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Challenges in Haptic Communications Over the Tactile Internet

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ABSTRACT The Tactile Internet presently constitutes a vision of an Internet over which, in addition to current communications modalities, a sense of touch can be transported. In that case, people would no longer need to be physically near the systems they operate, but could control them remotely. The main problem that needs to be solved to realize the Tactile Internet is summarized by the "1 ms challenge." If the response time of a system is below 1 ms, the end-user will not be able to tell the difference between controlling a system locally or from another location. This paper offers a summary of the requirements for haptic communications, followed by an overview of challenges in realizing the Tactile Internet. In addition, possible solutions to these challenges are proposed and discussed. For example, the development of the fifth generation mobile communication networks will provide a good foundation upon which a Tactile Internet could be built. This paper also describes the design of a modular testbed needed for testing of a wide variety of haptic system applications.

INDEX TERMS Tactile Internet, haptic communications, 5G communications.

I. INTRODUCTION

Recent developments in communication technology have brought us many useful applications, from sharing simple files to distributing audio and video with an increasing level of quality. Not only have we obtained the ability to share various types of content, the Internet has also enabled us to share thought and to collaborate over great distances using services such as Skype and Google Hangouts.

Today, the audio and visual modalities are well represented in terms of communication, computation and data storage on the Internet, but a modality involving the other sense "touch" is lacking. Perhaps the most important reason for this gap is the problem at the heart of what was first described as the Tactile Internet by Gerhard P. Fettweis in 2014 [1].

A. THE TACTILE INTERNET

Imagine a surgeon in Delft, the Netherlands, performing real-time surgery on a patient residing in Bangalore, India. Because a surgeon has to feel what he is doing, this requires transmitting data involving the sense of touch. The Tactile Internet specifically deals with this kind of haptic (or tactile) data. The main problem currently limiting the Tactile Internet from becoming a reality stems from its most ambitious requirement, the requirement of extremely low latency. Latency conditions for haptic response in the human body must be in the order of 1 millisecond to avoid any noticeable delay [1]. This poses a real challenge for future communication networks, since current technologies have a typical delay of 15 ms [4]. Moreover, often haptic data are synchronized with visual and audio signals. In that case, if the time interval between visual and tactile movement exceeds 1 ms, unwanted effects similar to motion sickness may occur. The "1 ms Challenge" forms the main problem that has to be solved to materialize the vision of the Tactile Internet [1].

Potentially, with the next generation communication technology (5G) being designed for ultra-responsive connectivity, 5G could be an important foundation upon which the Tactile Internet could establish connectivity [1], [3]–[5].

The Tactile Internet is expected to provide a "paradigm shift." Networks which previously only provided content

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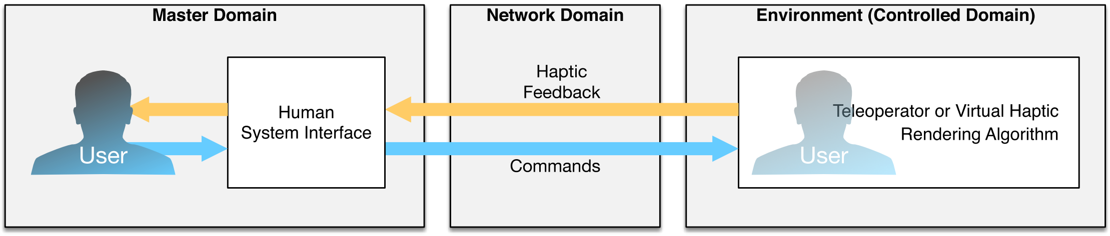

FIGURE 1. Simplified haptic teleoperation system connecting the teleoperation system in [2] to the Tactile Internet domains in [3]. It is important to note that in an ideal system, the user feels as if (s)he is actually present in the environment. Besides haptic data, also audio/visual feedback may be communicated.

delivery will now be able to move towards the delivery of entire skill-sets. This change will likely influence almost every part of society. Robots could be controlled from all over the world, health-care would no longer be location dependent [3], and telepresence systems (such as videoconferencing systems) could be extended with real-time haptic feedback, enabling interaction between environments not physically accessible to every participant [6].

It is important to make a clear distinction between the technology that empowers the Tactile Internet and the specific requirements of the Tactile Internet itself. To point this out, a comparison between the developing Internet of Things (IoT) and the 5G network can be made. While their goals are different, they partially overlap in requirements and features. Among overlapping features are low latency, high reliability, and security in Human-to-Human and Machine-to-Machine communication [5]. Due to this overlap, the concept of the 5G communication network appears promising to enable the Tactile Internet. 5G does, however, not deal with Tactile Internet specific requirements, such as communicating haptic information, as described in [6]. The overlap in specifications makes any future technology enabling the Tactile Internet also suitable for other applications, such as autonomous driving and automation in industry, as described in [3].

B. HAPTIC COMMUNICATION

Physically interacting with remote objects or humans requires communication of haptic data. Haptic data are data related to the haptic perception handled by the human senses. To visualize the flow of haptic data, a simplified model showing the flow of haptic communication in a telepresence system is shown in Fig. 1. In this figure, a mapping of the general structure of a teleoperation system, as given by [2], to three distinct domains of the Tactile Internet [3] is illustrated. Haptic data generated by a Human System Interface (HSI) in the master domain, pass through the network domain to the controlled domain. In the controlled domain, the haptic data are used to control a teleoperator or in the case of a virtual environment a haptic rendering algorithm [6]. Ideally, haptic communication systems in the form of telepresence and teleaction systems are transparent to the user, where the remote system interaction feels the same as if the remote system were replaced by the user [6], [7].

C. FIFTH GENERATION MOBILE COMMUNICATIONS NETWORK (5G)

The fifth generation of mobile communications (5G), is expected to be available for commercialization at the start of the next decade. Currently, we are in the standardization activities phase of the time plan for International Mobile Telecommunications (IMT), as specified by the International Telecommunication Union (ITU). The standardization phase ranges from 2017 to approximately early 2020. Eventually, it should lead to IMT-2020, a specification for 5G [8]. Because we are now in the standardization phase, this is the ideal moment to also consider the Tactile Internet, to make sure its requirements are taken into account while building the 5G specification. 5G has a diverse set of requirements: (1) high data rates, a few orders of magnitude higher than the current 4G systems, (2) a low round-trip latency in the order of 1 ms to support mission-critical machine-type-communications (MTC), and ideally (3) a decrease in costs and energy consumption [4], [8].

Because of the stringent requirements for a future tactile communication network, new possibly disruptive technologies may have to be introduced. Among these technologies are device-centric architectures (moving away from existing base-station centric approaches), the use of the Extremely High Frequency (EHF) spectrum, massive multiple-input multiple-output (MIMO), device intelligence, and native support for machine-to-machine communications [9].

D. SCOPE & OUTLINE

The scope of this work is set to haptic communications and the corresponding haptic data. First, in section II, key requirements for haptic communication over the Tactile Internet will be listed. Then, in section III, an overview of recent challenges and possible solutions to these challenges will be given. In section IV, we discuss how our paper differs from that of existing papers on the topic. We conclude in section V.

II. REQUIREMENTS

In this section, the most important requirements for haptic communication over the Tactile Internet are listed. These requirements are needed to improve the Quality of Experience (QoE) [10] for the user. The requirements will be compared to features of already existing technologies.

A. TRANSPARENT EXPERIENCE

Remotely performing a physical task, requires reliable and sensitive communication. When interacting with a remote environment, the user has to feel a certain degree of immersion to produce the desired actions. One such action could be selecting the heaviest object present. These actions must, in real-time, correctly be performed in the remote environment to produce the appropriate feedback to the user. Without this perceptual transparency the efficiency and realism of this communication loop cannot be ensured [2], [6], [11]. When a noticeable latency exists, full transparency becomes infeasible. In the case of a virtual environment mirroring a remote environment, correct simulation of physical interaction is required as well [7].

