A Perceptually-Motivated Deadband Compression Approach for Cutaneous Haptic Feedback

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***Abstract*— Data compression techniques enable the transmission of highly informative data using little bandwidth. Examples of popular compression formats are Google's VP9 and MPEG's MP3 for video and audio data, respectively. Recently, researchers focused on the applicability of compression techniques for haptic data too. One of these approaches, called the deadband compression approach, transmits new haptic stimuli to the receiver side only when the user is able to actually perceive the change of the stimulus with respect to the previously transmitted one. However, no deadband compression approach has been presented and evaluated for cutaneous stimuli. In this work we extend the deadband approach to cutaneous haptic data. A force-controlled cutaneous device provides the human operator with cutaneous feedback from a virtual environment. A new cutaneous stimulus is applied at the master side only if the human operator is able to sense the change with respect to the previous one. This perceptual threshold is the just notifiable difference (JND). Results show an average bit rate reduction of 61.7% with no performance degradation.**

I. INTRODUCTION

Cutaneous stimuli are detected by mechanoreceptors in the skin, enabling humans to recognize the local properties of objects such as shape, edges, and texture. Cutaneous perception for exploration and manipulation principally relies on measures of the location, intensity, direction, and timing of contact forces on the fingertips [1], [2]. Cutaneous feedback has recently received great attention in robotic teleoperation, since it has been proven to convey rich information to the human operator while guaranteeing the stability of the teleoperation loop [3], [4], [5], [6], [7], [8]. For example, cutaneous feedback has been successfully used by Pacchierotti et al. [9] to provide force information in a teleoperated needle insertion task. The authors employed a 1-DoF cutaneous device to remotely teleoperate a needle mounted on a robotic manipulator. Cutaneous feedback made the subjects able to successfully complete the task, it outperformed visual substitution of force and made the system intrinsically stable. Meli et al. [5] found cutaneous feedback more effective than sensory substitution via either visual or auditory feedback in a pick-and-place task similar to the da Vinci Skills Simulator's Pegboard task. King et al. [10] used cutaneous feedback in a robot-assisted surgery scenario and evaluated it in a peg transfer tasks with 20 subjects (including 4 surgeons). All subjects used lower force when the cutaneous feedback system was active. van der Putten et al. [11] presented a cylindrical rotating device able to provide cutaneous feedback of slip sensations to the fingertip. To understand the influence of this type of cutaneous feedback on laparoscopic grasp control, the authors carried out a two-handed lifting experiment employing two custom laparoscopic graspers. Subjects who received cutaneous feedback could control their pinch force significantly better than subjects who did not receive cutaneous feedback. McMahan et al. [4] developed a cutaneous system for the Intuitive da Vinci robot that enables a surgeon to feel instrument vibrations in real time. 114 surgeons and non-surgeons tested this system in dry-lab manipulation tasks and expressed a significant preference for the inclusion of cutaneous feedback [12]. More recently, Quek et al. [13] used skin stretch cutaneous feedback for force-feedback substitution and augmentation. Providing skin stretch feedback together with kinesthetic feedback led to higher performance than providing kinesthetic feedback alone. Pacchierotti et al. [14] successfully provided contact deformation and vibrotactile cutaneous feedback to surgeons using a da Vinci Surgical robot. A SynTouch BioTac tactile sensor was mounted to the distal end of a surgical instrument and a custom cutaneous display was attached to the corresponding master controller. The authors tested the proposed approach by having eighteen subjects use the augmented da Vinci robot to palpate a heart model. Cutaneous feedback significantly improved palpation performance with respect to not providing force feedback.

