INVITED PAPER

Haptic Codecs for the Tactile Internet

This article presents the fundamentals and state of the art in haptic codec design for the Tactile Internet.

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ABSTRACT | The Tactile Internet will enable users to physically explore remote environments and to make their skills available across distances. An important technological aspect in this context is the acquisition, compression, transmission, and display of haptic information. In this paper, we present the fundamentals and state of the art in haptic codec design for the Tactile Internet. The discussion covers both kinesthetic data reduction and tactile signal compression approaches. We put a special focus on how limitations of the human haptic perception system can be exploited for efficient perceptual coding of kinesthetic and tactile information. Further aspects addressed in this paper are the multiplexing of audio and video with haptic information and the quality evaluation of haptic communication solutions. Finally, we describe the current status of the ongoing IEEE standardization activity P1918.1.1 which has the ambition to standardize the first set of codecs for kinesthetic and tactile information exchange across communication networks.

KEYWORDS | Haptic codecs; haptics; perceptual coding; Tactile Internet

I. INTRODUCTION

Visual and auditory information are predominant in modern multimedia systems. The acquisition, storage, transmission and display of these modalities have reached a quality level which is typically referred to as high-definition (HD) and beyond. For example, high-end video cameras capture ultra-high-definition content, highly efficient video codecs such as H.265/HEVC achieve remarkable compression factors, and high-resolution monitors and virtual reality (VR) head mounted displays (HMDs) enable high-end virtual experiences. Similar HD technology for audio is also available. Technical solutions addressing the sense of touch (also referred to as haptic technology), in contrast, have not yet reached the same level of sophistication.

In the context of the Tactile Internet [1], these solutions, however, will significantly gain in relevance. Enabling remote physical interaction with convincing touch experiences is one of the key technologies that allows motor skills to be available across distances and enables fully immersive multi-sensory remote exploration of real or virtual environments where users can see, hear and, in particular, feel remote objects. For the latter, haptic information needs to be captured, compressed, transmitted and displayed with minimum latency. The compression of haptic information is handled by haptic codecs which is the focus of this paper.

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Haptic data consists of two submodalities, i.e., kinesthetic and tactile information (see Sections II-A and III-A for a detailed description of the characteristics of both of these haptic submodalities). While the compression of kinesthetic information has been studied extensively in the context of bilateral teleoperation systems with kinesthetic feedback (see, e.g., [2]–[8]), the compression of tactile information has received comparatively little attention so far. This is an increasingly active area of research as the focus in machine and computer haptics during recent years has clearly shifted toward the realization of tactile touch experiences [9]. This is not surprising as we humans heavily rely on the tactile modality to interact with objects in our environment. Also, from a technical perspective, the tactile modality has high relevance in many applications. In a VR application, for example, a typical intention of a user is to interact physically with the objects in the virtual scene and to experience their material and surface properties. Many challenges have to be overcome before tactile solutions will reach the same level of sophistication as corresponding HD video or audio solutions. With recent advances in VR, augmented reality (AR), and telepresence, however, the topic is rapidly gaining in relevance and is becoming an enabling technology for novel fields of application, such as E-Commerce with tactile feedback (T-Commerce), telepresence applications like Skype with touch interaction (T-Skype), or touch-augmented VR systems (T-VR).

The main contributions of this paper can be summarized as follows.

- We describe selected use cases and application scenarios for haptic communication. This discussion motivates the development of haptic codecs for the Tactile Internet.
- We present the state of the art in the area of kinesthetic and tactile data compression. In order to make this discussion as accessible as possible, we provide the relevant background in psychophysics and human haptic perception.
- We introduce the kinesthetic codec currently under investigation by the IEEE standardization group P1918.1.1. In this context, we present the reference hardware and software setup used to develop the kinesthetic codec as well as the provided reference data traces. Furthermore, we present the recently completed cross-validation experiments which demonstrate that the selected kinesthetic codec solution shows remarkable data reduction performance.
- We introduce a novel tactile processing pipeline which covers the acquisition of surface material properties, the processing of the acquired sensor signals, the compression of the raw or processed tactile data as well as the presentation of corresponding tactile experiences to the user. The latter takes the interaction pattern of the user into account.
- We present the recently approved hardware and software reference setup for tactile codec development within IEEE P1918.1.1 which consists of a sensorized surface material scanning tool and a voicecoil-based display. In this context we also show example data traces which can be used to evaluate tactile codecs.
- We provide an overview of the available objective quality evaluation measures for kinesthetic information. These objective measures are experimentally evaluated and compared with subjective evaluation results.
- Additionally, we discuss several topics which become relevant in the context of the Tactile Internet, such as the multiplexing of several video, audio, and haptic data streams as well as handshaking mechanisms for session establishment.
- Finally, we present the requirements for haptic codec design identified by IEEE P1918.1.1 as well as the current status of this standardization activity.

This paper is organized as follows. In the remainder of Section I, we further discuss the relevance of haptic communication for the Tactile Internet. Additionally, we present several use cases for the Tactile Internet which require high-fidelity haptic codec solutions. Section II is then dedicated to tactile information and tactile codecs. Section III provides details about kinesthetic information and the state-of-the-art data reduction approaches for this type of data. Section IV addresses the multiplexing of audiovisual information with haptic information. Section V discusses objective and subjective quality evaluation approaches for haptic communication solutions. Section VI summarizes the current status of the ongoing standardization activity IEEE P1918.1.1 *Haptic Codecs for the Tactile Internet*. In Section VII, we conclude the paper.

A. Relevance of Haptic Communication for the Tactile Internet

Emergence of the Tactile Internet [1], which aims at providing ultra-low delay and ultra-high reliability communications, has enabled a paradigm shift from conventional content-oriented communication to control-oriented communication. The Tactile Internet is of particular relevance for the realization of human-in-the-loop applications which are highly delay sensitive and require a tight integration of the communication and control mechanisms [10]. The human-in-the-loop Tactile Internet paves the way for delivering human skills in addition to the human knowledge, remotely, giving life to the Internet of skills [11]. Within this paradigm, human multi-sensory information for interaction and communication with the remote environment needs to be exchanged. To this end, haptic communications, by exchanging kinesthetic and tactile information, provides the platform for the human-in-the-loop Tactile Internet, and the possibility of delivering remote physical experiences globally.

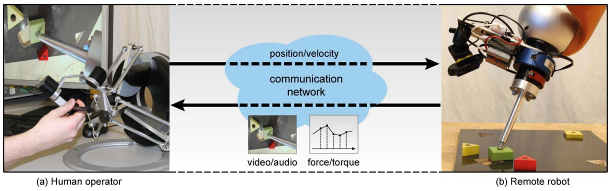

Fig. 1. ***Bilateral teleoperation with kinesthetic feedback. The operator controls the position of the remote robot (teleoperator). Interaction forces are measured during contact and sent back to the operator. Additionally, visual and auditory information is streamed back to the operator.***

B. Use Cases and Application Scenarios

The human haptic perception system processes kinesthetic and tactile stimuli simultaneously. Different sensing mechanisms are responsible for perceiving the two haptic submodalities [12]. Depending on the Tactile Internet use case or application scenario considered, one modality or the other or a combination of both form the input to the haptic codecs. Please note that in haptic technology the two modalities are often considered independently, as different sensing and actuation principles are applied. For a human user, however, both types of information are fused into a joint touch experience. In the following, we discuss selected use cases and application scenarios which rely on either kinesthetic or tactile information exchange. Finally, we will discuss a virtual material showroom as an example where the user benefits from a combination of both modalities.

1) Bilateral Teleoperation With Kinesthetic Feedback: We start with bilateral teleoperation with kinesthetic feedback which is the classical use case for kinesthetic information exchange. We keep this part relatively short as it has been discussed in detail in many other works, e.g., as early as in 1967 by [13], or, later in the context of stabilizing the closed-loop kinesthetic interaction in the presence of communication delay in, e.g., [14] and [15], or more recently in overview papers such as [16] and [17]. Traditional teleoperation scenarios with purely kinesthetic feedback enable the remote control of robots in, e.g., distant or dangerous environments. Fig. 1 illustrates a typical setup where the user is connected to a kinesthetic input/output device and the teleoperator is realized using a robotic arm equipped with force sensors, a video camera, a microphone and an end-effector or tool. Possible use cases are telemaintenance and telesurgery. Although most previous works in teleoperation consider the kinesthetic submodality only, the combination of kinesthetic and tactile feedback promises improved user experience [18], [19]. Besides low-frequency kinesthetic force feedback, high-frequency tactile signals and thermal feedback allow, e.g., for the remote perception of object surface properties [20].

2) E-Commerce With Tactile Feedback: The presentation of object surface properties on touch screens enables novel applications for online-shopping, which we denote as T-Commerce in the following. For example, novel tactile displays [21], [22] as shown in Fig. 2, allow for the display of fine surface roughness information on glass displays. A high-fidelity T-Commerce scenario, however, requires additional effort in the object data acquisition, transmission and display. If we want to provide the user with a high-quality and comprehensive remote touch experience, a complete object representation should be available which includes all relevant kinesthetic and tactile properties. Ideally, the user will not be able to distinguish between locally touching the real object and the provided online experience.

3) Telepresence With Tactile Feedback (T-Skype): Today's telepresence systems (e.g., video conference or video chat) exchange high-quality audio and video among two or more participants. While these systems at least partially fulfill the promise of immersing a user into a remote space and to generate a certain level of presence, they lack the capability to also exchange touch experiences during interaction. If the users are equipped with tactile actuators, tactile feedback experiences (e.g., vibrotactile stimuli) can be provided. This could be, for instance, useful for calming a child by touching her or him gently from a distance during a business trip.

4) Virtual Reality With Kinesthetic and Tactile Feedback: Current VR systems only display visual and audible information to the user. The most intuitive reaction in VR, however, is trying to grasp and interact with objects. A large number of wearable haptic devices have been proposed during recent years to address this issue (see [23] for an extensive survey in this field). As a common problem, these devices generally lack the ability to combine kinesthetic and tactile feedback in a lightweight system. The first nonwearable approaches have been proposed that combine tactile and kinesthetic feedback. For example, Culbertson and Kuchenbecker [24] use the capabilities of a kinesthetic interface (a Phantom Omni device) augmented with a vibromechanical actuator to create selected tactile stimuli (friction, stiffness, and roughness). In [25], they use a solenoid plunger and a rolling stainless steel ball to render different friction forces. Fig. 3 shows the example of a haptic showroom where the user can freely move around and interact with material samples while receiving both kinesthetic and tactile feedback.

Fig. 2. ***Example applications which allow users to experience selected surface properties of offered products on websites using surface haptics displays (left: Tanvas Touch tablet [21], right: TPad Phone [22]).***

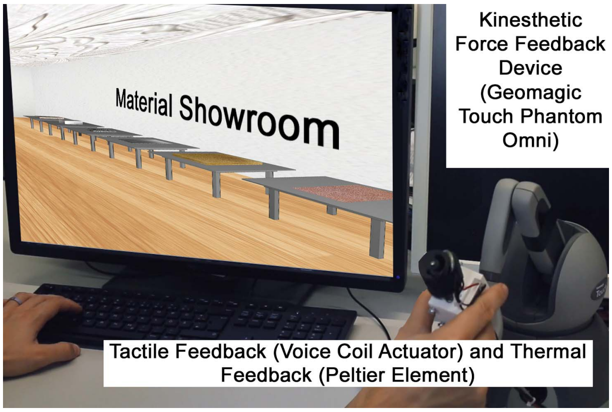

Fig. 3. ***Material Showroom. A user can interact with different material probes and receives kinesthetic and tactile feedback.***

II. TACTILE INFORMATION AND TACTILE CODECS

Besides a solid understanding of human psychophysics, the provision of high-quality tactile experiences in the context of the Tactile Internet requires, in our opinion, three main components: efficient acquisition of tactile object properties, analysis and compression of tactile information, and tactile display technology which ideally can reproduce all relevant tactile dimensions simultaneously. The corresponding tactile pipeline is shown in Fig. 4.

