile displays are still a compromise of stimulator density and amplitude, actuation frequency, force and overall size. An ideal tactile display would consist of about 100 stimulators in an area of 2 cm^2, running with a frequency of 500 Hz with an amplitude of up to 2–3 mm. A small overall size of about 2 cm × 2 cm × 2 cm would allow the installation on a haptic input device to combine force and tactile feedback. This is currently not feasible with the low power density of available actuation techniques.

From our literature research, we conclude that the haptic or tactile feedback has to be intuitive for the user to make full use of it. A haptic signal that still has to be interpreted will increase the cognitive load. As the hardware is difficult to improve, the aim of our work is to explore software based possibilities for improving the tactile sensation. Our question was, what kind of stimuli added to pure tactile representation will support the user in tasks such as detection and recognition of objects. We use a tactile display with relatively simple hardware and developed a control software as basis for the supporting features. The software, the ideas behind the supporting features and their realization are presented in detail. Finally, we carried out a user study to evaluate the potential of these features and the performance of the tactile display.

2. Tactile display

The control and the supporting features were developed for the tactile display in Fig. 1. It provides a matrix of 4 × 3 pins made of copper wire in an area of 7 mm × 5 mm (see Fig. 2). The diameter of the pins and the spacing is 1 mm. Each pin is driven by a servo motor (Graupner Digital-Servo DES478BBMG). A servo horn with a length of 7 mm connects the pin to the motor. The rotation of the servo motors is transformed into a linear movement. A parallel movement of all pins can be achieved for an amplitude of 4 mm. We trimmed the amplitude down to 2.7 mm which is sufficient for tactile stimulation. This allows to move the pins downwards so that they do not touch the finger. The use cases are presented in Section 3. The angular resolution of the servo motors is 0.2° which corresponds to a resolution of 0.03 mm in pin height. From the rotational speed of the motors results a linear speed of the pins of 44 mm/s.

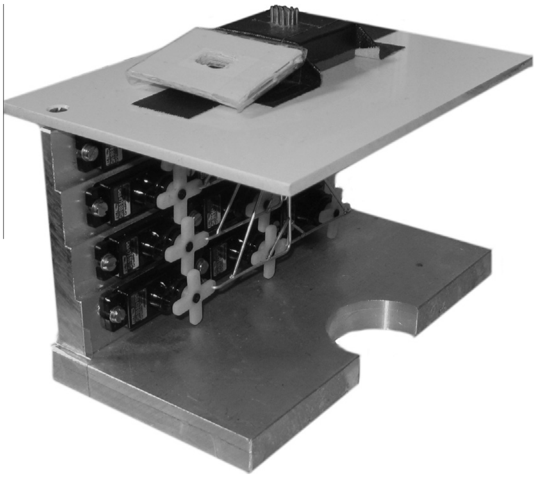

Fig. 1. Prototype of the tactile display.