Teleoperated robotic systems are usually composed of a slave robot, which interacts with the remote environment, and a master system, operated by a human. Master and slave systems are often located in the same room/building, such as for the da Vinci Surgical System or the DLR MiroSurge. However, this is not always the case. During the so-called "Lindbergh operation", for example, a team of French surgeons completed a surgical operation from New York to Strasbourg using a Zeus surgical robot [15]. Another notable example of remote teleoperation is the remote control of unmanned aerial vehicles (UAV), such as the Lockheed Martin Indago and Fury, and of unmanned ground vehicles (UGV), such as the Foster-Miller TALON and Spartacus. However, the need for fast and reliable transmission of visual, audio, and haptic data from and to the remote scenario faces several challenges. The use of internet as a mean for this communication has lately gained increasing attention due to its cost-effective and flexible

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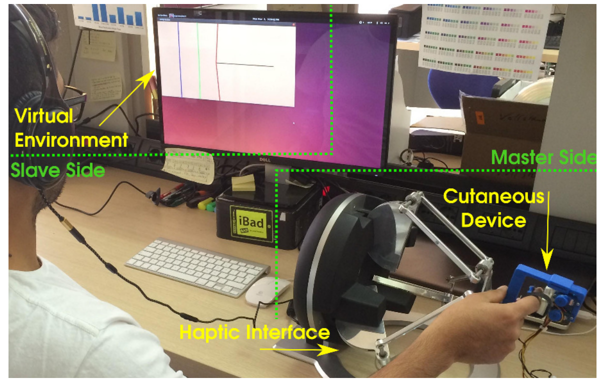
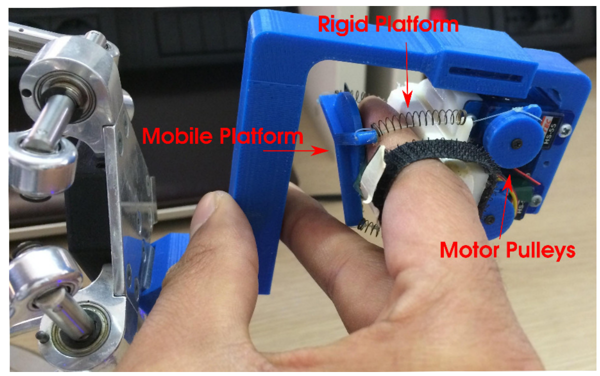
applications [16]. However, this type of digital transmission exchanges data packets through a network characterized by significant variations in time delays and available bandwidth, which are consequences of several factors, such as congestion and distance. Compression of the information flow is one very effective approach to achieve the transmission of highly informative data using little bandwidth. Several compression techniques already exists for the transmission of audio and video streams. In this respect, average bit rate reduction with respect to uncompressed data for current audio and video lossless compression techniques are 60% (FLAC 8 [17]) and 27% (lossless x265 [18]), respectively. On the other hand, average bit rate reduction for current audio and video perceptually-lossless compression techniques are 77% (320 kbps MP3) and 99% (15Mbit/s VP9), respectively.

However, only recently, researchers started to investigate effective ways to compress *haptic* data. One of the most promising techniques is the so-called "deadband transmission approach". The main idea standing behind this approach is that new haptic stimuli needs to be applied at the master side only when the human operator is actually able to sense the change with respect to the ones previously applied. For example, if the system provides the operator with a force of 1N, and the deadband is d = 5%, the next force sample value is only transmitted once it gets either below 0.95 N or above 1.05 N. Any force change in the interval from 0.95 N to 1.05 N is considered undetectable by the human operator and, therefore, it does not need to be transmitted. In the literature, the deadband has been often defined to be the just notifiable difference (JND) of the considered stimulus. If the difference between two consequent stimuli is lower than the registered JND, the second stimulus is not transmitted, saving bandwidth. On the other hand, if the difference between two consequent stimuli is higher than the registered JND, it means that the user is able to perceive the difference between the two, and it will be therefore transmitted. This approach is similar to lossy compression techniques such as the audio coding format MP3, that uses psychoacoustic models to discard or reduce precision of components less audible to human hearing.