B. END-TO-END DELAY

To be able to ensure a transparent experience, one of the most important requirements is supplied by ''the 1 ms challenge'' a.k.a. ''the real-time challenge'' [1], [12]. The delay between a user performing an action and when he perceives it is called lag [13]. Several studies show that for haptic information, lag will be noticeable if it is larger than 1 ms [14], [15]. If this lag is noticeable it negatively affects the transparency and it can cause unwanted effects like cyber-sickness, with symptoms comparable to motion sickness.

One of the main contributing factors to this lag is the end-to-end delay for haptic data sent over the network. The factors that contribute to the end-to-end delay are queuing, processing, coding, propagation and transmission delays. One of the most limiting factors for the end-to-end delay is the fact that the propagation delay is limited by the speed of light. The propagation time for a packet sent from Amsterdam to New York alone would be approximately 20 ms. Yet, to overcome the 1 ms challenge, the propagation delay needs to be sufficiently smaller than 1 ms and is hence seemingly only possible for short-distance communication. Of the currently available cellular technologies, the fourth generation of cellular mobile technologies gets closest to the 1 ms requirement. Unfortunately, with a typical end-to-end delay of 15 ms for short distances, it cannot fulfill the 11 ms requirement [4]. 5G technology has a requirement for an end-to-end delay of less than 5 ms with a packet size of around 1500 bytes [16]. The packet size for the haptic data is significantly smaller than these 1500 bytes [11]. Since the transmission delay, and in smaller amounts the coding and processing delays, depend on the packet size, a smaller packet size will reduce the end-to-end delay even further [12], bringing it closer to the 1 ms required for communicating haptic data.

C. RELIABILITY

Any incorrect data received by the user could result in an incorrect response given back to the remote environment. UDP provides fast transmissions and low delay variations, but is an unreliable connectionless service. TCP is connection-oriented and employs packet retransmission in case of packet loss. Unfortunately, its algorithms lead to delay jitter, which is not desirable for transferring real-time data [17]. To ensure haptic (and the supporting audio and visual) data are correctly transported, we require a highly reliable system with a maximum packet loss probability of 0.001% [18]. This means new protocols should be created or existing ones modified [17], a requirement shared with 5G [5].

As argued in [6], multisensory integration is a general principle of the human brain to increase perception. The human brain can thus complement any lost haptic information by consulting, for instance, visual signals and vice versa. Even the noise produced by the different (haptic) sensors will cause less confusion as the brain will place emphasis on the more reliable information.

High reliability is also needed to address the correspondence problem; the brain needs to know which information belongs together. This also raises the question of which information needs to be communicated in case of environments with ''too much'' going on; will the human brain still be able to filter out the reliable information? It is known that humans can adapt very quickly to persistent perceptual conflicts, but it can affect the QoE if the user has to adapt to conflicting situations frequently [6].

D. SECURITY

Security is an issue for the communication of all kinds of data via the Internet. For the communication of different kinds of data, different levels of security are required. The level of security that is already available in technologies like IPSec will suffice for most applications where haptic data need to be sent over the network [1]. However, the increase in end-to-end delay caused by current implementations is large and conflicts with the latency requirement. Therefore the security requirement is not solely a matter of limiting access to data by unauthorized individuals, but is also a problem of trying to limit the increase in end-to-end latency. Whether this increase in security outweighs the increase in end-to-end latency depends on the application. An example of this is the usage of haptic communication in the medical field, where the data are of high confidentiality [1]. On the other hand, a lower end-to-end delay may be desired for virtual reality applications with a lower requirement for secrecy of the haptic information. Therefore, the required security level should be traded-off with the increase in delay, which will lead to different security levels across the wide range of haptic applications.

III. CHALLENGES

The requirements discussed in the previous section manifest themselves in numerous challenges. In this section, an overview of the most important challenges is provided. Both the challenges that have partially been solved and the ones that still remain open are discussed. The challenges are discussed in the order in which they occur in the haptic communication system of Fig. 1. First, the Human

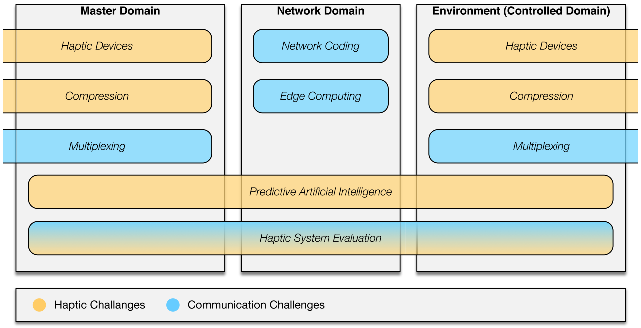

FIGURE 2. A map of the challenges discussed. Each challenge is placed according to its position in the teleoperation system domains described in Fig. 1.

System Interface devices that generate the haptic data are discussed. Next, compression methods will be discussed that decrease the amount of data that need to be sent. One step remains before the data can be sent, namely multiplexing with the other modalities. Once all the methods to preprocess the haptic data have been covered, the challenges regarding the communication of that data are treated: SDN, NFV, network coding, predictive AI and edge computing. Finally, the challenge of fast evaluation methods and testbed design for complete haptic communication systems is addressed. A visual representation that links the challenges to the specific domains of Fig. 1 is presented in Fig. 2.

A. HAPTIC DEVICES

To facilitate haptic communication, haptic devices such as: (a) haptic sensors (b) haptic actuators are required. Haptic sensors are devices that sense the tactile information. They are mounted usually at the tele-operator end and sense the pressure/force experienced by the tele-operator when interacting with its surroundings. This information is relayed back and conveyed to the user in the form of haptic feedback. Haptic actuators are used for providing the haptic feedback; for this reason, haptic actuators are also termed haptic feedback devices.

1) HAPTIC SENSORS

Haptic sensors are primarily pressure sensors that detect the pressure in the range perceivable to humans, which typically is in the range of <10 kPa for gentle touch, 10-100 kPa for object manipulation, and in the worst case can be up to 325 kPa [28], [29].

Of the many different methods reported in the literature to sense pressure, capacitive and resistive methods are most popular. In capacitive methods [28], [30]–[34], a flexible dielectric is sandwiched between two conducting plates. Upon experiencing pressure, the dielectric contracts and thereby reduces the distance between the two conducting plates. This results in change in capacitance. This change is then measured using an electric circuit and digitized using an Analog to Digital Converter (ADC) to report pressure. In resistive methods, a pressure-sensitive resistive material is used to create the sensor [35]. Upon experiencing pressure, the resistance of the material changes. Again, the change is measured using an electric circuit and digitized using an ADC to report pressure.

For the design of capacitive haptic sensors, elastomer polydimethylsiloxane (PDMS), popularly known as silicone, is widely used as the dielectric. PDMS has a low young modulus and good dielectric constant, enabling the design of sensors that are highly flexible and sensitive. However, elastomer PDMS exhibits various non-idealities in its stress-strain curve, which makes the design of sensors with PDMS difficult. Non-idealities observed include hysteresis, stress, creep relaxation, etc. These non-idealities have to be accounted for when building the capacitive pressure sensors. Another important factor to consider in capacitive pressure sensors is sensitivity. Sensitivity corresponds to the change in capacitance that occurs for a given change in applied pressure. Higher sensitivity helps to use ADCs with lower resolution, which in turn reduces the conversion time, speeding up the sensing process. At the same time, higher sensitivity can reduce the measurement range of the sensor owing to saturation effects. A combination of high- and low-sensitive sensor layer stacks may be a possible solution, but this will add to the complexity and cost of fabrication. Another possibility is to structure the PDMS. By structuring the material, the sensitivity, range and even relaxation time of the sensor can be adjusted. However structuring also adds to the cost and complexity of sensor fabrication [28], [34].

