Controlling Humanoids: A Comprehensive Analysis of Teleoperation Interfaces

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***Abstract*— Humanoid teleoperation describes the remote operation of a humanoid target robot. This teleoperation not only demands real-time synchronisation of human actions with robotic responses but also necessitates overcoming issues such as latency and sensory feedback limitations. Additionally, the intricacies of mimicking human-like gestures and movements demand sophisticated control systems. The interfaces used play a crucial role in achieving seamless interaction between humans and robots in diverse environments. In this work we aim to provide an overview of these interfaces between the operator and the robot. We include a variety of designs for visual interfaces as well as body mappings and their feedback. Several designs for whole-body teleoperation interfaces are presented and discussed. Particular emphasis is placed on the modelling of hand interfaces and the transmission of cutaneous sensations.**

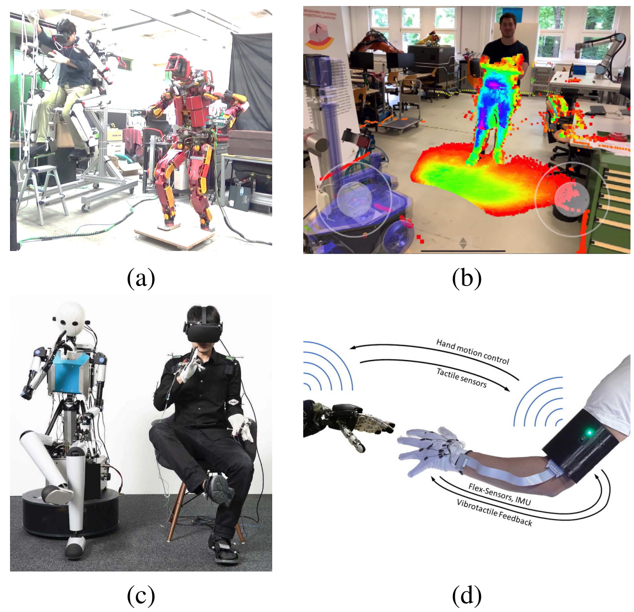

Fig. 1. A selection of different teleoperation interfaces. Figure 1(a) shows the whole body exoskeleton cockpit TABLIS [8]. Figure 1(b) displays a visualisation utilising augmented reality [12]. Figure 1(c) presents the telexistance humanoid robot TELESAR VI [11]. Figure 1(d) shows a sensory glove for teleoperation [13].

I. INTRODUCTION

Humanoid robots are one of the most fascinating areas of research in robotics today. Recent advances in computing, manufacturing and machine learning are opening up previously unimaginable possibilities. At the turn of the century, building a humanoid robot required specialist equipment and a dedicated laboratory [1]–[3]. Today, you're able to assemble your own basic robot with 17 degrees of freedom (DOF) by following a YouTube tutorial [4]. But we are still a long way from having a clone-like robot friend for everyone.

One of the biggest challenges is modelling the correct behaviour for different tasks. Especially if your robot is supposed to perform intricate tasks in a flexible way, the implementation difficulty of the associated software can range from challenging to impossible. So let us take advantage of the specific shape of the robots - their humanoid design. It allows them to fit into our familiar environments, which have been optimised for humans over centuries. Moreover, human operators are able map their particular expertise directly onto the robot. Many complex sequences of commands, such as grasping an object, don't need to be calculated in advance because the human operator's skills are used to control the robot [5]–[7]. Transferring relevant information to the operator, inaccurate approximations of the operator's position, or even motion sickness caused by the hardware used, are all challenges in teleoperation. How to interface a humanoid robot with its operator is a lively area of research [6], [8]–[11]. This work aims to provide a comprehensive overview of the different aspects and possible implementations of interfaces for humanoid teleoperation.

It is structured as follows: First, section II provides a background on key concepts such as teleoperation, communication channels, and the haptic primary colour model. Then section III deals with differences in visual interfaces. Next, section IV covers body mapping and feedback, divided into hands, upper body, bipedal movement, and whole body. The section V gives a rough idea of possible applications and additional areas of interest.