A. Tactile Perception

This section first describes the human tactile perception of object properties. It is followed by approaches to collect and display such tactile information as well as how it can be compressed and transmitted. Table 2, which is adapted from [26] and reproduced from [27], shows the mechanoreceptors that are responsible for human tactile perception of, e.g., fine roughness or friction.

1) Object Identification: The human haptic perception system relies on kinesthetic as well as tactile sensory information in the interaction with objects. Humans typically perform six types of exploration patterns, as described in [28] and [29], to identify unknown objects. During the interaction with objects, enclosure and contour following reveal spatial content about the object shape and its coarse contour properties. Humans lift objects to estimate their weight. Static touch is used to identify the thermal conductance through the bare finger. Pressing on the material reveals information about its stiffness. Finally, arbitrary sliding motions allow for the perception of the fine roughness, also known as haptic texture, and the friction properties of the object surface.

Table 1 Function, Roles and Respective Frequency Range of Four Types of Mechanoreceptors in Human Skin (Reproduced from [27])

	Merkel cell	Ruffini ending	Meissner corpuscle	Pacinian corpuscle
Best stimulus	Pressure (hardness), edges, corner, points	Stretch	Lateral motion	High-frequency vibration
Example use cases	Reading braille	Holding large objects	Sensing slippage of objects (friction)	Sensing haptic texture
Frequency range (Hz)	0 – 100	/	1 – 300	5 – 1,000
Most sensitive frequency (Hz)	5	/	50	200

2) Tactile Dimensions: Based on the evaluation of the adjectives used to describe tactile information in previous studies, the authors in [30] have identified five major tactile dimensions.

a) Friction between a bare finger and a surface forces the human to apply a specific lateral force during sliding motions. Components of friction models [31] commonly are the surface-specific force to break the adhesion with it, or, the required traction to slide the bare finger [32] [33].
b) Hardness perception results from specific exploration patterns such as tapping on an object surface, pinching an object, or pressing on the surface [34]–[36]. The authors in [37] compared the realism of virtual surfaces using a database approach, an input–output approach, and Hooke's law. The study showed that overlaying either the recorded acceleration transients or manually tuned and velocity-scaled decaying sinusoids on a virtual surface resulted in a perceived hardness that closely matched that of a real surface. LaMottes study of tool-based interactions found that humans were significantly better at discriminating the hardness of surfaces when tapping rather than when pressing into the surface [34]. This result indicates that the transient vibrations elicited by tapping largely determine the surfaces perceived hardness and can be used to change the perceived hardness of a virtual surface. This dimension further considers, e.g., the compliance or the persistence of the material deformation [32].
c) Warmth conductivity is perceived by the thermal receptors in the human skin [29]. The combination of the ambient temperature and the warmth conductivity of a material determine how warm or cold the direct touch is perceived [38]. The response range of thermal receptors lies in the range of 5 °C – 45 °C. The influence of warmth conductivity is underscored in current research [29], because materials like glass and steel can only be discriminated by their different warmth conductivities [38] in the absence of visual surface information. While some object properties such as the shape or size can be visually determined by a human without touch, thermal attributes of objects or the environment can only be sensed through the skin. Basically, humans are very sensi-

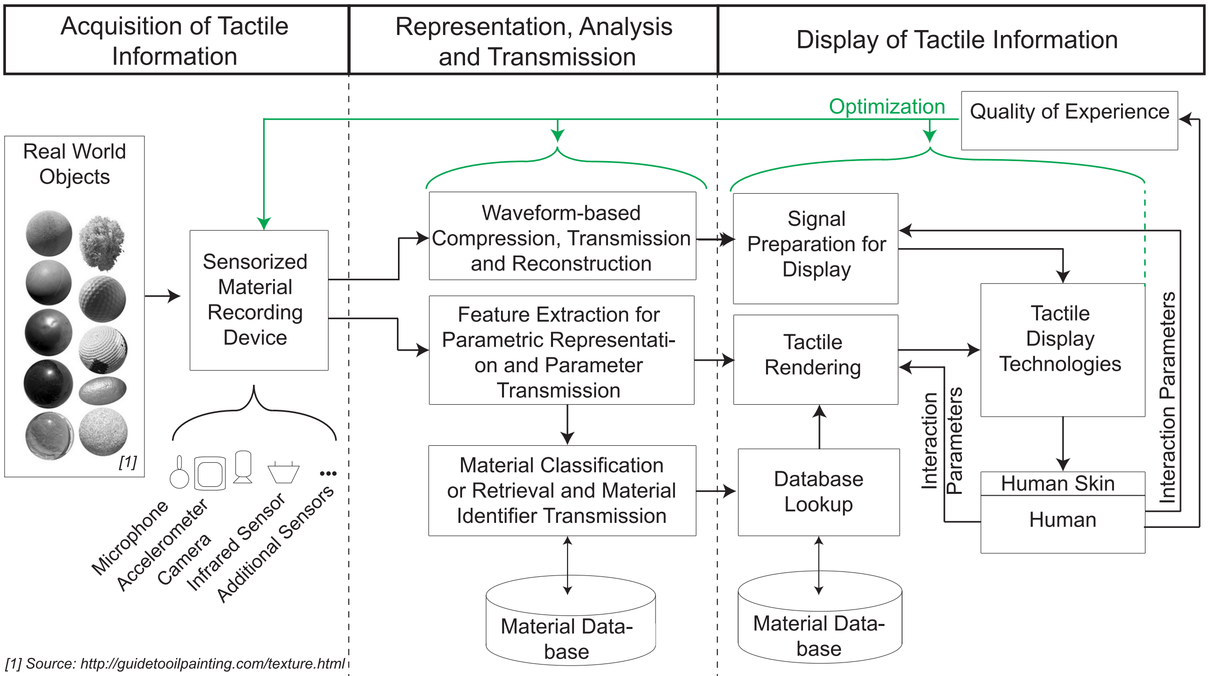

Fig. 4. ***Acquisition, analysis, transmission, and display of tactile information.***

tive to rapid changes in temperature, but respond slowly to gradual changes [27]. As a result, temperature scenarios are classified into four types, i.e., cold, cool, warm and hot. The recent study in [27] presents that the receptors responsible for thermal sensation include four classes of thermoreceptors: 1) high-threshold cold receptors; 2) low-threshold cold receptors; 3) high-threshold warm receptors; and 4) low-threshold warm receptors; and two classes of nociceptors, i.e.; 1) heat nociceptor and 2) cold nociceptor. The low-threshold cold receptor is sensitive to sudden cooling changes, such as a breeze from an open window, whereas the high-threshold cold receptor is less sensitive to the temperature change, but functions sensibly when the temperature is very low, even below 0 °C. Low-threshold and high-threshold warm receptors are classified in a similar way. Nociceptors are responsible for sensing pain when the skin temperature is beyond a certain threshold [39].

d) Macroscopic roughness and microscopic roughness: The duplex nature of roughness (introduced by David Katz in 1925 [40]), consisting of microscopic and macroscopic roughness, has been described and confirmed in different works like [29] and [30] and is based on the presence of different mechanoreceptors in the human skin. The surface material structural threshold between coarse and fine haptic textures has been determined as approximately 200 microns [41]. Four types of receptors, namely, cutaneous and subcutaneous mechanoreceptors, are responsible for the sense of touch. These mechanoreceptors, including Meissner corpuscles, Merkel cells, Pacinian corpuscles and Ruffini endings are described in [26]. Their function and roles are also shown in Table 1.

Macroscopic roughness comprises the existence of visible height profiles and the regularity of the surface of the object. These spatial cues are responsible for coarse structures and sensations described as uneven, relief or voluminous. Object surfaces can be regularly structured, possess perceivable irregular patterns or be completely flat.

Microscopic roughness, also known as fine roughness, results from high-frequency vibrations during active surface-tool or surface-finger sliding motions. Vibrations between 40 and 400 Hz are perceived by the Pacinian corpuscles, also known as FA2 receptors [29]. Current technical systems mainly concentrate on the acquisition and display of vibrotactile signals using accelerometers during tool-mediated material surface interactions [42]–[44]. These tactile signals are either used to recreate the feel of real object surfaces using voice coil actuators, or to recognize material surfaces using robots [33], [45] or during human freehand movements [46], [47].

There is still an active discussion about the feature space describing all relevant tactile experiences [48]. The previously described feature space with five major dimensions as proposed by [30] appears to summarize most of the sensations except perceived surface moistness. The inventors of the BioTac sensor (Syntouch, USA) propose a 15-D feature space [32] which allows for a further subtle distinction between these five major dimensions by separating, for example, hardness into compliance, yielding, relaxation, damping and local deformation around the sensing device.

B. Acquisition and Display of Tactile Information

Capturing relevant tactile information is the first step of the proposed tactile pipeline (see Fig. 4). In the following, we list potential sensing and actuation principles for each of the five major tactile dimensions.

1) Friction: Friction requires the measurement of normal and tangential interaction forces following the Coulomb friction model [31] and is mainly measured using 3 degree-of-freedom (DoF) force sensors [44], a combination of force sensitive resistors [47], or as the required motor current to drag a linear stage [33]. The authors in [49] and [50] also explored presliding and sliding friction using data recorded with a tribometer.

Friction forces can be displayed using common haptic devices, e.g., the Phantom Omni device (Geomagic Touch), or, by mechanically changing the friction between moving elements of the device with the underlying ground [25].

2) Hardness: Hardness is usually defined as spring stiffness according to Hooke's law [51] and can be represented by using the values of force sensors divided by the indentation depth measurements. It has additionally been observed that acceleration signals aide to represent hardness as high-frequency components of tappings [52]. The work in [37] confirmed that such accelerometer-recorded high frequency tapping transients can appropriately represent the dynamic component of object hardness and be used for haptic display as well using vibrotactile actuators.

The spring stiffness of virtual objects is generally displayed by using commonly available haptic devices [51] or using dc motors [53]. These approaches, however, need to be extended to display high-frequency tapping transients using vibrotactile devices as shown in [24] and [37] for realistic recreation of hardness sensations.

3) Warmth: Warmth, or thermal conductivity, can be measured using thermistors [33] or by thermal camera-based nondestructive infrared recordings as shown in [54]and [55]. Note that thermal sensing using any device requires the surface of the object to be heated in advance, e.g., using a laser [54], to measure the temporal dissipation of thermal energy. If a liquid is part of the sensing device, as, e.g., in [33], the thermal conductivity can directly be measured without prior heating of the surface.

Thermal displays generally are realized using closed-loop controlled Peltier elements, as e.g., reported in [55]–[57].

4) Macroscopic Roughness: The studies in [47], [58], and [59] capture the surface structure of objects using a laser scanner or infrared reflective sensors during non-contact scans and then generate height profiles for the simulation of coarse structural information. Most recently, stereoscopy-based approaches have been presented to determine the surface structures in [60].

Basdogan *et al.* [61] built a discrete height-field model and subsequently applied the well-known bump mapping technique from computer graphics to map the model to the virtual objects for simulating height structures on surfaces perceivable using common haptic devices. Other displacement-based approaches are reported for wearable haptic interfaces [23] using mainly servo motors.