Hinterseer et al. [19], [20] presented a deadband transmission approach for a 1-dimensional teleoperation system with kineshetic feedback. This approach reduced packet rates up to 90%, without any perceivable reduction of realism. Hinterseer and Steinbach [21] extended this approach to multi-dimensional teleoperation tasks. Zadeh et al. [22] presented a deadband transmission approach for velocity-based interactions with kinesthetic feedback, in which the human operator or the remote object are in relative motion. Sakr et al. [23] combined two compression approaches. Haptic data packets are not transmitted when they are estimated to be within a predefined tolerable perceptually-motivated error. Otherwise, data packets are compressed prior to transmission using uniform quantization and adaptive Golomb-Rice codes. Kuschel et al. [24] used two passive lossy compression techniques. The first one is based on a passive interpolative compression strategy, while the second one is based on a passive extrapolative compression strategy. This approach



(a) Experimental setup.



(b) Detail of the cutaneous device.

Fig. 1. Experimental setup. It consists of an Omega 3 haptic interface whose end-effector has been replaced by a custom 3-DoF cutaneous device. The user wearing the cutaneous device controls the motion of a virtual needle penetrating three tissues. Force feedback from the virtual environment is provided to the human operator through the cutaneous device. The Omega interface is only used to track the position of the fingers and it does not provide any force.

reduced packet rates up to 89%, without any perceivable reduction of realism. Chaudhari et al. [25] introduced a methodology to model and simulate a networked haptic interaction and objectively evaluated the quality of the experience. Results showed that simulations of these models produce good estimates of carefully performed subjective user studies. Finally, Lee and Payandeh [26] presented a performance evaluation of various haptic compression methods for teleoperation systems with kinesthetic feedback.

In this work we extend the above mentioned deadband approach to *cutaneous* haptic interaction. A force-controlled cutaneous device provides the human operator with cutaneous feedback coming from a virtual environment. A new cutaneous stimulus is applied at the master side only if the human operator is able to sense the change with respect to the previous one. This perceptual threshold is the just notifiable difference (JND).

Sec. II presents the cutaneous haptic system, Sec. III describe the experimental setip, and Sec. IV describes the cutaneous compression algorithm. Sec. V describes the experiment that we ran to evaluate the presented approach, wherein human subjects are asked to differentiate the stiffness of three virtual tissues. We conclude the article and discuss avenues for future work in Sec. VI.

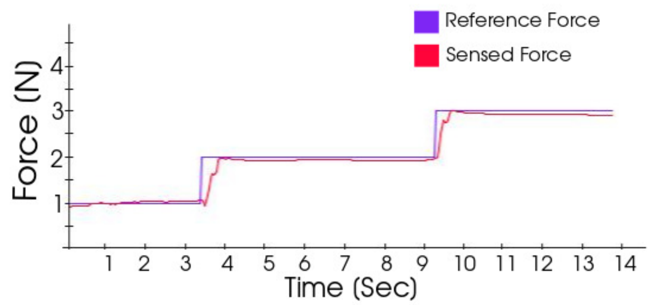


Fig. 2. Response of our cutaneous device to a sudden change of target force. In red it is shown the force sensed by the FSR sensor, while in blue the commanded reference force.

II. Cutaneous Haptic System

Our cutaneous haptic system is composed of an Omega 3 haptic interface (Force Dimension, Switzerland), whose end-effector has been replaced by a custom 3-DoF cutaneous device, as shown in Fig. 1. It is composed of a static body, that houses three servo motors above the user's fingernail, and a mobile platform, that applies the requested stimuli to the fingertip. Three cables connect the static body to the mobile platform, and springs around the cables keep the mobile platform in a reference configuration, away from the fingertip, when not actuated. By controlling the cables length, the motors can orient and translate the mobile platform in three-dimensional space. A piezoresistive force sensor (408, Interlink Electronics Inc., USA) is placed on the mobile platform to measure the force applied by the device on the fingertip. The non-linear relationship between the voltage variation on the sensors and the equivalent applied force was simplified considering a piecewise-linear function. Moreover, a Vernier dynamometer (Vernier, USA) was used to calibrate and verify the output of the sensor. The actuators used in our prototype are PWM-controlled HS55 MicroLite servo motors. The PWM signals are generated by a microcontroller At-mega 328 installed on an Arduino Nano board. The force sensor is interfaced using its analog input channel. The device parts are 3D printed with ABS (Acrylonitrile Butadiene Styrene, ABSPlus, Stratasys, USA) material. The device fastens to the finger with a fabric strap.