II. BACKGROUND

This section covers important background that is considered relevant to understanding the concepts introduced in later sections. It is divided into the three distinct topics. First, background on the concept of teleoperation is provided. This includes the difference between uni- and bilateral architectures, as well as the different levels of assistance, especially with regard to bipedal movement. Secondly, the communication channels used in the application of teleoperation are discussed and their limitations are shown. Thirdly, the concept of haptic primary colour theory is explained.

A. TELEOPERATION

The prefix *tele* comes from the ancient Greek têle, which translates to ”at a distance”. So tele-operation is a really descriptive name for remote control, in this case of a humanoid robot. An operator controls a robot from a distance

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to perform a specific task [5]. This control takes many forms and shapes with different levels of autonomy, control complexity, cost and setup requirements [6], [7]. While the focus of this work is on interfaces that facilitate the interaction between the operator and the target robot, the fundamentals of teleoperation design choices are explained briefly.

Teleoperation begins with recording the operator's actions. The capture process can be anything up to and including placing the operator in a full body exoskeleton cockpit [8]. When using humanoid robots, operators often take advantage of the intentionally similar anatomy. This advantage is utilised by recording the kinematics and dynamics of the operator.

The information obtained in this way has to be remapped from the operator's space to the robot's space, i.e. different sizes and forces have to be compensated. So called retargeting is divided into unilateral and bilateral architectures. In unilateral architectures the control is one-way [5]. The operator gives commands to the target robot and that is basically it. In bilateral architectures the feedback is two-way [5]. The operator receives active information from the robot. For example, the robot could prevent the operator from moving his arm, if the robot's arm were to be obstructed by an object [14]. This kind of interaction obviously requires an interface that supports the desired level of feedback.

Another important choice in teleoperation is the level of autonomy [15]. Autonomy ranges form manually controlling the torque of each joint to simply setting waypoints on a satellite map [5], [16]. In general, the more control you give your operator, the less autonomous the robot will be. At the same time, the operator's workload increases [5]. An interesting approach is to share control of different parts of the robot. A typical example is to give the operator full control of the robot's upper body, while the lower body is balanced autonomously [5]. This split operation model allows fine-grained control of the manipulating extremities, namely the arms and hands, while removing the tedious task of maintaining the robot's balance. Safeguards can also be implemented in a similar way [14]. These override commands to prevent dangerous movements or loss of balance [14].

B. COMMUNICATION CHANNEL

Transmitting the information required for successful teleoperation is a challenge in itself [17]. Three of the most prominent problems are limited bandwidth, delays and signal distortion [17].

Depending on the setting, the available bandwidth can be severely limited [18]. This problem has a direct impact on the amount of information that is transmitted from the robot to the operator. For example, the resolution of visual or audio information may need to be reduced in order to achieve a stable connection and transmission of movement commands [19].

Transmission delays are a very plausible problem that is exacerbated in bilateral architectures [20]. Simply put, the further away the robot is from its operator, the longer it takes for the operator's inputs to reach the robot. This delay is particularly important when considering applications such as remote satellite repair [10]. Latencies in excess of 100 ms can have a significant impact on the operator's experience [17]. Ferrell noted that in the presence of a delay, most operators adopt a "move-and-wait" strategy [17]. Here the operator simply waits for the perceived state of the robot to catch up with his inputs before making another. Although this strategy is effective, it is also time consuming. But since the latency is limited by the speed of light, one either has to limit the operating range or use highly predictive software that could be wrong in its prediction.

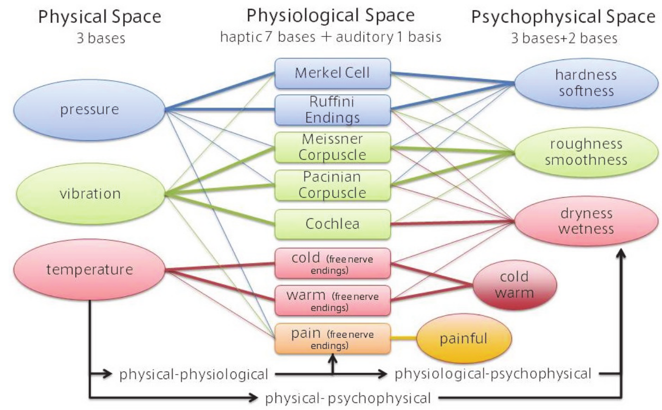

Fig. 2. The haptic primary colour model breaks down cutaneous sensations into three physical bases - pressure, vibration and temperature [22]. Facilitated by a variety of specialised cells and free nerve endings, a wide range of haptic sensations can be generated.