5) Microscopic Roughness: Traditional haptic rendering algorithms (e.g., the aforementioned bump mapping technique) and devices cannot output high-fidelity reproductions of finger-surface interactions [62]. The motor drive circuitry as well as the friction and flexibility in the device limit their ability to accurately reproduce high-frequency vibrations. As a result, the display of virtual surfaces often does not include haptic texture and thus feels smooth and slippery. Also, while it is straightforward to acquire data that changes slowly, such as temperature and pressure, accurately recording high-frequency vibrations is a more challenging task since these signals heavily depend on, e.g., scan force and scan speed [42], [63]. Approaches have been developed both for tool-mediated haptics and for bare-finger haptics. The authors in [42] and [63]–[68] recorded such high-frequency acceleration signals using tool-mediated setups and created data-driven models for tactile display. The work in [69] additionally considers the speed components v_x and v_y to account for anisotropic (i.e., direction-depending) haptic textures, e.g., wooden structures.

Several tactile display technologies can be used to present tactile information to human users. The three major current trends in research are based on vibrotactile, ultrasonic and electrostatic actuation. On the one hand, vibrotactile actuators come in different implementation forms like voice coil actuators, eccentric mass motors, piezo-ceramic actuators or tactile pattern displays [70]–[72]. Most commonly, voice coil actuators are used to recreate high-frequency mechanical vibrations within a range of 50 Hz to 1 kHz. Fig. 5 shows our proposed setup for the acquisition and display of tactile signals using an accelerometer and a voice coil actuator. This setup currently serves as the reference setup for tactile codec development in IEEE P1918.1.1 (see also Section VI). Various 3-D printed steel tool tips (lower right image) can be used to collect vibrotactile data during surface interaction. The measured signals are stored for further use, e.g., applying compression schemes, and subsequently displayed on the attached vibrotactile actuator for subjective evaluation of the recorded data trace, or objective evaluation measurements using another acceleration sensor. On the other hand, electrostatic actuation has been investigated in multiple studies [21], [73]–[77], or ultrasonic actuations [78] as, e.g., the TPad Phone [22], the ultraShiver device [79], or combinations of these approaches [80], [81].

6) Combinations of Tactile Dimensions: Several approaches present multiple tactile dimensions simultaneously to the user. For example, the haptography-based approach in [24] renders friction, stiffness and

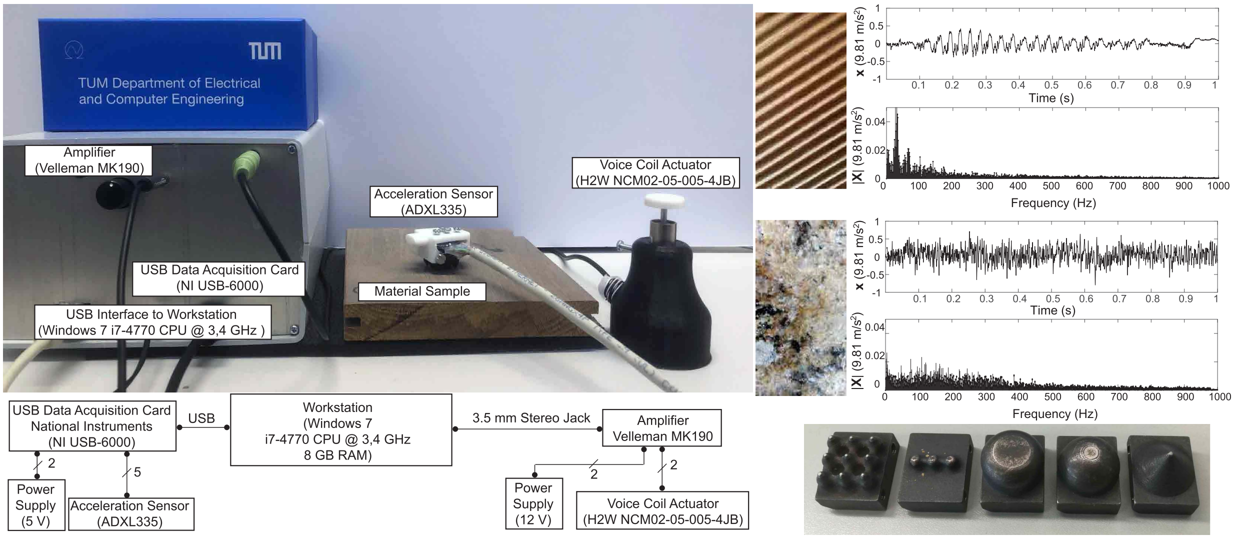

Fig. 5. ***Setup for the acquisition and display of tactile signals, which can be reproduced using commonly available hardware. Example signals (1-s-long) and corresponding spectral domain plots are shown in the upper right for two different materials. Several stainless steel tool tips have been printed (lower right) to collect tool-surface interaction signals.***

roughness material properties during tool-mediated interaction, or the approach in [57] displays thermal and vibrotactile sensations. Fig. 6 shows a recent approach of combining all five tactile dimensions into a single output device. The Tactile Computer Mouse (TCM) described in [82] enhances the input capabilities of a common computer mouse with additional actuators which are used to change the friction between the TCM and the underlying pad, display macroscopic roughness cues by changing the inclination of the upper mouse body, generate microscopic roughness impressions using voice coil actuators, simulate thermal flow using Peltier elements, and generate different hardness perceptions.

C. Compression of Tactile Information

The data size of single point of interaction tactile information is much smaller than that of video and is comparable to that of speech signals. Moreover, a large number of tactile sensors is expected to be deployed in future haptic communication systems, thereby it is essential to develop tactile codecs that exploit the properties and conceptual limitations of tactile information. Depending on the transmission scenario (see Fig. 4), either a waveform-based or parametric representation of the tactile signal is required.

1) Waveform-Based Representation and Compression of Tactile Signals: Recent works in [42], [44], and [83] define data-driven models for single interaction point tactile information captured with acceleration sensors, which output signals that depend on scan force and scan velocity. In [44], a 2-D space of scan velocity and scan force is defined and the autoregressive moving average (ARMA) coefficients of the acceleration segments are extracted. These ARMA coefficients can be transmitted over a network, and, depending on the exerted force and velocity, the displayed tactile signal is generated by filtering a white noise signal using the received ARMA coefficients. The work in [69] further improved the procedure to take anisotropic surface properties into account and proposed a compression scheme for n-dimensional data-driven tactile signal representations which considers the dimensions of scan force and scan velocity in x and y dimensions and report a twofold compression rate.

Based on Weber's law, [58] presents a frequency-domain compression algorithm for tactile information. Firstly, the researchers use a high-resolution laser to scan the surface of objects with constant velocity, and then model roughness as a height profile. Next, the height profile is transformed into frequency domain using the discrete cosine transform (DCT). Assuming that stimuli which fall below the perceptual threshold can be removed without reducing subjective quality, [58] modifies the DCT coefficients by eliminating the stimuli that have amplitudes beneath the thresholds. The perceptual threshold is preliminarily determined by psychophysical experiments. Finally, the modified DCT coefficients are converted to a new height profile through an inverse DCT. Subjective experiments are conducted and demonstrate that this algorithm achieves a compression ratio of 4:1 with acceptable perceptual quality. However, this approach is an offline algorithm as it requires the height profile of the whole surface at the beginning.

The authors in [84] proposed a real-time compression algorithm by adapting a standard speech codec (G.729). The results of subjective tests show that the algorithm achieves a compression ratio of 8:1 without perceptual degradation. Subsequently, they empirically showed that masking phenomena are applicable to tactile signals

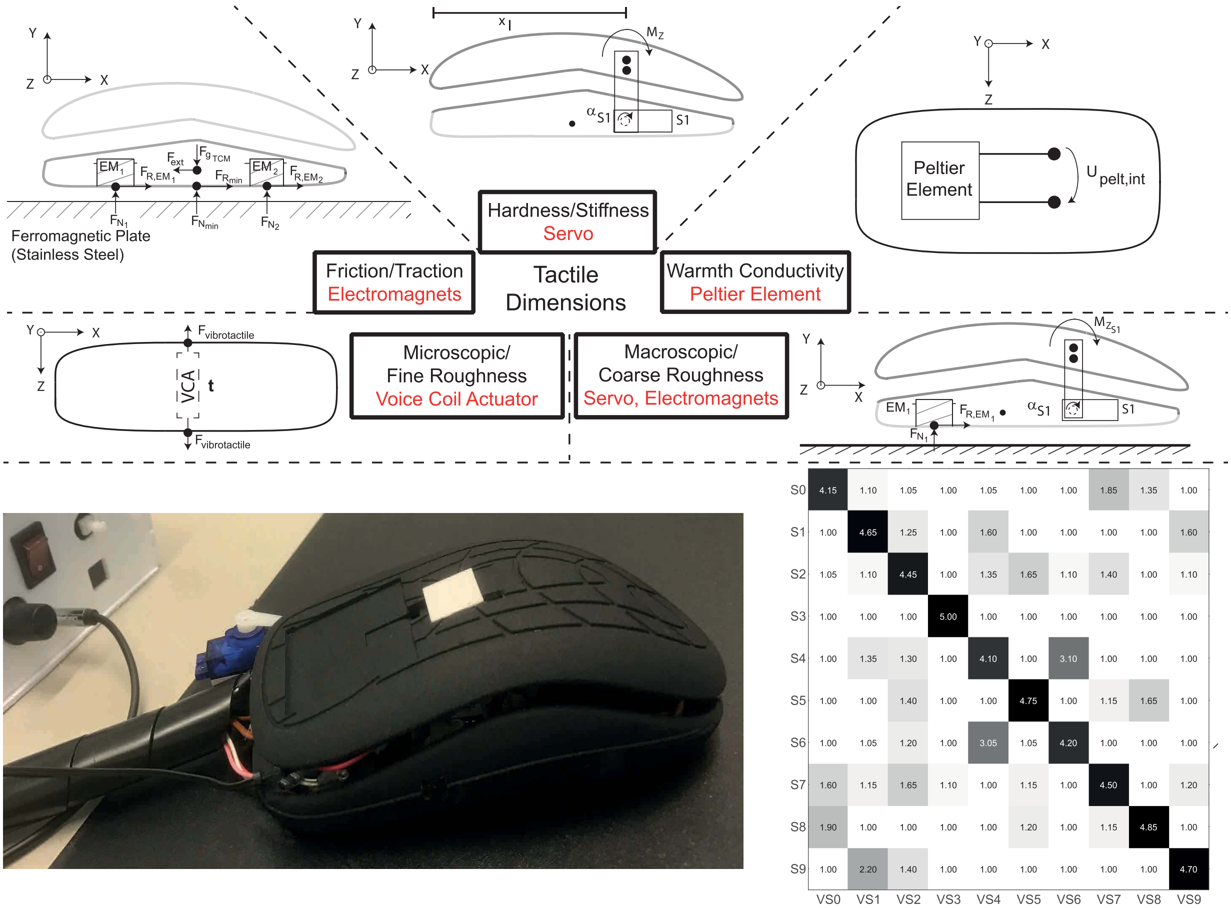

Fig. 6. ***Presentation of the five major tactile dimensions (upper plot) on a computer mouse-like tactile display (lower left). The Tactile Computer Mouse described in [82] uses several actuators to display surface material properties. It has been shown that this device is able to represent the five major tactile dimensions in a real–virtual material comparison test and that subjects were able to identify ten virtual surfaces (VS0 to VS9) using this device absent visual and audible information (lower right confusion plot).***

and extend the codec from [84] into a bitrate-scalable version [85].