Pressure sensitive piezo resistive materials are commonly used in the design of resistive haptic sensors [35]. Though the underlying physics involved may be different, many of the issues discussed so far for the PDMS-based sensor design are also valid for piezo resistor based resistive sensor designs.

In general, regardless of the method used for sensor design, the variables like sensitivity, range, response time, spatial resolution, reliability, temperature dependence, cost and complexity of design, etc., are to be accounted for when deciding upon the haptic sensors. Often, these variables depend on the haptic use cases, for instance if the use case involves the need for a user to feel the texture of a fabric at a remote place, the sensitivity and spatial resolution of the haptic sensors should be increased. However, if the use case is simple enough to pick and place a uniformly shaped heavy object at the remote end, both spatial resolution and sensitivity will not be a factor, but the sensor range will have to be considered.

Another factor generally overlooked in the literature that needs to be considered when designing haptic systems is the placement. Haptic sensors can be fabricated as single-element sensors or as multiple-element sensor arrays [28], [30]–[34], [36]. Single-element sensors are generally costly and thus a right placement strategy is needed to position these sensors in the sensing area to maximize the coverage with limited numbers. Placement of sensor arrays is crucial. With the increase in array size, the number of individual sensors to scan also increases, increasing the sensing time and overall power consumption. Certain use cases may demand a combination of high/low spatial resolution for the sensing area. This means that certain regions in the sensing area may demand high spatial resolution, while certain others may not. In such a case, a combination of sensor arrays and single-element sensors to cover the sensing area may be a design possibility. This further complicates the sensor placement problem.

The design of sensing circuits is another area of research. In particular when dealing with scanning of sensor arrays that house many individual sensors. Traditionally, sensor arrays are scanned by multiplexing the individual sensors in the array to a single sensing circuit. This method many not be ideal for haptic sensors demanding high spatial resolution, as it will increase the scan time. A possible solution would be to have multiple sensing circuits addressing sensors in different regions of the sensor array, which also is an optimization problem to research [33].

To conclude, designing a haptic sensor for tactile applications is not straight forward: many open challenges exist and need to be resolved. Optimizing spatial resolution, sensitivity, scan time and placement being the top priorities.

2) HAPTIC ACTUATORS

Within haptic feedback, a distinction can be made between cutaneous and kinaesthetic [37], [38] touch: kinaesthetic touch is the sense of the relative position of neighboring body parts and force or muscle tension, whereas cutaneous touch is touch pertaining to the skin, such as pressure, vibration, temperature and pain.

Over the years, research into haptic feedback has shown that it is challenging to design a haptic feedback system that delivers a feeling of touch to the user that is similar to what the user would feel in the real world. However, it does need to be stated that the aim of haptic feedback is not necessarily delivering a realistic sense of touch: if some other form of haptic feedback would outperform actual sensing in the real world, it is even desirable that haptic feedback does not represent actual touch. An experiment, in which participants try to recognize textures using both their hands and two haptic devices, shows that this might be the case for texture recognition [19]. Haptic feedback can also be used for cases where humans would not feel anything in the real world, such as proximity of objects. Therefore, it can be by design that haptic feedback does not represent actual touch.

Haptic feedback can be delivered in many different forms, depending on its intended use. Many haptic displays that present the user with haptic feedback have been created and experimented with. The types differ from non-contact tactile displays, such as displays using radiation pressure of ultrasound [20] to vibrotactile gloves using vibration motors on the fingertips [21]–[23], [39], [40].

One of the problems of non-contact displays is that movement is limited by the area of the display. This can lead to scalability issues and also makes applications where the user can freely move around harder to implement.

Glove-based displays have often been used in research. The advantage they offer over other displays is that they are often non-grounded, meaning that they are not attached to some bigger object and can freely move around. However, gloves that are only vibrotactile and do not offer kinaesthetic (force) feedback have the problem that their feedback is limited. This will be clearly noticeable for applications that involve touching virtual objects, such as in [22]: the user will be able to move through virtual objects, while only receiving vibrotactile feedback when moving through the borders of the objects. In the case of a teleoperated, instead of a virtual, system this could result in the feeling of moving through objects, knocking objects over, squeezing them with too much force and other problems that result from a lack of realistic feeling. To get a more realistic feeling of the objects, kinaesthetic feedback will also be needed. This type of feedback can limit or completely prevent movement through objects and can also enable perception of properties such as hardness, flexibility and elasticity. The perception of weight can also be accounted for [24].

Current glove implementations of haptic displays that include kinaesthetic feedback often have the disadvantage of a limited workspace by attaching the user's arm or hand to some grounded construction, such as in [24]. Another implementation that is ungrounded [21] adds weight to the glove itself, which might limit the time duration that users can work with this type of glove without supporting their arms or hands.

An alternative approach to kinaesthetic feedback is discussed in [25], where a device that applies force to the fingertips is complemented with a superimposed electrical stimulation of the muscles, which allows actively changing the position of the fingertips. However, this method has not yet been tested on all fingers simultaneously and also still requires proximity of the user's hand to a motion sensor. Also, while more kinaesthetic feedback is present for vibrotactile-only gloves, it is still not a complete solution in that it would still be possible to move through objects in a virtual system or feel like moving through objects in a teleoperated system.

From the studies discussed in this section so far, it becomes clear that kinaesthetic feedback is one of the challenges that does not have a (complete) solution yet. In [39], an experiment shows that the test subjects were able to distinguish between smoothness, weight, friction, elasticity and hardness using a glove with only vibrotactile feedback. However, being able to distinguish between these properties is completely different from perceiving a remote object realistically. While vibrotactile feedback might be sufficient to create a usable haptic display, a realistic perception will also require real kinaesthetic feedback.

The current challenge is to design a realistic haptic display, with both cutaneous and kinaesthetic feedback, that is ungrounded and not limited to a specific area by other means, while being lightweight at the same time. Once such a system has been developed, other senses such as heat can also be added. This would be an ideal, general case of a