In this work the Omega interface is only used to track the position of the cutaneous device and it provides no force feedback to the user. Moreover, although the cutaneous device is able to provide forces in three-dimensional space [27], in this work it is controlled as a 1-DoF system (all motors pulled the cables together), so that only forces in the sagittal plane of the finger were actuated (see Fig. 1b). A similar approach was adopted in [6], [28].

Since the servo motors are controlled in position but we are interested in applying forces, we control the device using a position-based explicit force control [29], [30]. The device adjusts the position of the mobile platform to minimize the error between the force commanded by the deadband control system and the actual force registered by the sensor on the fingertip. If the target force is greater than the sensed force, the controller moves the mobile platform towards the finger. On the other hand, if the target force is lower than the sensed force, the controller moves the mobile platform away from the finger. The device can provide a normal force up to 5 N. Fig. 2 shows the response of our cutaneous device to a step force signal.

III. Experimental Setup

The experimental setup consists of a human operator controlling the cutaneous haptic system to interact with a virtual environment, as shown in Fig. 1a. The virtual environment consists of a needle, whose position is fixed to the position of the Omega end-effector, and three soft tissues (see Fig. 3). As mentioned before, the force feedback from the virtual environment is provided to the user only through the cutaneous device, while the Omega interface is only used to track the position of the fingertip.

A spring is used to model the contact force F_t between the needle and each tissue. As for the haptic rendering, the interaction is designed according to the god-object model [31] and the position of the Omega handle is linked to the needle position moving in the virtual environment. The tissue position changes according to the interaction with the needle, which is able to penetrate the surface only when the exerted force F_h is larger than a predetermined threshold F_p.

It is thus possible to discriminate three different operating conditions for the needle-tissue interaction model:

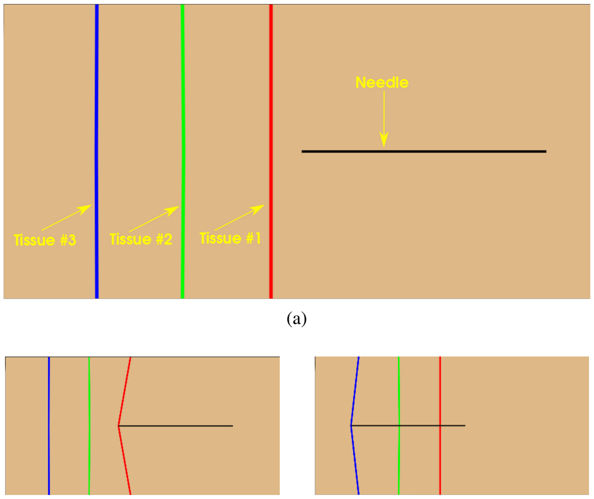
- no contact,
- contact without penetration,
- penetration.

In the first case, since the needle is out of the tissue, the model is designed to feed back no force to the operator and the surface of the tissue tends to return to its predetermined initial position. When the needle touches the tissue, but the force F_h is not yet sufficient to penetrate it, the tissue surface is deformed by the movement of the needle (as in Figs. 3b and 3c). As soon as $F_h > F_p$, the needle penetrates the surface.

The force thresholds of the three tissues are always different from each other and randomly set to one of these values: 2.0 N, 3.5 N, or 5.0 N. The stiffness of each tissue (K_{red}, K_{green}, and K_{blue}) is then chosen such that the tissue always breaches at half the distance from the next tissue. In this way subjects cannot infer the stiffness of a tissue from its displacement.