The compression algorithms developed so far are not sufficient because they only address single-point tactile interaction. In practice, humans commonly use multiple fingers for perceiving objects and multi-point scenarios are gaining importance as tactile data acquisition is improving (e.g., artificial skin, finger-like tactile sensors like the BioTac [33], etc.). Consequently, spatial compression algorithms for multi-point tactile scenarios need to be developed in future work. Since [27] demonstrates that tactile and audio signals share similarities, one possible direction is to adapt the available audio codecs and treat multi-point tactile interaction as multichannel audio interaction. With this approach it should be possible to build a family of tactile codecs similar to what researchers have done for audio codecs.

2) Feature Extraction for Parametric Representations and Classification: Instead of using raw signal representations as discussed in the previous section, tactile features can be extracted to form a parametric representation. Inspired by the dimensions of tactile perception, related approaches like [33], [44], [45], and [47] define mathematical tactile features capturing for instance the friction, roughness, or hardness of the object surfaces. A feature vector for each material can then be sent to a remote tactile rendering framework to reproduce the tactile impressions in a VE. Either handcrafted features, or deep learning-based features, as reported in [86], can be used in this context.

The research in [87] made the first extensive scan material database (consisting of 100 materials) publicly available following the principle of data-driven approaches as introduced in [42]. The approaches in [47] and [88] follow the idea of defining tactile features that mitigate the influence of scan speed and scan force. Another haptic database has been recorded in [89] and further signal modalities, such as audio, infrared reflection or friction force, are considered. The work in [47] further uses the aforementioned tactile features to perform surface material retrieval of the most similar materials in the haptic database. The approach has been validated using ground truth data from a subjective experiment where human participants grouped the materials according to their perceptual similarity. In a teleoperation scenario, e.g., a remotely explored material may not be part of the database, but the most similar material is identified and the corresponding identifier is transmitted to the operator side, which uses the material representation to drive a tactile feedback system.

III. KINESTHETIC INFORMATION AND KINESTHETIC CODECS

In this section, we discuss kinesthetic information and state-of-the-art kinesthetic data reduction schemes.

A. Kinesthetic Perception

The sensory information provided by the mechanoreceptors in our muscles, tendons and joints is collectively referred to as the kinesthetic sense [29], [90], [91], and the resulting information contributes to human perception of limb position and limb movement (velocity) in space and the perception of applied forces/torques acting on the human body. This information also helps in determining physical properties of touched objects such as viscosity, stiffness and inertia. In the literature, kinesthetic perception is also referred to as proprioception [92].

Similar to other senses, kinesthetic perceptual limitations are also captured in terms of just-noticeable difference (JND) explained in Section III-C. In the literature, the JND for force perception is reported to be between 7% and 15% [93]–[97]. For stiffness it is reported to be between 13% and 28% [98]–[100].

B. Acquisition of Kinesthetic Information

Kinesthetic information refers to the position/orientation of human body parts and external forces/torques applied to them. Hence, position, velocity, angular velocity, force, and torque all fall into the category of kinesthetic signals. Kinesthetic haptic interfaces (devices) are used to capture the position/orientation information and provide force/torque feedback to the user.

For instance, in a teleoperation scenario, while interacting with a remote real or virtual environment, kinesthetic signals are transmitted from the user (master) to the remote (slave) side, and the resultant kinesthetic feedback signals are transmitted from the slave to master side. In case the remote environment is geographically distant, the kinesthetic information needs to be transmitted across a wide-area communication network (see Fig. 1). More specifically, in a 2-port position/force architecture, the operator transmits position/velocity values to the remote robot, and the remote robot returns the resulting interaction force/torque signals to the operator. Local control loops exist at both the operator and the teleoperator side. These local loops are responsible for displaying the desired force/torque and moving the robot and its tools into the desired pose, respectively. These two local loops are connected into a global control loop which is closed over the communication network. In order to maintain the stability of this global control loop, kinesthetic signals are sampled at a rate equal to or greater than 1 kHz.

The global control loop gets unstable in the presence of communication delays [14]. In order to minimize delay, kinesthetic information is transmitted once available. Since kinesthetic signals are sampled, packetized, and transmitted at a rate equal to or greater than 1 kHz, this leads to a high packet rate which is difficult to be sustained over a shared network like the Internet [101]. Therefore, the kinesthetic packet rate needs to be reduced while maintaining perceptual transparency [102], [103]. Conventional approaches for lossy compression like DCT, DWT, and vector quantization have a block-based structure, which introduces additional processing delay. Thus, these methods cannot be employed here.

C. Compression of Kinesthetic Information

1) Kinesthetic Data Reduction Based on Weber's Law: In the literature, perceptual deadband (PD)-based data reduction schemes for kinesthetic information have been proposed [104]–[106]. These codecs are based on Weber's law of just-noticeable differences. According to this law, only if the relative difference between two subsequent stimuli exceeds the JND, will the signal be perceivable and need to be transmitted. For example, if X is the current stimulus, and X_{n-1} is the last transmitted stimulus, then the current stimulus is perceived as different only if the following condition is satisfied:

$$\left| \frac{X - X_{n-1}}{X_{n-1}} \right| \geq \delta \tag{1}$$

where δ is the Weber fraction. In the kinesthetic codecs the parameter δ can be selected smaller or larger than the Weber fraction. Values of δ which are smaller than the Weber fraction indicate that the kinesthetic codec is operating conservatively below the JND. Values of δ above the Weber fraction refer to a more aggressive mode of operation where perceivable impairments are introduced. In the following we refer to δ as the deadband parameter (DBP).

Fig. 7 illustrates the perceptual deadband-based data reduction approach for a 1-D kinesthetic signal. Black dot samples are the output of the kinesthetic data reduction scheme. These samples determine a perceptual deadband for subsequent values, illustrated as gray zones. Samples falling within the currently defined perceptual deadband are perceptually insignificant, and thus can be dropped. Consequently, only perceptually significant samples are transmitted using the PD approach. This approach reduces the average packet rate by 80%–90%, while maintaining a high quality of experience. For compression performance results of the kinesthetic codec, please refer to Figs. 14 and 15 in Section VI.

The authors of [106] employ a data-driven approach to understand the structure of the perceptual threshold

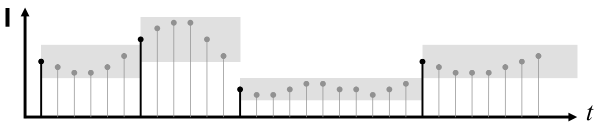

Fig. 7. ***Illustration of the perceptual deadband principle. The size of the perceptual deadband depends on the stimulus intensity I. Samples falling within the perceptual deadband are considered as perceptually insignificant, thus can be dropped (adopted from [105]).***

region for 1-D force stimuli in the range of 0–3 N. For that purpose, machine learning classifiers are designed to predict the label (perceiced/nonperceived) of recorded user responses. The authors have defined two classifiers: Weber classifier and level crossing classifier. The Weber classifier is based on Weber's law of perception, and thus labels the user responses (perceived/nonperceived) based on the absolute relative difference criterion as given in (1). On the other hand, the level crossing classifier considers the absolute difference criterion (i.e., $|X - X_{n-1}| > c$ where c is a level crossing constant) to label the user responses as perceived or nonperceived. Each classifier is optimized with respect to its threshold parameter (i.e., δ for the Weber classifier and c for the level crossing classifier), and the corresponding misclassification error is computed. The overall classification performances of both classifiers are observed to be nearly equal, and thus their classification criteria may be used in defining the structure of the perceptual deadband defined above. During reconstruction of the signals at the receiver end, the level crossing classifier-based sampler provides less mean-squared error (MSE) between the original and the reconstructed signal than the Weber sampler for small values of force stimuli and vice versa for high force values. Thus, both classifiers are complementary to each other. As Weber's law is unable to capture perceptual limitations for small values of the force stimulus, the level crossing-based classifier may be used in this range for defining the perceptual deadband.

In [104] and [107], the single degree-of-freedom (DoF) perceptual deadband approach has been extended to three DoF. For higher dimensional signals, Weber's law [mathematically defined in (1)] is applied on vectored stimuli, and the perceptual deadband is defined accordingly. Thus, the approach gives a circular and spherical deadband around a typical 2- and 3-D reference stimulus, respectively. Their radii are directly proportional to the magnitude of the reference stimulus, and the DBP parameter is the proportionality constant. For determining these structures of the perceptual deadzone for higher dimensional signals, Hinterseer *et al.* [104] consider only the force magnitude, not the force direction. As the direction of the force stimulus comes in to the picture when we extend the perceptual deadband approach for higher dimensional signals, the effect of the force direction on the Weber fraction needs to be investigated. Pongrac *et al.* [108] studied the effect of force direction on the Weber fraction. Results show that the Weber fraction is a function of both the reference force magnitude and force direction, thus, the perceptual deadband approach should also consider the force direction for data reduction performance. The exact shape of the multi-dimensional deadzone needs further investigation as the data-driven study in [109] did not observe the effect of the force direction on the perceptual deadzone. The quality of the used haptic interfaces might play an important role in this context.

In the literature, there are studies on parameters which affect the Weber fraction, and thus the perceptual deadband approach. In the aforementioned studies, the Weber fraction is assumed to be independent of temporal variations of the force stimulus, thus considering it a fixed quantity for an individual. In [110], Bhardwaj and Chaudhuri examine how the rate of change of the force stimulus (i.e., slope in N/s) affects the Weber fraction. The Weber fraction tends to decrease monotonically with an increase in the slope of the force stimulus. This means that for fast varying signals, we easily perceive the change in the signal. Thus, this study claims that the Weber fraction is not a fixed quantity, but a function of the temporal variations of the force stimulus. Another example is the study in [111] which showed that the perceptual deadband for force signals is affected by the velocity of the operator movement.

2) Integration of Kinesthetic Data Reduction and Stability-Ensuring Control Schemes: Several types of control schemes, e.g. the wave-variable (WV) transformation [116], [117], the time domain passivity approach (TDPA) [118], and the model-mediated teleoperation (MMT) architecture [119], [120], were developed to guarantee the stability of closed-loop kinesthetic communication in the presence of communication delays. The originally proposed versions of these control schemes ignore the high packet rate of kinesthetic information. As a result, there is a strong need for the integration of stability-ensuring control schemes and kinesthetic data reduction algorithms for the realization of the Tactile Internet. Table 2 summarizes the related work in this research direction.

The PD-based kinesthetic data reduction scheme has been combined with the WV control scheme in [112]. The resulting approach operates on haptic signals in the time domain (i.e., directly on the force and velocity signals). This scheme, however, is suited only for constant communication delay.

Recently, the integration of the PD-based data rate reduction approach and the TDPA control scheme was proposed in [114]. The resulting joint compression/control approach preserves stability of the system in the presence of time-varying and unknown delays.

D. Display of Kinesthetic Information

Kinesthetic information (force, torque, position, orientation) is captured and displayed with the help of force feedback devices (also called kinesthetic devices). A force feedback device comprises sensors and actuators

Table 2 Overview of Combination of Teleoperation Control Architectures With Haptic Data Reduction Schemes For Different Communication Assumptions. Studies on Combining Control Schemes With Haptic Data Reduction Approaches Are Not Quite Complete. Missing Parts (Marked With '–') Are Mainly With Respect to Handling of Time-Varying Delays and Packet Loss

	known const. delay	unknown const. delay	time-varying delay (known stat.)	time-varying delay (unknown stat.)	packet loss
WV + compression	[112]	[113]	-	-	-
TDPA + compression	[114]	[114]	[114]	[114]	-
MMT + compression	[115]	[115]	-	-	-

controlled by dc motors. Sensors provide information about the position and orientation of the device in virtual/real world. Once the device interacts with an object, actuators display the resultant force/torque to the user. Thus, a kinesthetic device enables us to perceive force and torque feedback. Kinesthetic devices are typically categorized based on the degrees of freedom provided for inputs (position/orientation) and outputs (force/torque).