The third major problem in communications is transmission distortion [20]. Transmission distortion includes things like packet loss, but also, as a result of transmission delays, the use of outdated position information [20]. There are several methods to mitigate this problem, including time-stamping position information, using the last valid information, or even interpolation [20], [21].

C. HAPTIC PRIMARY COLOUR THEORY

Primary colour theory, as developed by Thomas Young, has shaped our understanding of vision for more than two hundred years [23]. Broadly speaking, the human eye can distinguish only three colours and perceives any other as a mixture of these three *primary* colours. Their intensity is irrelevant. As long as the ratio between them is identical, the resulting colours will also appear identical. A prominent example of this is the ubiquitous RGB model. Typically, each colour is represented by three 8-bit values (0 to 255) for red, green, and blue respectively. This decomposition allows the representation of over 16 million different colours and is essentially a transition between the space of physical objects and psychophysical perception.

Tachi et al. have suggested that something similar can be established for cutaneous sensations [22]. Figure 2 shows the haptic primary colour model. Similar to the RGB model, haptics can be broken down into three basic physical components - pressure, vibration and temperature. Physiologically, these components are experienced by a number of specialised cells in combination with free nerve endings. Working together, they convey the sensation of something being hard or soft, rough or smooth, dry or wet, cold or warm, or even painful. Capturing tactile information is surprisingly easy. Temperature and pressure, for example, are measured using a thermometer and a piezoresistive pressure sensor. And because air vibrations are perceived as sound, it is possible to use a microphone to record the vibrations of an object [22]. This recording method also makes it easier to store the tactile information.

III. VISUAL INTERFACES

The most important interfaces for controlling a humanoid robot are almost always the visual ones. It feels natural to see what you are doing. Consequently, visual interfaces are of paramount importance for locating and interacting with the environment and with oneself [5].

Different types of information can be displayed visually. In addition to colour images recorded by conventional video cameras [24], [25], information provided by LIDAR [26], [27], or even thermal cameras can be displayed [28], [29]. It is also possible to visualise auditory information, such as the direction of a sound source through visual indications [30]. In addition to these types of data, it is possible to display higher order information [31]. For example, it is possible to support the underlying algorithms by manually identifying particularly interesting areas in camera images [32]. This support provides assistance in finding target positions and identifying obstacles [32].

Apart from the use of conventional monitors, virtual reality (VR) headsets have become increasingly popular over the past decade [9], [33], [34]. They allow the operator to be immersed in the target robot's environment. However, this technology still has it's drawbacks. A common problem is motion sickness during locomotion due to unstabilised images and the lack of visual reference points [35]. Both root causes have simple solutions, such as hardware or digital image stabilisation, but are still rarely addressed [35], [36]. Another problem can be caused by delay [5]. Typical human reaction times are between 250 and 300 ms for visual stimuli [5]. If the communication channel has a higher delay, the operator experience is severely compromised and he might experience increased motion sickness [5].

Another approach offers the use of augmented reality (AR) [31], [37], [38]. The operator remains in his physical environment, which is augmented with information provided by the target robot. This reference helps, for example, to reduce motion sickness [35]. It is possible to do this either, using an AR headset [31], [35], similar to VR [38], or with an auto-stereoscopic three-dimensional (3D) display [22], [37], [38]. Such displays project a 3D image into space so that it can be viewed without additional equipment such as glasses [22]. For example, an operator might use one to interact remotely with a 3D object lying on a table [38].

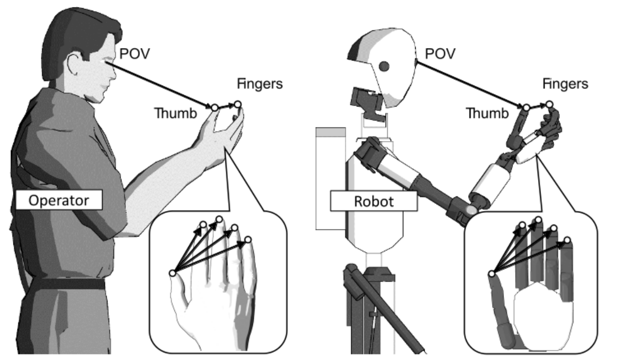

Fig. 3. The congruence of the distances between the POV and thumb/fingers of the operator and the target enables precise manipulation [11]. It resolves bone length differences by providing mapping constraints.