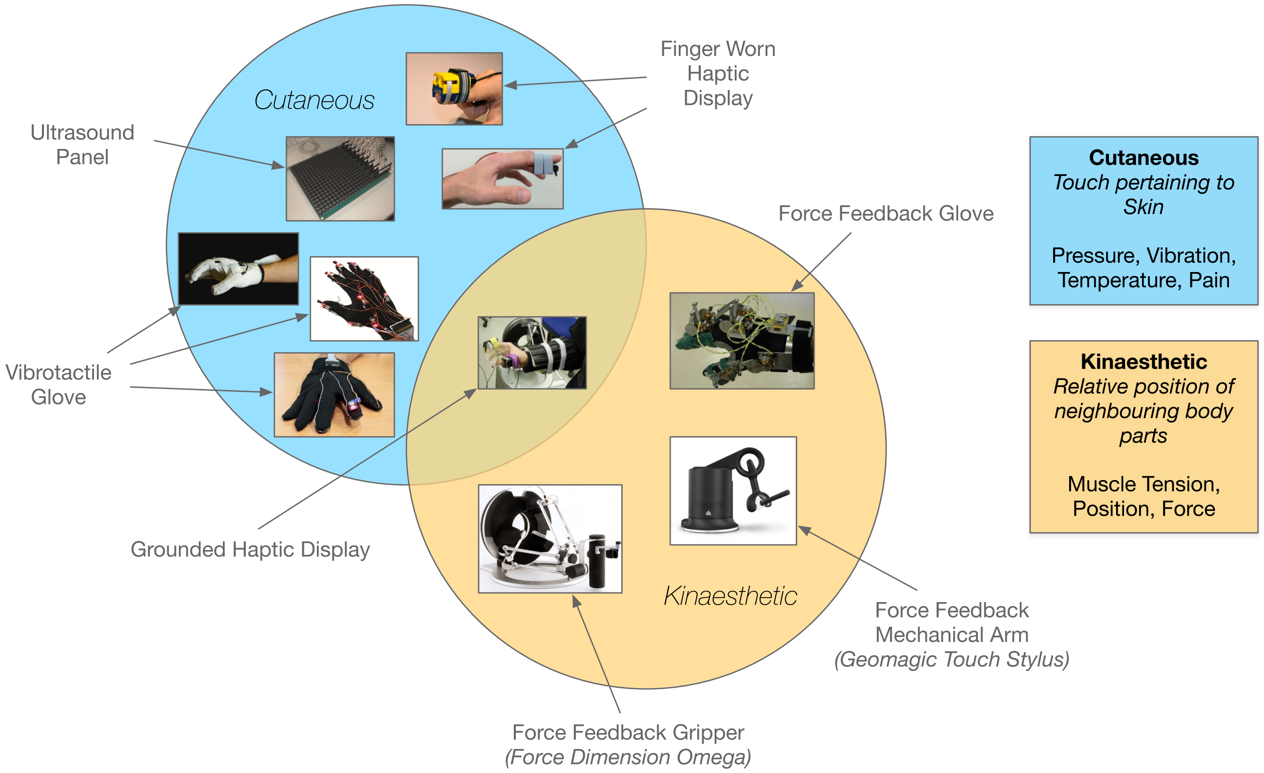

FIGURE 3. **An overview of haptic feedback devices discussed. Devices are grouped based on cutaneous or kinaesthetic properties. It is important to note the lack of ungrounded devices with both kinaesthetic and cutaneous properties. The figure contains devices from [19]–[27].**

haptic display. For specific uses such as telesurgery, such a display would not be suitable. Instead, for telesurgery and other specialised cases, a replica of the actual equipment that contains realistic feedback mechanisms would be suitable as a haptic display, so that the user cannot distinguish between the real-life and remote cases [41].

An overview of the discussed haptic feedback devices is shown in Fig. 3.

B. KINEMATIC DEVICES

Kinematic devices capture the motion of the operator and recreate the same at the tele-operator end. These include kinematic sensors and kinematic actuators. Kinematic sensors capture motion at the operating end, which the kinematic actuators recreate at the tele-operator end.

1) KINEMATIC SENSORS

From using simple mechanical techniques, to methods employing magnetic, capacitive, e-field, IMU, acoustic and optical sensors, the literature reports many different ways to devise kinematic sensors [42]–[51]. In magnetic-based methods, change in the position of magnetic materials positioned at different parts of the body are sensed using a magnetic sensor. The data is then used to infer the position and motion of the body. Capacitive methods track the body motion using an array of capacitive sensors placed near to it. The body and sensors form a parallel plate capacitor whose capacitance changes when the body moves. E-field methods sense the changes in the static e-field to infer the body motions. RFID-based methods employ tags and sensors to infer the motion; the concept is similar to that used in magnetic methods. Inertial measurement units (IMU) are also used to devise kinematic sensors: they track the position and motion with the help of attached IMU sensors, which encompass a combination of accelerometers, gyroscopes and magnetometers. Optical methods use image sensors to capture the image at regular intervals and then use post-processing algorithms to infer the motion. Acoustic-based methods use sound wave emitters and receptors to track the position and motion of a body, by sending a sound wave and measuring the time it takes for it to get the echo back. Simple mechanical systems are also used to track motion and they are usually made with series of connected links and electromechanical transducers, like potentiometers to track the movement.

Of the methods discussed above, many are useful in capturing only the gesture [48], [50], [51]. This is not useful in haptic systems where the operator motion is to be faithfully tracked and reproduced. Though these methods can be leveraged to track the motion, such efforts will only give coarse data points for the motion being sensed and, moreover, such efforts will need computationally intensive algorithms, thereby increasing the scan time. Capacitive, e-field, and magnetic methods restrict the operator from handling conductive/magnetic objects when using the haptic system.

While this works well in several haptic use cases, this does not work as expected in cases where the operator handles a replica of the remote object. Optical and acoustic methods will demand the operator to be in the field of view of the sensors, which limits the operating area of the user. Optical and acoustic methods also suffer from occlusion, which happens when a part of the body masks the other part from the line of sight of the sensors. Occlusion can constrain the actions a user can perform, like handling, gripping or twisting an object, as in these actions the fingers get masked by the palm. Barring few exceptions, mechanical, IMU, e-field, RFID, capacitive, and magnetic methods require the operator to attach sensors as wearable devices. Usually in these methods a glove is created with necessary sensors. The operator wears to track his motion. In such cases, the operator is required to wear a glove, the same glove can also incorporate haptic actuators to provide haptic feedback. On the other side, glove-based systems can be cumbersome to wear in certain use cases.

Another important consideration to be accounted for is the scan time. For haptic systems, an end-to-end delay of few milliseconds is imperative. This also includes the time it takes to scan and track the operator kinematic motion. In many of the kinematic sensing methods described above, multiple sensors are used to track the motion, even if the individual scan time of these sensors meets the scan time constraint (which is not the case presently), reading data from each of these individual sensors for post-processing is a challenge. Many of these sensors support low baudrate embedded protocols like I2C, SPI or UART to send the sensor data, which a master embedded computer reads using I2C/SPI/UART master blocks. The issue is that often the number of I2C/SPI/UART master blocks are limited in an embedded computer. This forces the master to read sensor data one at a time. This read time can add to the overall scan time of the kinematic method. A solution here would be to devise algorithms to dynamically pick the sensor of interest and read the data, rather than always read the sensors in a stipulated order. More work is required to devise such algorithms.

Yet another challenge is with regard to the post-processing time. Kinematic methods make use of sophisticated kinematics algorithms to track the motion. Predictive algorithms and optimization techniques are also employed in many of the methods described above. For the glove-based systems, usually the low cost, low MIPS embedded computer housed in the glove does this computational work. This results in higher orders of post-processing time. A possible solution would be to push this computational work to the cloud. A detailed study on the time savings with this solution needs to be conducted.

2) KINEMATIC ACTUATORS

In many use cases of haptic systems, at the tele-operator end, a robot will be placed to mimic the operator actions. This robot, in many cases will not have a mechanical structure that resembles that of the operator. For instance there could be a difference in the degree of freedom of movement between the operator and the robot. In such cases, inverse kinematics algorithms are used. These algorithms compute the link angles of the robot to ensure that the final posture of the robot resembles closely that of the operator. A kinematic actuator thus has two parts to it, a computational engine that runs the inverse-kinematics algorithm and a driver circuit to drive the physical actuators connecting the robot links.

For simple structures, inverse kinematic algorithms involve solving simple kinematic equations representing the robot links. This is not the case when the number of links increases. In such cases, the analytical equations become hard to solve and numerical solvers are then used to find an approximate solution. Numerical solvers are computationally intensive, which can increase the actuation time and thus increase the end-to-end latency numbers. Here too, as discussed in section III-B1, the computational work can be pushed to the cloud. More research is required to analyze the savings in time we attain with this method.

Driver circuits and physical actuators are well researched in academia and industry; it largely depends on the use case what type of driver circuit and physical actuator is needed. However, work is still required to analyze the impact of driver circuit and physical actuators on the end-to-end latency for specific haptic use cases.

C. COMPRESSION

To improve the freedom to move for users of haptic devices, there is an increasing integration of more and more degrees of freedom (DoF) in haptic devices. Each DoF needs continuous sampling, which means that the total amount of data from sensors and actuators rapidly increases. For digital audio and video, methods to reduce the amount of data sent are widely used and standardized [52]. However, this is not yet the case for haptic data. In order to comply with the requirement for the end-to-end delay, data reduction methods that are specific to haptic data should be used. These data reduction methods must have a low execution time, because otherwise the time savings of the lower latency will be neutralized by the execution time of the data reduction method. In this subsection, the first possible method of data reduction is discussed, namely compression.