There are various kinesthetic devices available. The Novint Falcon developed by Novint Technologies [121] and the phantom devices (Phantom Omni and Phantom Premium) initially developed by Sensable (now offered by 3D Systems) [122] are the most widely used devices because of their low cost. The Novint Falcon device provide three DoFs for inputs and three for force outputs while the phantom devices provides 6 DoFs for inputs and three for force outputs. The Novint Falcon and the Phantom Omni devices are generally used for low-end applications, and the Phantom Premium device is generally used for high-end applications. Devices developed by Force Dimension such as the omega.x, delta.x and sigma.x [123] are also preferred for high-end applications because of their high position resolution and large peak force.

The kinesthetic devices mentioned above are termed as grounded devices because they apply their reaction force to a massive stationary object such as a desk, ceiling or wall [124]. There is another category of haptic devices, such as gloves or exoskeletons, which apply their reaction force to a part of the operator's body. These devices are called ungrounded since they generate self-equilibrating forces that do not need to be mechanically grounded (such as grasping an object). Examples of ungrounded haptic devices include the Rutgers Master displays (Master I and Master II) [125], TorqueBar [126], Gyro Moment Display [127], Gyro effect [128], HapticGear [129] and joystick [130]. Recently, Sauvet *et al.* [131] designed an ungrounded haptic device for spatial guidance where a piezoelectric actuator is used to generate the haptic illusion of an external force. An ungrounded haptic augmented reality system is designed in [25] to alter the roughness and friction properties of a rigid 3-D object. Note that ungrounded device design is focused mainly on tactile sensations [132]–[134].

E. Kinesthetic Interaction Setup

Bhardwaj [135] describes an example hardware and software setup for the evaluation of the kinesthetic codecs. The setup realizes a teleoperation scenario in a virtual environment with closed-loop kinesthetic interaction. It is implemented based on the widely used haptic application development platform *Chai3d*. Fig. 8 shows a snapshot of the virtual environment which consists of a rigid cube (movable) lying on a rigid planar surface. In the virtual space, the haptic device is represented by the small grey colored ball (virtual tool) shown in the figure. The operator controls the position and velocity of the virtual tool using the Novint Falcon kinesthetic device, and receives three DoF force feedback whenever the virtual tool makes contact with the objects in the environment. The implementation of this setup is available at [136]. The setup is independent of the design/structure of the kinesthetic codecs being used. For illustrating the principle of a kinesthetic codec in the setup, [135] includes the perceptual deadband-based data reduction scheme (described in Section III-C1). In Fig. 8, selected parameters of the perceptual deadband-based codec are shown under demo settings. Here Force DB and Velocity DB denote the deadband parameters for the force and velocity signals, respectively. In addition, one can also see the velocity packet rate (forward channel), and force packet rate (backward channel) generated by the perceptual deadband-based kinesthetic codec. The setup also comes with raw data traces (position and velocity signals of master, force signal of slave) for both static interactions with the rigid planar surface and

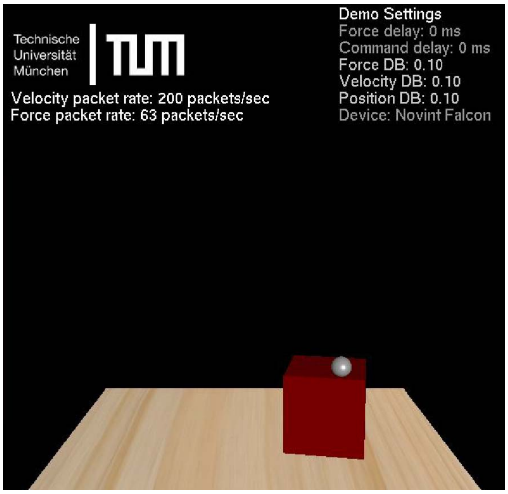

Fig. 8. ***A screenshot of the virtual environment designed for the kinesthetic codec development setup.***

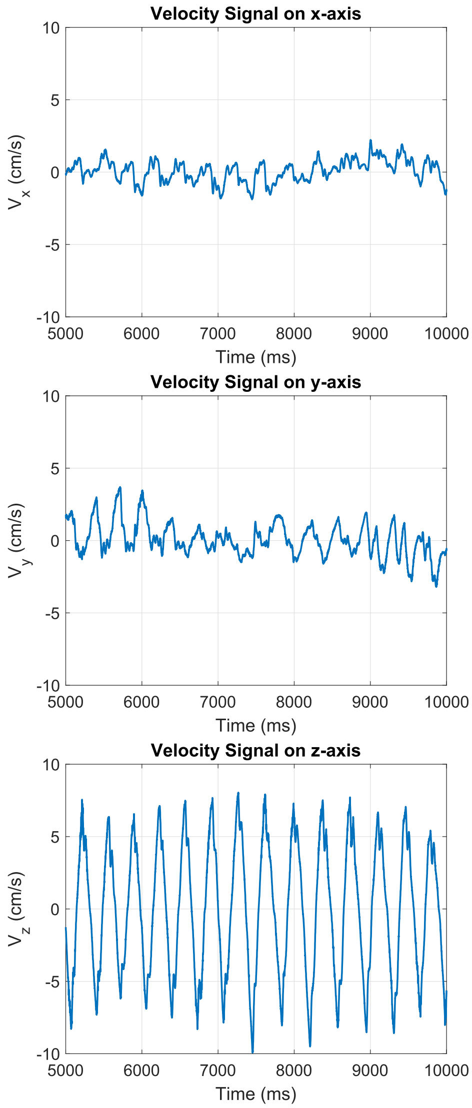

Fig. 9. ***Velocity data traces of the operator for the static interaction scenario.***

dynamic interactions with the movable cube. These traces allow the evaluation of kinesthetic codecs even without installing the setup. Figs. 9 and 10 show an excerpt of the 3-D velocity and force traces recorded for the case of static interaction. The complete recorded data traces can be downloaded from [137]. Performance evaluation results for the perceptual deadband-based kinesthetic codec on these traces are presented in Section VI-C.

IV. HANDSHAKING AND MULTIPLEXING

Handshaking protocols for haptic devices support the exchange of device capabilities such as the number of degrees of freedom, the workspace dimensions, the signal representation and the maximum input and output values. Multiplexing schemes support the simultaneous transmission of multiple data streams over the same communication channel. Multiplexing in the context of the TI in its most general form refers to the joint transmission of several video, audio and haptic data streams. The multiplexing scheme provides appropriate network shares to each of the streams depending on both the application needs (requirements) and/or the available network resources. Finally, the multiplexing scheme provides synchronization information across multiple streams.

A. Tactile Internet Meta Data (TIM)

With the rise of the TI, haptic devices will undergo wide deployment and use. Currently, haptic devices are highly diversified in their specifications (input/output degrees of freedom, workspace, update rate, etc.), and they use different APIs which results in making application development device and API specific. Similar to audio or video clips, that can be recorded and/or played back with standard

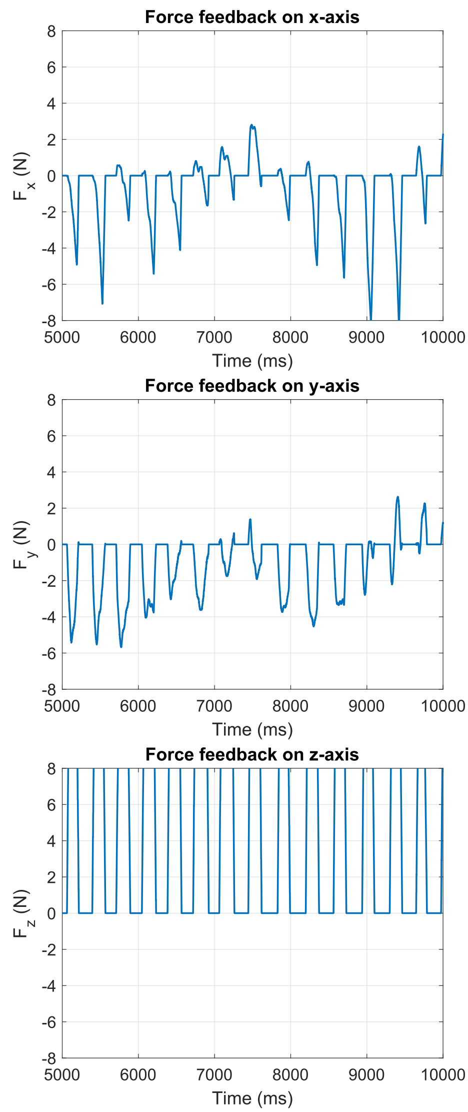

Fig. 10. ***Force data traces of the teleoperator for the static interaction scenario.***

commercial players independently from the recording device, a standard technology-neutral metadata by which haptic application components such as haptic devices and haptic APIs, or graphic models, make themselves and their capabilities known becomes a necessity.

Several modeling languages, such as SensorML [138] and Transducer Markup Language (TML) [139] have been proposed that can describe a haptic application to some extent. For instance, SensorML models a sensor or actuator as a process that has input(s) and produces output(s) based on predefined methods. SensorML cannot be efficiently used to describe haptic applications for two main reasons. First, the haptic interface is characterized by bidirectional flow of data where the division between input and output is fine and difficult to define. Additionally, SensorML does not provide a description for the mechanical design and behavior of the device—such as applied forces and workspace dimensions. Virtual environment modeling languages such as VRML [140] and Web3D Consortiums X3D [141] fall short in describing the haptic interface hardware and consequently, designing the virtual environment to fit to a particular haptic device is not desired. Furthermore, neither VRML nor X3D provide descriptions for communication specifications such as QoS network requirements.

Recently, haptic application metadata (HAML), which can be extended to define Tactile Internet metadata (TIM), is designed to provide a technology-neutral description of haptic applications [142], [143]. HAML defines five description schemes (DS): 1) application DS; 2) haptic rendering DS; 3) haptic device DS; 4) haptic data DS; and 5) quality of experience (QoE) DS. The application DS describes the application owner, the system requirements, and metadata. The haptic rendering DS describes the haptic rendering API, kinesthetic and/or tactile rendering mechanisms, and graphic modeling. The haptic device DS includes physical properties about the haptic interface, actuation technology, and performance characteristics (including spatial and temporal). The haptic data DS describes the data format, acquisition, and encoding of haptic data. Finally, the quality of experience DS describes kinesthetic, tactile and thermal perception attributes, in addition to quality of service parameters.

B. Multiplexing Scheme for Multiple Haptic Streams

A haptic application may involve the communication of multiple haptic data streams (such as different degrees of freedom of kinesthetic and/or tactile data). A key challenge arises due to the fact that different haptic streams have different requirements in terms of communication (QoS) requirements. A multiplexing scheme addresses this challenge by combining multiple haptic streams into one. The multiplexing scheme provides appropriate network share to each of the haptic streams depending on both the application needs (requirements) or dynamics and/or the available network resources. Finally, the multiplexing scheme provides synchronization information across the multiple haptic streams.

Several approaches have been proposed to address the problem of haptic data multiplexing (along with audio-visual data stream). One effective approach is to use statistical multiplexing. This technique has proven to achieve high efficiency and better network utilization [144], compared to other multiplexing schemes such as neural networks [145] and Round Robin approaches [146].