IV. Compression Algorithm

The proposed deadband compression algorithm is designed to send only the perceptually significant bits to the cutaneous device. At each sampling interval, the system checks if the next stimulus to be transmitted is different enough from the previous one to be perceived by the user. This perceptual threshold is the just notifiable difference (JND). This differential threshold can be defined as "the smallest amount of stimulus change necessary to achieve some criterion level of performance in a discrimination task" [32].



(a)

(b) (c)

Fig. 3. Virtual environment. (a) The needle is shown at its home position while the three tissues with different stiffness in red, green, and blue color are visible. (b) The needle is interacting with the red tissue and the operator can feel the deformation through the force rendered by the cutaneous device. (c) The needle is interacting with the blue tissue.

It gives us information about how different, two displacements provided with our device need to be in order to render a force perceived as different by the human user. The JND also reflects the fact that people are usually more sensitive to changes in weak stimuli than they are to similar changes in stronger or more intense stimuli. The German physician Ernst Heinrich Weber proposed the simple proportional law JND = kI, suggesting that the differential threshold increases with increasing the stimulus intensity I. Constant k is thus referred to as "Weber's fraction".

We used the ascending method of limits to find out the JND for cutaneous force applied normally to the fingertip [32]. Each participant repeated this perceptual experiment 5 times. Once we found the JND for reference stimuli 0.5 N, 1 N, and 1.5 N, we evaluated the Weber's fraction k across subjects. Given a cutaneous stimulus being applied to the user, the control system is able to calculate the next perceivable stimulus using the constant k. The compression algorithm is summarized below.

Algorithm 1: Cutaneous deadband compression algorithm

foreach *time step w* **do**
  ΔS = |stimulus(w) - stimulus(q)|,
  if $\Delta S > JND$ **then**
    stimulus(k) is applied to the user,
    q = w,
  else
    no transmission, old stimulus(q) is applied to the user
  end
end

For example, if the system provides the operator with a force of 1 N, and the Weber's fraction is k = 0.1, the next force sample value is only transmitted once it gets either below 0.9 N or above 1.1 N. Any force change in the interval from 0.9 N to 1.1 N is below the threshold level, it is therefore considered undetectable by the human operator, and it is therefore not transmitted. As will be clear from the next section, this approach leads to a great reduction of data exchanged between the master and the virtual environment.

V. EXPERIMENTAL EVALUATION

A. Task Description

Six males and two females took part in the experiments as subjects. They were in good health and all were right handed. No subject was known to have any sensorimotor disorder. Each subject was seated on a chair facing a computer monitor and asked to place his or her right index finger in the cutaneous device, as shown in Fig. 1b. Once the subjects were seated comfortably and secured, they underwent a perceptual experiment to evaluate their JND, as described in Sec. IV. During the test, their right arm and fingers were shielded from view with an opaque piece of black paper. They were also isolated from outside noise by headphones playing white gaussian noise. The JND value we found was used by the compression algorithm as indicated in Sec. IV. The JND values found for each subjects are tabulated below.

Subject	JND [N]	Subject	JND [N]
1	0.05	5	0.05
2	0.04	6	0.06
3	0.06	7	0.05
4	0.05	8	0.04

The experimental task consisted of using the Omega interface to guide the needle into the three tissues, penetrating them one by one. Subjects were then asked to order the three tissues by their stiffness, from the softest to the hardest. Subjects were free to penetrate the tissues as many times as they preferred. Once they communicated the stiffness order to the experimenter, the setup moved to the next trial, in which the tissue stiffnesses were changed randomly, as described in Sec. III. Moreover, during each trial, the system recorded the amount of data exchanged between the virtual environment and the cutaneous device. Subjects repeated the task 10 times.

The experiment was also repeated in four different conditions (40 trials per subject in total), changing the compression ratio:

1) No compression.
2) Compression with perceptual threshold set at JND.
3) Compression with perceptual threshold set at twice the JND.
4) Compression with perceptual threshold set at four times the JND.