A possible compression technique is described in [11], where the authors make use of the perceptual masking phenomenon. This is a limitation of human perception, which implies that movements of an actuator with a strong frequency will mask movements with a weaker frequency. Therefore, the weaker frequency movements have no influence on the perceived haptics and can be filtered from the signal. This technique is also used in audio compression, where the threshold for a certain frequency becomes higher when a masking tone is present. This limitation of human perception could also be used to compress the amount of haptic data. In [11] it is shown that it is possible to get an compression ratio of approximately 8:1 without any perceptual degradation.

TABLE 1. QoS Parameters for audio, video, graphics and haptics.

QoS Parameter	Audio	Video	Graphics	Haptics
Delay	$\leq$ 150 ms	$\leq$ 400 ms	[100 - 300] ms	[3 - 60] ms
Jitter	$\leq$ 30 ms	$\leq$ 30 ms	$\leq$ 30 ms	[1 - 10] ms
Data Loss Rate	$\leq$ 1%	$\leq$ 1%	$\leq$ 10%	[0.01 - 10]%
Data Rate	[22 Kbps - 200 Kbps]	[2.5 Mbps - 40 Mbps]	[45 Kbps - 1.2 Mbps]	[128 Kbps]

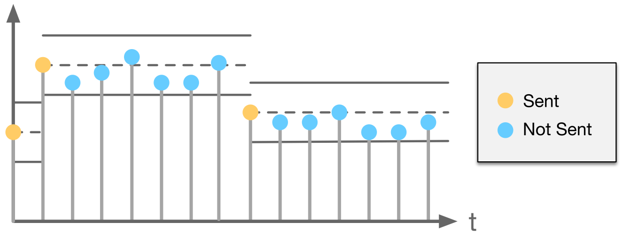

FIGURE 4. Illustration of perceptual deadbands as described in [7]. In this example a data reduction of 80% is achieved.

In [7] masking is described in the form of perceptual deadbands. Perceptual deadbands are adapted to human perception thresholds and give a zone in which differences are too small to be perceptible. When a sampled value from a haptic sensor falls in this zone the sample will not be transmitted, which results in a reduction of the number of samples that need to be transmitted. An example of this principle is shown in Fig. 4. The underlying principle for these compression techniques is the mathematical relationship between the intensity of a stimulus and the perceived intensity proposed by Ernst Weber [7].

$$\frac{\Delta I}{I} = k \tag{1}$$

(1) is known as Weber's law of just noticeable difference (JND). It describes the relationship between the noticeable difference and the stimulus intensity. Weber's law is applicable to almost every human sense, including haptic perception [7]. It is possible to achieve a data reduction of 97% using deadband-based data reduction [6].

The distortion introduced by these compression techniques should be kept as low as possible. Otherwise, another requirement for haptic data communication could be violated, namely perceptual transparency [2]. In the ideal case, the distortion created by the compression would be below the human perceptual thresholds. Another challenge for these masking compression techniques is choosing the right size for the deadbands. They must not be too large, because then it becomes noticeable by the users. The deadbands should also not be too small, since then almost every sample has to be sent and there is no data reduction accomplished. The amount of reduction that can be accomplished with these reduction techniques depends largely on the data to be sent. When the values that have to be sent fluctuate a lot, there would not be a significant data reduction. Further research is necessary to achieve a reliable data reduction for every combination of data samples.

D. MULTIPLEXING WITH AUDIO AND VIDEO

By communicating multiple modalities together, improved perceptual performance in a telepresence system can be achieved. Improving the perceptual performance helps in satisfying the reliability and transparency requirements. Since each modality has different requirements in terms of latency and data rates, a multiplexer combining these modalities is required [6]. Table 1, adapted from [53], contains an outline of Quality of Service parameters for audio, visual, graphics and haptics, based on various studies. From this outline, it becomes clear that there is a large variation in requirements per media type and also that haptic media is an order of magnitude more sensitive to delays and jitter than other modalities [53]. Large delays and jitter lead to quality loss and unstable behaviour of haptic devices, requiring the haptic modality to have a high priority [54].

To make sure this prioritisation is achieved, [54] describes an adaptive multiplexing model that selects the most urgent pieces of information to be transmitted, in case there is a lack of available resources. The proposed multiplexer assigns more network resources to more demanding modalities, such as the haptic modality, based on a statistical model. The multiplexer is also in line with the requirements for haptic communication, since the overhead in computation time complies with the 1 ms challenge and it adapts to the network conditions (improving reliability). An implementation of [54] is proposed in [53] under the name ADMUX (Adaptive Multiplexer). Among the important features of ADMUX is that its implementation can be used together with compression and control algorithms, as described in the previous subsection, to improve the quality of communication. ADMUX has been tested in a game using both kinaesthetic and vibrotactile feedback.

In that game a demonstration is given, pointing out two main features: (1) synchronization of audio, video and haptic modalities, and (2) adaptation to network conditions [55]. Because ADMUX is based on UDP, an algorithm dealing with packet loss is required. Also, in its current form, research is required for applications involving many users. Another multiplexing scheme supporting haptic multiplexing together with audio and video is proposed in [56]. This scheme is designed for use over constant bitrate communication links. This approach will always give the haptic modality the highest priority, assigning other modalities a higher share of the total available bandwidth, in case there are no haptic data available. As described in the previous subsections, devices with a higher DoF are being developed. This poses a problem for the approach described in [56], since the proposed packet structure is limited to only three degrees of freedom.

Another possibility is to look at multiplexing from a visual perspective. Are current teleconferencing implementations ready to be multiplexed with haptic data when low-latency communication is required? The video transmission equivalent of the end-to-end delay is the glass-to-glass delay (G2G) [57], [58]. The G2G has been measured for several modern teleconferencing and teleoperation applications. Due to factors such as processing within devices, buffering, and propagation within the network, the worst-case G2G delays measured are in the order of 1 second [57]. If we translate these results back to the problem of multiplexing, the importance of low G2G delay video applications to be combined with the haptic modality becomes clear.

Current work done in the field of multiplexing the haptic modality together with audiovisual modalities is limited. From the requirements described in the previous section, it becomes clear that we need a multiplexer that provides the user with a sufficient QoE and complies with the 1 ms challenge. We also need to assign enough bandwidth to each modality to improve performance [6]. Looking at these requirements, the algorithm described in [53]–[55] currently fits best, but still requires more research, especially in the QoE domain.

E. SDN AND NVF

We have discussed techniques to pre-process the haptic data. Unfortunately, compressing data from the Human System Interface and correctly multiplexing haptic data is not enough to satisfy the requirements for haptic communication. The haptic data have to be sent to a destination. In this section, some techniques to accomplish this are discussed, as well as some open challenges.

Current network algorithms are unable to adapt swiftly to frequently changing network conditions and are therefore not well-suited in case we need hard QoS guarantees or advanced traffic management. Software-defined networking (SDN), together with network function virtualisation (NFV), forms a way to implement this flexibility. SDN is defined as decoupling of the network control and data planes [59], which means that every node in the network is centrally controlled from software-based controllers. Because these controllers have a centralized view of the network, they are able to react and adapt to changing network conditions faster. They also provide easier network management and monitoring [60]. Because of the strict requirements for the tactile flows, these flows need to be differentiated and network resources need to be allocated to ensure the priority of this low-latency traffic. In traditional networks, two main QoS architectures exist (IntServ and DiffServ), but to date have been hardly used in the Internet. While IntServ is complex and not scalable, DiffServ only provides relative QoS guarantees, which is not suitable in case of hard QoS constraints. SDN changes this as it offers new ways to implement QoS control. A lot of work has been done in the area of applying QoS routing to SDN [61]–[63], but these papers mostly consider the bandwidth constraints and do not take the delay as the primary metric. Additional research in this area is needed because, in the case of a tactile flow, the goal is to find the path with the lowest latency, while also taking into account the fact that network conditions can change rapidly. Another important aspect that needs to be taken care of is the resilience of the network. Failures in networks are common and efficient failure recovery schemes need to be implemented. In [64], [65] a fast failover mechanism for SDN is implemented by precomputing and installing backup paths in the switches and using specialized protocols, such as Bidirectional Forwarding Detection (BFD), to detected link failures.