The authors in [147] proposed an adaptive statistical multiplexer, termed as Admux, to integrate different modalities where each haptic stream is provided with a dynamic share of the network resources depending on the respective priorities of each stream (contribution to the quality of user experience). A visual-haptic multiplexing scheme is proposed by Cizmeci *et al.* [148], [149] for teleoperation over constant bitrate (CBR) communication links. The proposed approach divides the shared channel into 1-ms resource buckets and controls the size of the transmitted video packets as a function of irregular haptic transmission events that are generated by a kinesthetic codec such as the one described in Section III-A1. Further developments in this area are needed to support generic haptic data multiplexing (involving both tactile and kinesthetic haptic data) for the Tactile Internet.

V. SUBJECTIVE AND OBJECTIVE QUALITY EVALUATION FOR HAPTIC CODECS

To evaluate haptic codec technologies for the Tactile Internet, evaluation metrics need to be defined that capture the end users' QoE. In addition, the evaluation process has to consider the bidirectional nature of haptics, i.e., users not only feel haptic feedback, similar to audio/video, but also physically act upon an environment [150]. QoE is defined as a multi-level paradigm of the users' perceptions and behaviors, representing emotional, cognitive, and behavioral reactions that are both subjective and objective, while dealing with services, products, or applications [151], [152]. Accordingly, the QoE taxonomy for Tactile Internet applications should include: technical metrics, i.e., quality of service (QoS) and nontechnical metrics, i.e., user experience (UX). The UX category includes three parts: perceptual, physiological, and psychological metrics. This higher level organization, as shown in Fig. 11, replicates an apparent taxonomy for TI applications evaluation and all together is more customizable depending on the parameters needed for evaluation. For instance, service providers desiring to only evaluate the QoS of the application can neglect the UX parameters.

The QoS parameters for haptics typically involve technical factors such as delay, jitter, synchronization and packet loss, etc. The rendering quality relates to the quality of the major modalities in Tactile Internet applications. Each modality is considered separately first and eventually blended and mixed modalities are considered.

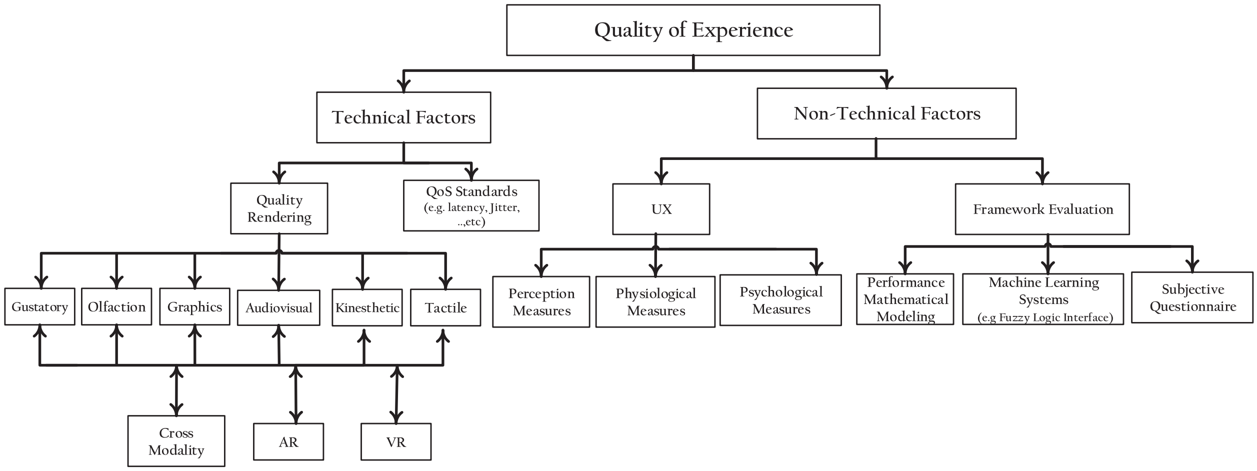

Fig. 11. *Higher level organization of QoE evaluation model for TI applications (adapted from [153]).*

On the other hand, relevant UX parameters have been classified as: perception-related parameters, psychological, and physiological parameters. Perception measurements reflect how users objectively perceive the haptics-based application. The psychological and physiological parameters capture subjective user-states. Examples of parameters that represent these categories [153] are media synchronization (QoS parameter), fatigue and user intuitiveness (perception-related), haptic rendering (rendering quality parameter), and degree of immersion (psychological).

A. Subjective QoE in Haptic Systems

So far, QoE in haptics has mainly been evaluated through subjective tests with the user-in-the-loop [8]. Classically, subjects evaluate system artifacts on an absolute category rating (ACR) scale that uses a five-category quality judgment [157] labeled with adjectives like imperceptible, perceptible but not disturbing, slightly disturbing, disturbing, and strongly disturbing. Guidelines for designing experiments with human subjects can be found for instance in [153].

B. Objective QoE in Haptic Systems

Subjective QoE testing in haptics is usually time-consuming and expensive [155] since customized haptic hardware makes it challenging to parallelize tests. In addition, since the test persons are typically new to haptics technology, extensive experimenter monitoring is needed. To tackle these issues, objective QoE testing is desirable. The evaluation of QoE through objective testing is based on algorithmic models of human perception and/or the measurement of several parameters related to service delivery. So far, only very few studies for QoE evaluation for haptic communications are available in the literature. They can be categorized in two groups based on how the quality is predicted.

1) Signal-Level Quality Prediction: The first work in this research line was introduced in [154]. In this work, a haptic perceptually weighted peak signal-to-noise ratio (HPW-PSNR) was derived to account for perceptual significance of haptic signal degradation using the just noticeable difference (JND). The mathematical formulation is described as follows:

$$\text{HPW-PSNR} = 10 \cdot \log_{10}\left(\frac{||v_{\max} - v_{\min}||^2}{\text{MSE} \cdot \text{HPW}}\right) \quad (2)$$

$$\text{HPW} = \begin{cases} C, & \text{if } |v - \hat{v}| \leq \text{JND}(v) \\ k \cdot (|v - \hat{v}| - \text{JND}(v)) + C, & \text{otherwise} \end{cases} \quad (3)$$

where $v_{\max}$ and $v_{\min}$ are the maximum and minimum values of the haptic original signal v. C is a constant term that weights the signal degradations below the perceptual threshold. k is a penalty factor that weights the haptic degradations beyond the JND of the signal. $\text{JND}(v) = a_v \cdot |v|$, with a_v being the percentage of the tolerable degradation of signal values.

Another work in [155] proposed a quality prediction framework for the compression of kinesthetic signals for closed-loop teleoperation. However, the proposed approach is only able to qualitatively predict user ratings. In [153], the perceptual mean squared error metric (P-MSE) is introduced. A perceptual comparison of a compressed haptic signal relative to the uncompressed one is made based on the Weber–Fechner law [158] which relates the psychophysical sensation S with the magnitude of physical stimulus x as follows:

$$S = c \cdot \log\left(\frac{x}{x_0}\right) \quad (4)$$

where x_0 represents the absolute detection threshold of the physical stimulus and c is a proportionality constant. For N

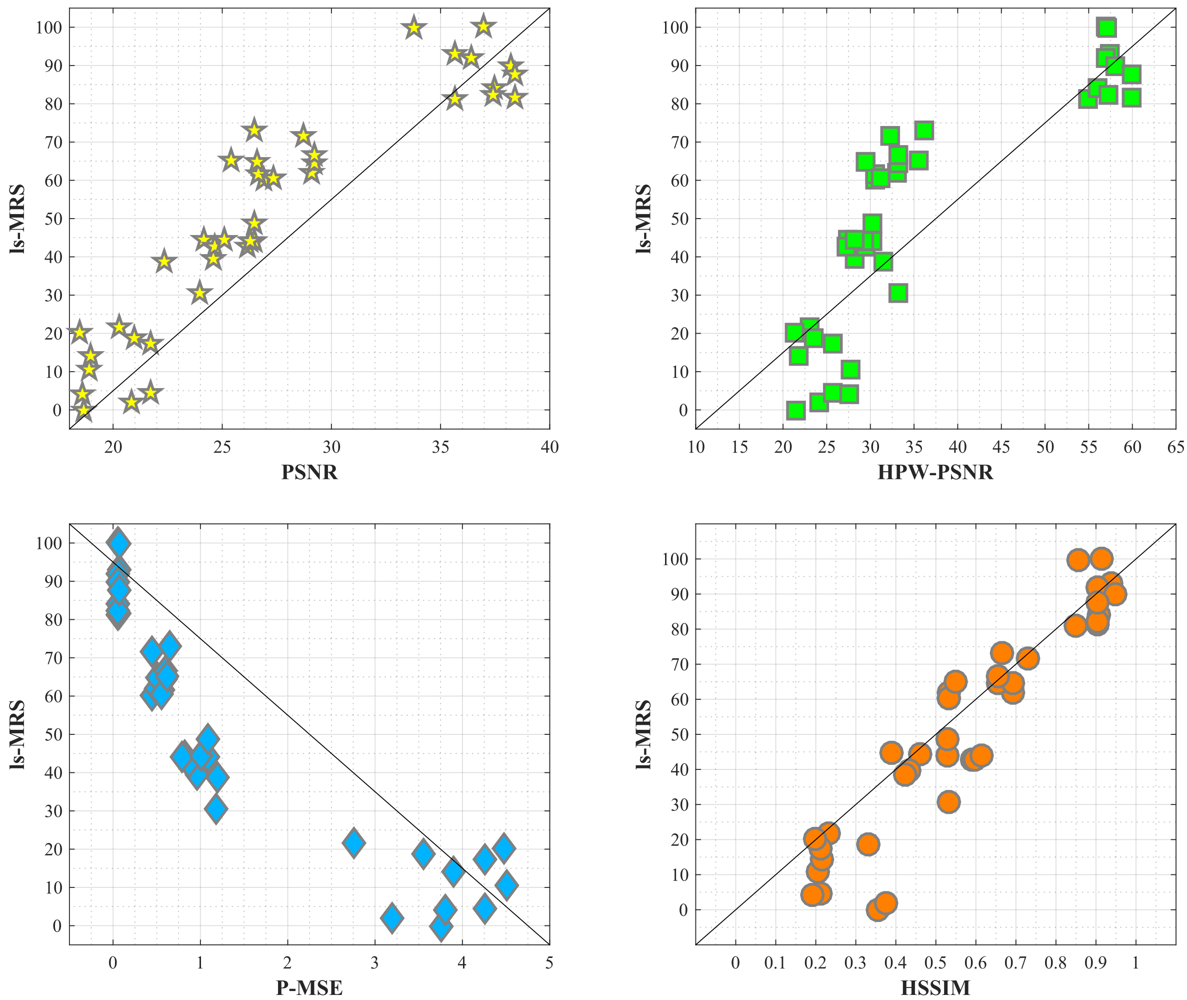

Fig. 12. ***Scatter plots of linear-scale mean rank scores (ls-MRS) versus objective quality assessment methods. Each sample point represents one force-feedback signal. (a) PSNR. (b) HPW-PSNR [154]. (c) P-MSE [155]. (d) HSSIM [156].***

samples in the time domain, the P-MSE is defined as

$$\begin{aligned} \text{P-MSE} &= \frac{1}{N}\sum_{i=0}^{N-1}[S(i) - \hat{S}(i)]^2 \\ &= \frac{c^2}{N}\sum_{i=0}^{N-1}\left[\log\frac{x_i}{\hat{x}_i}\right]^2 \end{aligned} \tag{5}$$

where S and $\hat{S}$ are the original and distorted psychophysical sensations, respectively, and x and $\hat{x}$ are their corresponding values of the physical stimulus, and c is a scaling constant that is determined experimentally. The quality-prediction results show a (decreasing) quality trend equivalent to that from subjective tests, as the strength of the applied compression increases.