B. Results

Fig. 4 shows the data transmitted between the virtual environment and the cutaneous device in the four compression conditions. The data usage has been normalized per penetration across the trials. Results show that setting the

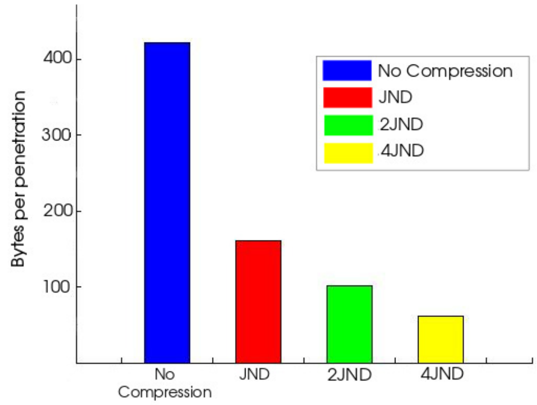


Fig. 4. Bytes exchanged between the virtual environment and the cutaneous device, per penetration and for each modality. We see that by using the deadband compression at the JND level the data usage is reduced by 61.7% with respect to uncompressed data.

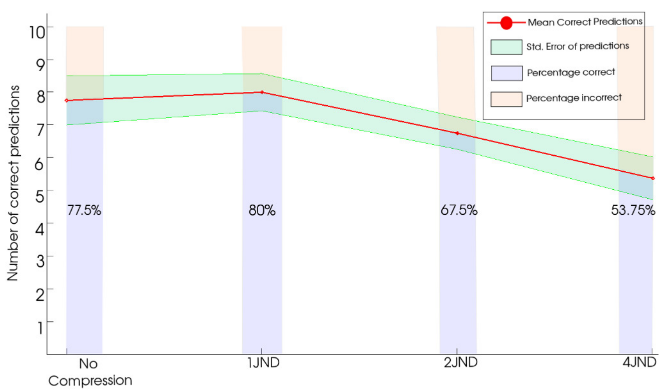


Fig. 5. Experimental evaluation. The deadband compression technique guarantees good performance while saving data. Subjects were able to judge the correct order of stiffnesses 80% of the times as compared to 77.5% of times without compression. On the other hand, compressing the data flow using a threshold higher than the JND, clearly affects the results.

perception threshold at the JND level reduces the data usage by 61.7%. This percentage is, of course, further improved if the threshold is increased. However, compressing the data using a threshold higher than the JND, significantly reduces the performance of the given task. Indeed, Fig. 5 shows how many times subjects were able to correctly order the stiffness of the the three tissues. A bar graph overlay also depict the correct judgments in percentage. The figure also displays the standard error of the mean mean of each results (green patch).

VI. Discussion, Conclusions, and Future Work

Results show that the deadband compression technique holds also for cutaneous haptic data transmission, achieving a data reduction of 61.7% with respect to uncompressed data. The performance achieved while using the JND as perceptual threshold for compression delivered a performance that is comparable to that without any compression. Subjects were able to judge the correct order of stiffnesses 80% of the times as compared to 77.5% of times without compression These measurements recorded a std. error of 5.6% and 7.5% respectively. On the other hand, compressing the data flow using a threshold higher than the JND, clearly affects the results. In fact, when using 2JND as the compression threshold, subjects were able to correctly order the tissue stiffness only 67.5% of the times with a std. error of 4.9%. This performance dropped to 53.75% with a std. error of 6.5% when using 4JND as the compression threshold.

The ease of implementation of this algorithm can be of significant value for cutaneous devices of all types. Cutaneous stimuli is a prime component in wearable and miniature haptic displays for applications of virtual and remote interaction [33], [34]. Lack of computing power in such setting may benefit from such strong data compression.

In the future we expect to further improve the results by trying more sophisticated techniques of finding the JND. We will also perform rigorous statistical analysis tests to determine how far away from the actual value of JND the performance starts to deteriorate exactly. We plan to test these approaches on wearable cutaneous systems.

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