While a lot of work has also been done in case of datacenter SDN networks (e.g. [66]), as well as networks that interconnect those data-centers (e.g. [67]), the case of carrier networks has been mostly neglected, i.e. networks that are more geographically dispersed and have a large number of nodes. In [68], the authors propose a recursive computing approach for these networks that combines the programmability of SDNs with the scalability of traditional hierarchical networks. More research in this field is required as the tactile flows are envisioned to traverse multiple carrier networks.

When NFV is applied, services like load balancing and caching are moved away from dedicated hardware (middleboxes). Since they are nowadays implemented in dedicated hardware, their maintenance and deployment is usually cumbersome and difficult. NFV solves this problem by shifting middlebox processing from specialized hardware to software that can then be easily deployed in the network. This allows for more elasticity, better performance and more flexibility [69], [70]. Typically, these network functions are not applied separately, since usually more than one is needed. Thus, in order to achieve better modularity and scalability, a service chain of connected network functions is created. This process is called network service chaining or service function chaining (SFC) [70]. To make sure that a certain network flow traverses a given set of network functions, and in the right sequence, we need to use SDN. The problem of placing the network functions, at the best physical locations, according to some given optimization goals and in the most cost-effective manner, is also not trivial. NVFs usually have different requirements and can depend on each other [70]. This might be particularly challenging in case of tactile flows, because end-to-end latencies may become intolerable, depending on how virtual network functions are positioned and chained in the physical network. In [71], it was shown that virtualization can cause significant throughput instability and abnormal delay variations, even in cases when the network was only lightly utilized. Also, the processing times can be higher compared to the solution where middleboxes were deployed on dedicated hardware and can also depend on the hardware configuration of the device hosting it [69], [72]. The flexibility and ease of deployment gained by the use of NVFs can thus become a flaw if we do not take all these things into account correctly so that the end-to-end delay remains within acceptable limits.

Using new dataplane programming techniques, like the P4 programming language, the implementation of some network functions can be done in the switch fabric. One of the main advantages of P4 is that chips compatible with the language can be reprogrammed in the field after they are installed. This can make the deployment of NFVs easier and faster [73].

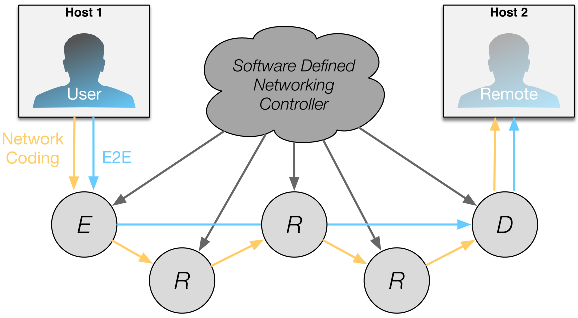

FIGURE 5. **An example of a Software Defined Networking controller flexibly allocating encoders, recoders and decoders.**

F. NETWORK CODING

Network coding is a coding strategy that could be used to decrease the delay over the network [74]. A coding strategy is a way to control how data is sent over an unreliable channel and it influences the communication's efficiency, scalability and error probability. The difference between network coding and the currently used coding strategies is that with network coding every node in the network is able to evaluate the situation and adapt its coding strategy [74]. Where, previously, every node in the network just stored and forwarded every incoming packet, network coding is able to recode every received packet. This way, the coding strategy is not end-to-end anymore and does not have to deal with losses over the whole path, but just between two nodes. Therefore a lower amount of retransmissions together with a decrease in delay are expected with network coding. This will only be the case when the recoding procedure in the nodes only takes a tiny amount of time. To achieve this, a highly adaptive energy-efficient computing (HAEC) box or system can be used, which makes it possible to have significantly more computing power in every access point or base station compared to the currently used devices [75]. Network coding can be used efficiently in a network if there is the possibility to flexibly allocate coders, recoders and decoders, which is not possible at this moment [74]. This flexibility is expected to become available with 5G, in which SDN and network coding are key techniques [76]. An example of an SDN controller allocating network coding nodes is given in Fig. 5. Using network coding in combination with SDN and NFV will significantly decrease the latency compared to end-to-end coding strategies in single-path communication [74]. However, the latency is still not in the range of the 1 ms requirement for haptic communication. Further research is necessary to investigate the possibilities of multi-path communication in combination with network coding and other combinations of networking techniques to come closer to the 1 ms end-to-end delay requirement.

G. PREDICTIVE ARTIFICIAL INTELLIGENCE

While the above-mentioned methods can reduce the latency of the network domain, they cannot improve the lower bound of the latency that is a given by the speed of light. In this subsection, prediction algorithms are discussed that aim to deliver a seemingly real-time experience to the user (while the actual latency is still bound by the speed of light) [3]. A prediction-based approach is the only way that a latency can be acquired that is seemingly lower than the speed of light, increasing the maximum travel distance to beyond the limit illustrated in Fig. 6. Because of that, the main focus in this subsection is the perceived latency and the immersiveness of the system. Note that separate algorithms are used for predicting motion in the remote environment and feedback data in the local environment. In the examples that follow, only the algorithms regarding the user feedback are treated, because the motion prediction algorithms work in an analogous way (on the other end of the communication link).

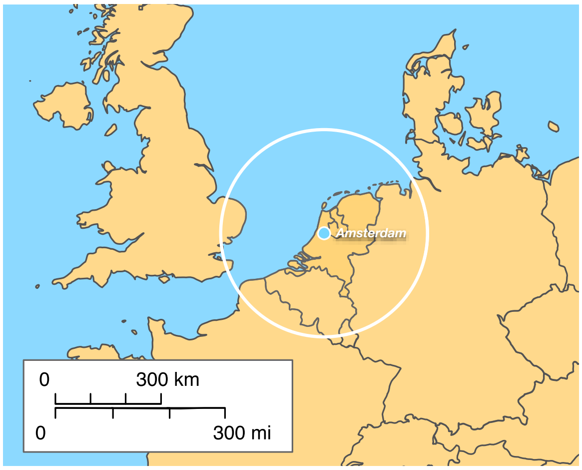

FIGURE 6. **Illustration of the distance that can be reached in 1 ms by signals starting in Amsterdam and traveling at the speed of light. Other types of delay in the network are not taken into account.**

The most basic prediction algorithm is a linear predictor, which outputs a prediction that is a linear function of a fixed number of previously received values [77]. The simplest way in which such an algorithm can be used is by executing it only at the side of the operator. In that case, the predicted values are directly used as feedback to the user to deliver a (seemingly) real-time experience. The received values could then be used to update the coefficients of the algorithm, if necessary. It is also possible to use the linear predictor in combination with the previously discussed perceptual deadbands. To do this, an exact copy of the algorithm is executed on both sides of the communication link. On the side of the operator, it determines the feedback that is given to the user (like it did in the previous method). In the remote environment, the algorithm outputs the exact same feedback predictions as in the local environment, based on the feedback that is sent to the operator. This leads to the presence of both the predicted values and actual values in the remote environment, which can then be compared to each other. Only when a value differs more than a specified threshold from the predicted value, it is sent to the local environment. This method does not only deliver a fluent experience to the user (like the simplest linear predictor), it also reduces the amount of haptic data that needs to be sent (like the perceptual deadbands compression method). A variation of this method is based around the same concept, but additionally to sending the actual value when the threshold is exceeded, new coefficients are calculated for the linear predictor and sent to the local environment. This threshold must be chosen such that the propagation time of sending these updated coefficients is lower than the time it takes for the deviation to become larger than acceptable for the given application [3]. Recalculating these coefficients can be done using machine learning or other artificial intelligence algorithms, which can lead to performance improvements of the system over time.