All of the above objective quality measures focus on measuring the signal fidelity by computing the "distance" between the two signals in a perceptual way. However, they all assess signal quality based on error measures that operate solely on a sample-by-sample basis such that content-dependent variations are not considered. To fill this gap, [156] introduced the haptic quality assessment measure haptic SSIM (HSSIM). HSSIM employs the generic definition of SSIM [159] in conjunction with Stevens power law as a haptic perception model. The underlying premise is that the signal quality is evaluated considering neighboring sample dependencies and that only perceived distortions are penalized after accounting for human sensitivities.

In order to quantitatively ascertain the potential of the above described objective quality measures to predict human haptic judgement, a force-feedback database was built and used to conduct subjective experiment. The database contains ten original and 40 distorted force-feedback test signals using the perceptual deadband-based data reduction technique described in Section III-C. The force-feedback test signals are generated from a static interaction with objects in a virtual environment. The DB parameters are chosen to span the range of below, within, and above distortion detection threshold. Twenty-five participants participated in the subjective experiment. More

Table 3 Overall Performance Comparison of Five Quality Assessment Measures

	PLCC	SROCC	KRCC	RMSE
MSE	0.3008	0.6156	0.4910	27.967
P-MSE [155]	0.8895	**0.9342**	0.7481	13.398
HPW-PSNR [154]	0.8500	0.8935	0.7172	15.448
PSNR	0.9235	0.9288	0.7661	11.245
HSSIM [156]	**0.9357**	0.9312	**0.7764**	**10.342**

details on the subjective experiment can be found in [156]. Fig. 12 depicts the scatter plots for four objective quality measures against subjective scores. Table 3 compares the overall performance using three most used correlation coefficients and root mean-squared error (RMSE). For most of these measures, HSSIM performs better with high correlation and low RMSE values, which suggests better prediction accuracy and monotonicity. However, it is worth noting that PSNR and P-MSE also perform quite well.

2) System-Level Quality Prediction: The work in [160] provides a system-level mathematical model for haptic audio visual environment (HAVE) applications based on a weighted linear combination between QoS and User-Experience parameters described as follows:

$$\text{QoE} = \zeta \cdot \text{QoS} + (1-\zeta) \cdot \text{UX}$$
$$\text{QoS} = \frac{\sum_i \eta_i S_i}{\sum_i \eta_i}$$
$$\text{UX} = A \frac{\sum_i \alpha_i P_i}{\sum_i \alpha_i} + B \frac{\sum_j \beta_j R_j}{\sum_j \beta_j} + C \frac{\sum_k \gamma_k U_k}{\sum_k \gamma_k} \quad (6)$$

where $\alpha_i, \beta_j, \gamma_k$ and A, B, C are the model weighting factors which are used to maintain the overall quality of experience between 0 and 1. S_i represents the QoS parameters in terms of delay, jitter, and packet loss whereas P_i, R_j, and U_k denote the user experience parameters in terms of perception measures, rendering quality measures, and user state measures. Lastly, ζ is used to control the relative priority of the QoS parameters versus user experience parameters. The authors' model was evaluated empirically using subjective testbeds on 30 participants who used a HAVE game called the Balance Ball game. A fuzzy logic inference system (FIS) was further implemented to predict the user's QoE based on input parameters which gives 4.6% error and 0.92 correlation.

In short, system-level QoE prediction for haptic systems can be done in three approaches. The first approach is based on subjective tests in which users explicitly give their opinion about the haptic system they used. Then, the results are passed through regression analysis to come up with the optimized technical factors that enhance the overall experience. This approach is very expensive, time consuming, and lacks repeatability. Also, it cannot be applied in real time. The second method is based on algorithmic and/or mathematical derivations. In this approach, QoE augments QoS but does not totally replace it. Such approach suffers from feasibility and accuracy issues as there is no comprehensive model that can quantify the multidimensionality and large individual variability. However, to precisely capture the QoE using objective testing, more developments are needed, such as the mapping of network performance metrics (intrinsic QoS factors) to user experience related factors (e.g., haptic perception), the integration of sophisticated models for human haptic control into the objective quality metrics, and the development of joint metrics for auditory, visual, and haptic modalities. The third type is based on a machine learning-based approach. In visual quality assessment domain, many universal machine learning models have been proposed [161], [162]. The main challenge for the machine learning approach is how to learn rules from human semantic description of what they are experiencing. For example, humans can describe their experience as "very good," "fair," or "horrible." Directly mapping human linguistic descriptions to meaningful features that well represent the quality of the stimuli is a crucial step. One way to tackle this challenge is to classify signal quality with respect to quality classes, and from the obtained classification class distribution can be modelled in order to design a quality function.

VI. IEEE P1918.1.1 HAPTIC CODECS FOR THE TACTILE INTERNET

The ongoing IEEE standardization activity IEEE P1918.1.1 (also known as the Haptic Codec Task Group) defines codecs that enable the interoperability of various haptic interfaces (kinesthetic and/or tactile). These codecs address TI applications where the human is in the loop (teleoperation scenarios) as well as applications involving machine remote control. The standard defines data reduction algorithms and schemes for the communication of kinesthetic, tactile, or combination of kinesthetic/tactile information. The haptic codecs are designed to support both time-delayed and no-delay scenarios. Finally, the standard also specifies the mechanisms and protocols for the exchange of the capabilities of the communicating haptic interfaces (e.g., workspace, degrees of freedom, temporal and spatial resolution, etc.), in order to enable plug-and-play haptic communication.

A. Requirements

This section presents the identified requirements within IEEE P1918.1.1 for the haptic codec development. These requirements capture the use cases defined in IEEE P1918.1 (Tactile Internet Working Group) [163], but are not limited to these use cases only. Haptic Codec requirements include: 1) handshaking mechanisms for plug-and-play haptic communications; 2) kinesthetic codecs; 3) tactile codecs; 4) subjective quality evaluation metrics; 5) objective quality evaluation metrics; 6) reference software; 7) reference hardware; and 8) haptic multiplexing systems.

Table 4 Requirements For Handshaking Protocols

Requirements	Type	Examples
Codec scheme and parameters (data)	Required	Kinesthetic or tactile (device-, data-, and session-specific)
Traffic types (device, session)	Required	Kinesthetic/tactile
Control scheme for kinesthetic information exchange and parameters (data)	Required	1. None; 2. One control scheme to be defined
Haptics modalities / streams (device, session)	Required	Position, velocity, kinesthetic force, torque, angular velocity, stiffness, temperature, haptic texture, etc.
Workspace of the transmitter (device, session)	Required	> 100 W x 100 H x 50 D mm (kinesthetic) Artificial skin (spatial arrangement of sensor elements) (tactile)
Temporal-resolution, amplitude-resolution and bit depth (data, device)	Required	1kHz (kinesthetic), 200 Hz (tactile) − temporal resolution 0.1 N (force), amplitude resolution 2 Bytes per sample − bit depth 32 bits (float) − bit depth
Degrees of Freedom (data, device)	Required	Input: 6 DoF, Output: 3 DoF
Inter- and intra-stream synchronization (data, session)	Required	Timestamp at each packet, or periodic preamble
Packet format and multiplexing of different haptic streams (data)	Required	Packet header: payload, max size, time stamp, etc. Payload: multiplexing of individual coded streams
Session management protocol (initialization, termination, setting up different streams, etc.) (session)	Required	To be determined if to be defined by the Haptic Codec Task Group or if existing protocols, such as SIP can be adapted.
Range (min/max value) (data, device)	Optional	Max. force, max vibration intensity, min/max frequency
Minimum update rate (data, device)	Optional	>100 packets per second
Mechanical bandwidth	Optional	Kinesthetic: 50 Hz Tactile: 400 Hz
Feedback about transmission characteristics from the remote side	Optional	Time stamp, packet ID

1) Requirements for Handshaking Protocols: IEEE P1918.1.1 shall provide means for handshaking between the communicating haptic devices in order to exchange their capabilities and define communication protocols (session management, packet format, multiplexing scheme for different haptic streams, etc.). The specifications for handshaking protocols are listed in Table 4.

2) Requirements for Kinesthetic Codec: IEEE P1918.1.1 shall provide means for kinesthetic data communication. The specifications for kinesthetic data coding are listed in Table 5.

3) Requirements for Tactile Codec: IEEE P1918.1.1 shall provide means for tactile haptic data communication. The specifications for tactile data coding are listed in Table 6.

4) Requirements for Objective Quality Evaluation: Contributions to IEEE P1918.1.1 are evaluated using a set of objective metrics, including average and peak packet rates and MSE as well as the P-MSE defined in (5). IEEE P1918.1.1 also encourages contributors to propose perceptual quality evaluation metrics for adoption in the evaluation or in the final standard.

5) Requirements for Subjective Quality Evaluation: Subjective testing uses the reference setup(s) provided and maintained by the Haptic Codec Task Group. The currently used reference setup for kinesthetic codec development is described in Section III-E. The reference setup for tactile codec development is shown in Fig. 5.

Table 5 Requirements For Kinesthetic Codec

Requirements	Type	Examples
Packet rate adaptability	Required	Low interaction quality to lossless
Minimum algorithmic delay	Required	Ideally, no algorithmic delay
Control scheme (delay tuneable/adaptable)	Required	None or one control scheme to be defined
Real-time capability	Required	Coder complexity related
Multi-point support	Optional	Strongly correlated to grasping scenarios

Proponents are invited to contribute to the reference setups. Every proposal that shows sufficient evidence in terms of relevance and performance needs to undergo a cross-validation step which means that a second group needs to reimplement the proposal and perform subjective tests to confirm the presented results.

B. Call for Contributions

The Call for Contributions (CFC) includes the timeline for the call, deadlines for submitting contributions, and a tentative date for a complete working draft for the kinesthetic codecs. The CFC also provides explicit definitions for several terms and notations that are commonly used. Finally, the CFC provides details on the reference hardware and software, the submission process, test data traces and conditions for codecs. The CFC: Part I (kinesthetic codecs) is available at [164].

C. Current Status

IEEE P1918.1.1 currently considers the kinesthetic codec described in Section III-C for standardization.

Table 6 Requirements For Tactile Codec

Requirements	Type	Examples
Support for single point / multi-point	Required	Single sensor, artificial skin
Bitrate control	Required	low interaction quality to lossless
Maximum algorithmic delay (T_{max})	Required	e.g. 50 ms
Real-time capability	Required	Coder complexity related

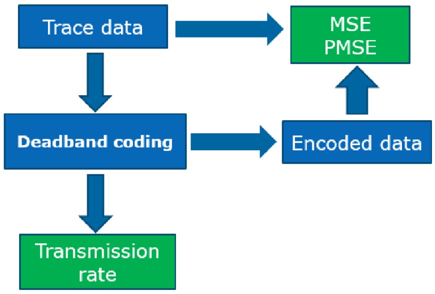

Fig. 13. ***Flow chart of cross-validation experiments at each group.***

Table 7 Transmission Rates (Percentage) of Velocity Signals

	TUM							DUT						
DBP	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**
Trace 1	100	67.5	55.2	26.7	16.3	11.0	6.2	100	67.5	55.2	26.7	16.4	11.0	6.2
Trace 2	100	63.6	59.7	31.6	23.4	17.5	10.4	100	63.6	59.7	31.6	23.4	17.5	10.4
Trace 3	100	77.0	69.6	35.4	15.2	10.5	6.9	100	77.0	69.6	35.4	15.2	10.5	6.9
Trace 4	100	74.2	48.3	28.3	20.5	16.1	11.4	100	74.2	48.3	28.3	20.5	16.1	11.4
Avg.	**100**	**70.6**	**58.2**	**30.5**	**18.9**	**13.8**	**8.7**	**100**	**70.6**	**58.2**	**30.5**	**18.9**	**13.8**	**8.7**

Table 8 Transmission Rates (Percentage) of Force Signals

	TUM							DUT						
DBP	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**
Trace 1	100	19.6	11.1	6.7	4.8	3.9	2.8	100	19.6	11.1	6.7	4.8	3.9	2.8
Trace 2	100	3.5	1.6	0.8	0.6	0.4	0.3	100	3.5	1.6	0.8	0.6	0.4	0.3
Trace 3	100	18.5	8.6	4.5	2.9	2.2	1.4	100	18.5	8.6	4.5	2.9	2.2	1.4
Trace 4	100	24.6	16.6	11.5	9.0	7.4	5.7	100	24.6	16.6	11.5	9.0	7.4	5.7
Avg.	**100**	**16.5**	**9.5**	**5.9**	**4.3**	**3.5**	**2.5**	**100**	**16.5**	**9.5**	**5.9**	**4.3**	**3.5**	**2.5**

Table 9 MSE of Velocity Signals

*10E(-3)	TUM							DUT						
DBP	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**
Trace 1	0	0.04	0.92	5.6	12.2	22.3	48.8	0	0.04	0.92	5.6	12.2	22.3	48.8
Trace 2	0	0.05	0.4	3.0	7.2	13.0	26.8	0	0.05	0.40	3.0	7.2	13.0	26.8
Trace 3	0	0.09	2.2	25.0	69.5	112	231	0	0.09	2.2	25.0	69.5	112	231
Trace 4	0	1.50	14.3	63.7	144	258	574	0	1.49	14.3	63.7	144	258	574
Avg.	**0**	**0.41**	**4.5**	**24.3**	**58.2**	**101**	**220**	**0**	**0.41**	**4.5**	**24.3**	**58.2**	**101**	**220**

The group has recently finished the cross-validation experiments for the proposed kinesthetic codec, which will be presented in the next section.

1) Cross-Validation Results: The proposed kinesthetic codec reduces the average haptic packet rate by approximately 80%–90%, while maintaining a high quality of experience (i.e., transparency). In order to verify the implementation feasibility of the proposed kinesthetic codec, the Haptic Codec Task Group has conducted a cross-validation process, as shown in Fig. 13. The codec was independently implemented by two groups, the Technical University of Munich (TUM) and Dalian University of Technology (DUT) and the results were presented at the Haptic Codec Task Group meetings. In the cross-validation experiments, four series of trace data were recorded using the reference software (described in Section III-E) representing different types of interaction with static and dynamic virtual environments. These data traces can be downloaded from [165].

When the experiment starts, the trace data are used as input to the implemented kinesthetic codecs, then the encoded signals are recorded. The transmission rate (i.e., percentage of original signal samples transmitted), MSE and P-MSE [see (5)] between the original signals and the decoded signals are considered as key metrics for the cross validation. The cross validation is considered to be successful only when all results from the two groups are identical except floating number precision errors (marked with red colors in Tables 7, 9, and 10).

We list the results of the key metrics from the two groups side by side for a direct comparison. In Tables 7–12, each row represents results for a given trace with respect to

Table 10 MSE of Force Signals

*10E(-3)	TUM							DUT						
DBP	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**
Trace 1	0	0.1	0.7	2.6	6.6	10.9	23.0	0	0.1	0.7	2.6	6.6	10.9	23.0
Trace 2	0	25.0	150	558	1324	2411	257	0	25.0	150	558	1324	2411	257
Trace 3	0	14.3	94.4	316	969	1516	3783	0	14.3	94.4	316	969	1516	3783
Trace 4	0	7.8	60.3	254	541	969	2028	0	7.84	60.3	254	541	969	2028
Avg.	**0**	**11.8**	**76.4**	**283**	**710**	**1227**	**3023**	**0**	**11.8**	**76.4**	**283**	**710**	**1227**	**3023**

Table 11 P-MSE of Velocity Signals

*10E(-3)	TUM							DUT						
DBP	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**
Trace 1	0	0.3	6.5	51.8	131	240	583	0	0.3	6.5	51.8	131	240	583
Trace 2	0	0.1	1.8	22.4	68.6	137	368	0	0.1	1.8	22.4	68.6	137	368
Trace 3	0	0.1	6.0	50.3	178	326	705	0	0.1	6.0	50.3	178	326	705
Trace 4	0	1.3	13.2	58.6	136	248	564	0	1.3	13.2	58.6	136	248	564
Avg.	**0**	**0.5**	**6.9**	**45.8**	**129**	**238**	**555**	**0**	**0.5**	**6.9**	**45.8**	**129**	**238**	**555**

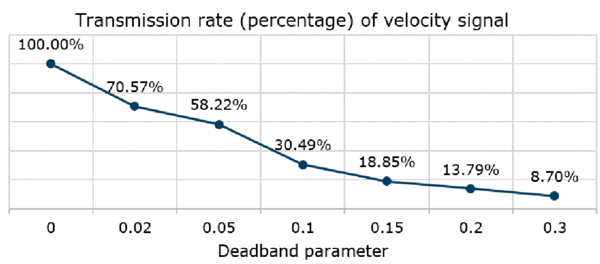

Fig. 14. ***Average transmission rate (percentage) of velocity signals.***

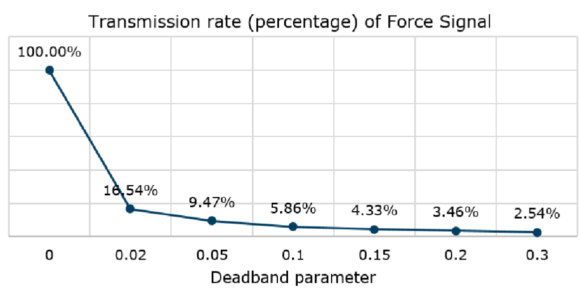

Fig. 15. ***Average transmission rate/percentage of force signals.***

Table 12 P-MSE of Force Signals

*10E(-3)	TUM							DUT						
DBP	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**	**0**	**0.02**	**0.05**	**0.1**	**0.15**	**0.2**	**0.3**
Trace 1	0	0.5	3.1	12.4	29.5	54.4	110	0	0.5	3.1	12.4	29.5	54.4	110
Trace 2	0	3.1	17.9	67.1	170	294	784	0	3.1	17.9	67.1	170	294	784
Trace 3	0	1.6	11.5	46.1	107	210	420	0	1.6	11.5	46.1	107	210	420
Trace 4	0	0.4	3.3	14.2	33.0	60.8	129	0	0.4	3.3	14.2	33.0	60.8	129
Avg.	**0**	**1.4**	**8.9**	**34.9**	**84.8**	**155**	**361**	**0**	**1.4**	**8.9**	**34.9**	**84.8**	**155**	**361**

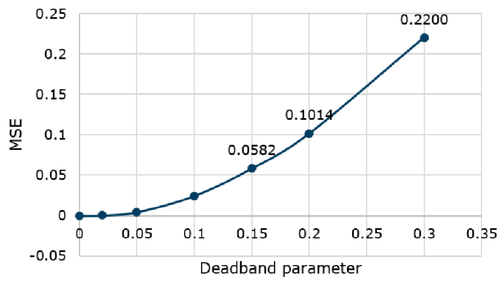

Fig. 16. ***Average MSE of velocity signals.***

all tested deadband parameters (DBP), while each column denotes results of a given DBP with respect to all four traces. Figs. 14–19 plot the averaged results.

These side-by-side comparisons show that the two groups achieved the same results through independent implementations. Therefore, IEEE P1918.1.1 has decided that the proposed kinesthetic codec passed the cross validation tests and is ready for standardization. The completion of the draft standard is expected for the end of 2018.

For the tactile codec development, the group currently prepares the respective Call for Contributions CFC: Part II (tactile codec). The group is planning to dedicate several face-to-face meetings to discuss and evaluate the competing (or complementing) contributions. An evaluation report will be prepared to document the evaluation process. After agreement of specific technologies to be adopted in the standard, a standard draft will be prepared and presented to the IEEE P1918.1 group at large for feedback and approval. The current timeline expects the submission of the tactile codec proposals until December 2018 and the completion of the draft standard by the middle of 2019.

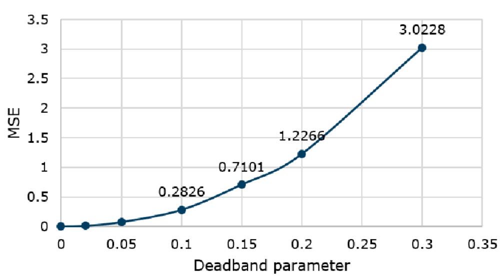

Fig. 17. ***Average MSE of force signals.***

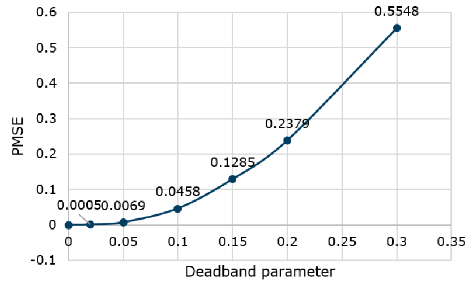

Fig. 18. ***Average P-MSE of velocity signals.***

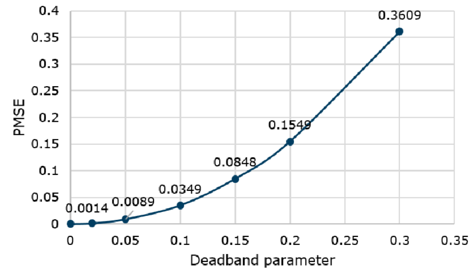

Fig. 19. ***Average P-MSE of force signals.***

VII. CONCLUSION

This paper discusses the development of haptic codecs for the Tactile Internet. It introduces relevant background on the acquisition and display of both kinesthetic and tactile information. Additionally, the most important aspects of haptic perception as well as the current state of the art in haptic quality evaluation are introduced. A substantial part of the paper focuses on kinesthetic and tactile codec development. We also discuss the status of the ongoing IEEE standardization activity Haptic Codecs for the Tactile Internet (IEEE P1918.1.1) which at the time of writing this paper is ready to standardize the first kinesthetic codec. We present the recently obtained cross-validation results for this kinesthetic codec which show its remarkable data reduction performance. The current work in IEEE P1918.1.1 focuses on the standardization of a corresponding tactile codec. ■

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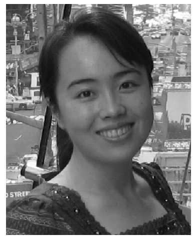

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Oliver Holland (Member, IEEE) is a Senior Researcher at Kings College London, London, U.K. He works at the forefront of numerous areas of wireless communication innovation, with interests spanning topics such as 5G mobile communication systems and their applications, and spectrum sharing and spectrum usage optimization, among many others. He recently led the 3M Euros EU ICT-ACROPOLIS Network of Excellence project for the second-half of its duration, and a major trial of TV white space technology as part of the UKs Ofcom TV White Spaces Pilot. He works on the leadership of several standards. As a couple of examples among many, he spearheaded the establishment of the IEEE P1918.1 standards working group on the Tactile Internet, which he Chairs, and also led the establishment of and Chairs the IEEE Mobile Communication Networks Standards Committee (IEEE MobiNet-SC), which is responsible for overseeing and sponsoring new IEEE standards in the scope of mobile communication networks.

Dr. Holland recently created and led the team/submission/idea that won the 0.5M Euros EU Collaborative Spectrum Sharing Prize, based on a distributed spectrum sharing concept.