Although a basic linear predictor with perceptual deadbands can lead to a significant decrease in packet rate without deteriorating the immersiveness of the user [7], improvements to the prediction accuracy are still possible. These improved algorithms rest on the same principle, but use enhanced functions of the previous input values to predict the current value [3], [78]–[84]. All of these improvements strive to increase the accuracy of the predicted values, which improves the real-time experience of the user.

Other than a mathematical function-based algorithm, in which the prediction is calculated from previously received values, a model-based algorithm can be used [7], [85]–[87]. In this type of algorithms, a model of the environment is created based on the sensor values at the remote location (slave domain). The parameters of the model are continuously updated and sent to the local environment (master domain). At the side of the operator, a copy of the model is constructed accordingly and haptic feedback is generated locally based on this model without any propagation delay. As a result, the sensor values themselves do not need to be sent, unless a combined method is used that also uses the sensor values, such as in [85]. An illustration of a real object and the model that is created from this object is shown in Fig. 7. The original model-based approach is further improved in [86], where a time-of-flight camera is used to create a point cloud of the environment. This allows for a more accurate representation of complex geometries, but comes at the cost of larger data transmissions.

Even though research is already quite extensive in the field of haptic data prediction, the predictive algorithms need thorough testing in actual use cases rather than experimental setups. While these prediction methods turn out to yield large data reduction percentages and increased immersiveness in experimental setups [77], [82], [84]–[86], this does not need to be the case for actual telehaptics systems. In [88], a linear predictor with deadbands is tested in a real scenario. In this scenario, the achieved data reduction is far lower than the ones in experimental setups. The prediction algorithm even caused an increase in the number of packets for some values of the deadbands. Other than testing of real scenarios, research also has to be done into cases where very small differences between predicted and actual values can be damaging or dangerous. In telesurgery applications, for example, small deviations in the controls of medical equipment might be unacceptable due to risks towards the patient. A final area within haptic data prediction that is still lacking is the application of artificial intelligence algorithms. These algorithms should be able to learn from false predictions, recognize patterns and improve over time.

FIGURE 7. Illustration of model-based prediction as described in [7]. In this example a bottle is modeled via 4 cylinders.

H. EDGE COMPUTING

When prediction algorithms become more and more advanced and computationally intensive, mobile edge computing (MEC) can be used [89]. MEC brings cloud-computing services geographically closer to the user than current cloud-computing services [89]. This means that they can be accessed with a lower latency compared to current services [3]. This approach can be used to provide mobile users with flexible access to computing power without the need for dedicated hardware. Since these services are available at a location that is physically close to the user, there will be no significant delay for accessing these and the 1 ms end-to-end delay constraint will not be violated. Some problems arise with security, however, when the haptic data are processed on a remote server, since the data have to be sent from the device to the MEC server and vice versa [89]. Encryption could solve this problem, but this inherently adds an additional delay in the communication with the MEC server.

I. HAPTIC SYSTEM EVALUATION

Once the challenges that are currently still unsolved will be solved in the future, the actual implementation of the

Tactile Internet can start. This implementation requires testing of the entire haptic communication chain. An objective metric for haptic communication would be of great value to evaluate the different requirements. With such a metric, it becomes possible to efficiently test a haptic communication system without the need for manual testing. Currently, almost all the haptic applications rely on subjective evaluation methods with human subjects. These evaluation methods are extremely time-consuming and expensive [90]. For digital signals, in general, there are currently already standard metrics such as Mean-Squared Error and Signal-to-Noise Ratio in use, but these are not adequate for haptic signals. These objective measures do not account for human perceptional characteristics. Haptic signals contain multidimensional attributes, such as position, force and velocity, for which the standard objective metrics do not account. A possibility to include these attributes in an objective quality metric is the Haptic Perceptually Weighted Peak Signal-to-Noise Ratio (HPWPSNR) [90]. This metric considers the perceptually noticeable differences. A short experiment is executed on two signals to see the improvement in comparison to a metric that does not consider the perceptually noticeable differences. In the experiment, it is shown that HPWPSNR is able to take the perceptually noticeable differences into account. However, in the experiment, only two signals are tested so to determine the quality of HPWPSNR more experiments are necessary.

J. HAPTIC SYSTEM TESTBED

Haptic system evaluation will advertently need a testbed, to test, characterize, and validate the many aspects of end-to-end haptic communication. A modular framework is desired to accommodate a wide variety of haptic and tactile internet use cases. This is in contrast to existing designs, which are either use-case specific or are not meant to test an end-to-end haptic communication system [91], [92]. Modular design will also help in the widespread adoption of the testbed among the research community, helping the researchers to focus more on the specific use cases and modules of their interest. A generic framework proposed for the testbed is outlined in Fig. 8. As shown in the figure, the testbed is built using multiple sub-blocks, which in turn are built with numerous pick and place modules. Depending on the use case to be tested, the sub-blocks are re-configured by adding/removing modules of interest. Such a design will minimize the cost, effort, and evaluation time of haptic systems. It should be noted that not all haptic system components can be physically realized in a lab environment at short notice. In such scenarios, simulation programs may come to the rescue. The envisaged testbed should be able to incorporate major simulation environments to model and integrate haptic system components for testing purposes. A generic configurable connector interface should be defined to glue the testbed sub-blocks and simulation programs to work without any hiccups. A connector interface should also wire the sub block modules to the centralized power management and control system. The centralized power management system should be responsible for powering and sequencing the testbed sub-blocks and modules. A centralized control and debug plane is needed to configure, monitor, and run experiments and take measurements with the testbed.

Careful definitions and design strategies are needed to ensure that the modular design of the testbed does not alter the performance metric of the haptic system being evaluated. Latency budgeting of each sub-block and module should be done a priori before being incorporated with the testbed. Provision should be there to evaluate the impact of simulated components (if used) on the performance numbers being quantified. The testbed should be designed to support industry-standard interfaces to enable plug-and-play support of lab instruments and modules. Since meeting end-to-end latency is vital in the operation of haptic communication systems, the testbed must include tools to characterize the latency of the end-to-end system. Additionally, the testbed tools must be designed to extract and report the latency of the sub-blocks and modules in use, to aid in research and development.

IV. DISCUSSION

Since survey papers regarding the Tactile Internet and haptic data already exist [2], [3], [5], [15], [18], [74], in this section, we present what distinguishes our work from the work of others.

When envisioning the requirements for the Tactile Internet, most papers agree on which have the highest priority. These can be summarized by the ‘‘1 ms challenge’’, perceptual transparency for ensuring the QoE, and a certain degree of reliability and security in the whole haptic communication system [1], [12], [75]. However, it is not always explained why these requirements should hold. When mentioning the maximal end-to-end latency, it is often only explained how this can be achieved. Omitting information on how this upper bound is determined creates confusion when other papers state maximum latencies of up to 60 ms [1], [5], [15], [53]. By stating the negative effects of delays higher than 1 ms, on the QoE and the whole communication system, we have tried to clarify this requirement. In [2] the definition of transparency is given, but its significance only becomes clear by discussing what affects transparency. In our work, this has been discussed separately to create a clearer link with the challenges.

General solutions for obtaining the desired reliability are given in [3]. These solutions range from improving the physical layer to AI-assisted cloud computing. We have approached this requirement in relation to handling haptic data. This results in a more detailed and uncluttered approach to related challenges in the three domains of the haptic communication system. The different technologies needed (SDN, compression strategies, network coding, prediction algorithms) have not only been stated, but current implementations and improvements have been provided as well.

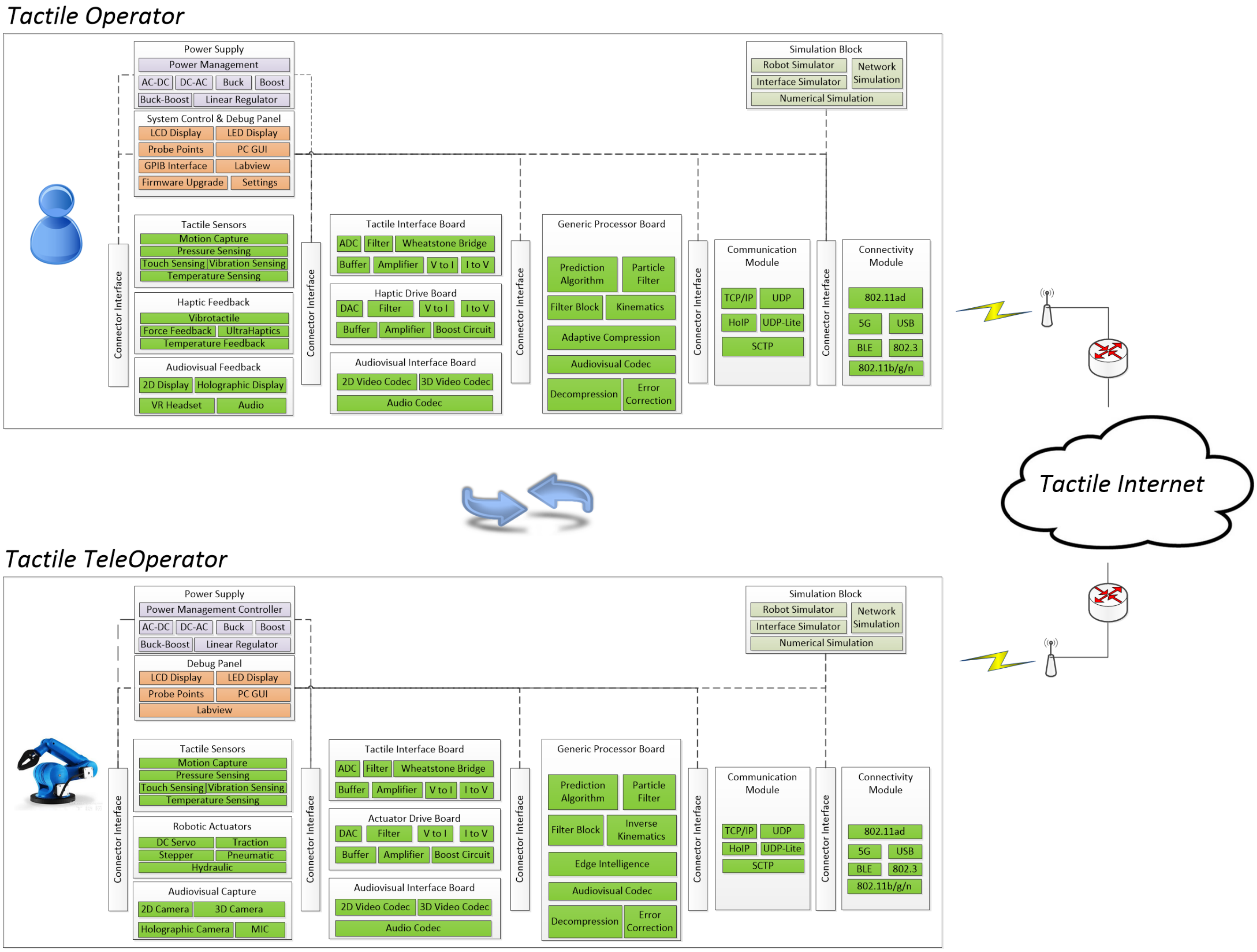

FIGURE 8. Proposed testbed architecture for haptic system evaluation.

[2], [3], [5], [6], [15], [75] list many applications using haptic data. Its improvement in many fields as health care and transportation are given and how it affects society and environmental issues. Our focus lies with the communication itself, resulting in only discussing the collection and sending of haptic data, instead of the haptic data's context. Independent of the application, haptic data need to be collected and sent in a reliable way. Compared to other papers [3], [15], we have given a more detailed analysis of current haptic devices, because of their important role in the performance of the whole communication system.

Finally, instead of presenting ideas and anticipations of haptic communication over the Tactile Internet [15], [75], we have aimed to inform the reader of the progress in solving its challenges.

V. CONCLUSION

In this survey, we have looked at the most prominent requirements for enabling haptic communication over the Tactile Internet. The most important one is an end-to-end delay that is at most 1 ms. Reliability is another key requirement, with a packet loss probability that does not exceed 0.001% being required for successful haptic communication. A third requirement is a sufficient level of security, while not increasing the end-to-end delay to above the 1 ms mark. A final major requirement is having a transparent experience, which largely determines the Quality of Experience; when a haptic communication link is transparent, the user will experience the remote situation as if (s)he is at the remote location.

These requirements are reflected in a number of challenges, some of which have proposed solutions within 5G technologies. Most of these challenges still need to be completely or partially solved, but research into the Tactile Internet is quickly emerging. The distinction between the different challenges is made based on the model of the teleoperation system of Fig. 1.

- **Haptic devices**: these devices are currently still unable to provide sufficient reliability and transparency. New devices need to be developed that can deliver both cutaneous and kinaesthetic feedback.

FIGURE 9. A graphical overview of all topics discussed in this work.

- **Compression methods**: to be able to comply with the latency requirement, a compression algorithm needs to be used that must not add distortion beyond human perceptual thresholds. Choosing the right parameters for this compression algorithm and achieving a reliable data reduction for every combination of data samples still require proper solutions.
- **Multiplexing**: resulting from the reliability requirement, this challenge involves developing a reliable multiplexing method that combines multiple modalities, including haptics. The haptic modality should be prioritized over the other modalities. Multiplexing schemes have been developed for this goal, but they are still limited in their degrees of freedom, making this an open challenge.
- **SDN & NFV**: these strategies aim to optimize the network domain in the model of the teleoperation system. Current networking algorithms are not able to efficiently implement QoS control and to adapt to frequently changing network conditions. The development of new SDN algorithms combined with NFV can help solve this problem.
- **Network coding strategies**: these strategies aim to decrease the end-to-end delay and thus contribute to fulfilling the latency requirement. The latency for currently existing methods is not yet in range of the 1 ms requirement. Thus, other strategies for improving the latency still need to be developed.
- **Haptic data prediction**: this challenge involves the prediction of haptic data when the propagation delay is larger than 1 ms, as a consequence of the distance between the endpoints. Existing haptic data prediction methods currently still need testing in real scenarios. Other than that, artificial intelligence solutions need to be combined with the currently existing algorithms.
- **Edge computing**: this challenge is derived from the use of computationally intensive prediction algorithms. Edge computing assigns these algorithms a place to run in the cloud, close to the user. A secure method that does not increase the latency needs to be developed.
- **Haptic system evaluation**: currently, testing a haptic communication link depends on subjective methods. An objective metric (HPWPSNR) has been developed, but it needs more elaborate testing before it can be used in practice.
- **Haptic system testbed**: existing haptic testbeds are designed either for specific use-case scenarios or for testing specific haptic system blocks. A modular testbed to test an end-to-end haptic communication system needs to be developed. It should be as generic as possible to use it for testing a wide variety of haptic use cases. More work is needed to define and design such a testbed.

Finally, Fig. 9 contains a short summary in the form of a mindmap to provide a complete overview of the topics that have been covered.

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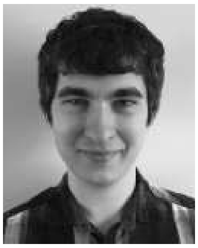

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