IV. BODY MAPPING AND FEEDBACK

In addition to visual and auditory interfaces, haptic interfaces and the mapping between operator and target are critical to successful, fine-tuned teleoperation [5]. (Auditory interfaces are not covered by this work.) Haptic interfaces range from a simple vibration on arrival at the destination [13], [39] to a full haptic reproduction of the surfaces the target robot is touching [11]. Like visual stimuli, haptic sensations also have a human reaction time [5]. However, at 100 to 150 ms, it is significantly shorter than its visual counterpart [5]. This restriction limits the irritation-free use of robot-triggered feedback to a range of about 45,000 km, assuming a unilateral design and perfect communication at the speed of light.

The other important facet is the mapping between operator and target. This work focuses heavily on the hardware aspects of this area.

The rest of this section examines designs for mapping different areas of the human body and is structured as follows. Firstly, the design of hand interfaces is discussed. Second, the idea of upper body designs is presented. Thirdly, the mapping of bipedal movement is outlined. Finally, several whole body designs are discussed.

A. HANDS

Our hands are paramount for interacting with our environment and tactile information is valuable for robots interaction with their environment [40], [41]. Therefore, when using a humanoid robot, special attention must be paid to the design of the hands. A prime example of what can be considered state-of-the-art are the hands and associated controllers of TELESAR VI. TELESAR VI was designed as a telexistance platform [11]. Telexistance describes the effort to give the operator the idea that he exists somewhere else virtually [42]. TELESAR VI was designed with telexistance in mind. It is a 67 DOF robot with special emphasis on the upper body [11]. More about this emphasis in section IV-B.

TELESAR VI is equipped with two 16 DOF hands [11]. Each finger has different DOFs to model the movement of human fingers. Therefore, the thumb is the most versatile finger with five DOFs, followed by the index and middle fingers with three each, and the ring and little fingers with two each. This models the opposable thumb, which is a unique human feature [43].

The movements of each hand are measured using a dual system of optical motion tracking and specially designed gloves [11]. The motion tracking uses eight cameras at a sampling rate of 240 Hz with retroreflective markers on the hands to estimate the position and attitude. In addition, active markers with LEDs are attached to the fingertips to provide additional information about the finger positions. Unfortunately, one of the main problems with optical motion tracking is occlusion [11], [44]. Here, this problem is mitigated by extending the system with wearable sensor gloves [11]. These are equipped with 16 inertial measurement units (IMUs) each, operating at a sampling rate of 60 Hz. An IMU provides information about its specific force, angular rate, and orientation. By combining both methods using a dedicated model, the position and orientation of the hands and each fingertip are precisely estimated. This method allows fairly accurate finger tracking with an average root mean square error of 5.2 mm [11]. However, it requires a special calibration phase and must be adjusted to the individual bone lengths of the operator.

Another challenge is the mapping between the operator's fingers and the target fingers [11], [13]. The length of individual fingers varies between humans and is unlikely to match the finger length of the target robot. Therefore, *perfect* control would only be possible for individually manufactured fingers for each operator [11]. However, a good compromise can be found. Since opposable thumbs are crucial for human hand manipulation, the position and orientation of the thumb requires special attention [11]. The position of the other fingers only needs to be correct in relation to the thumb. Figure 3 illustrates the vectors between the point of view (POV), thumb and fingers. The operator can use his own thumb and fingers precisely, as long as the distances between the operator's POV and the position of his thumb are the same as those of the robot [11]. Additionally, the relative positions between the operator's thumb and the other fingers must match those of the robot too. This congruence creates a shared task space in which the operator is able to work regardless of differences in finger and even arm length.

Since TELESAR VI was developed as a telexistance platform, the haptic features of the hands are quite extensive, using the knowledge of haptic primary colour theory [11]. The robot's 16 DOF hands have haptic sensors embedded in the fingertips. They consist of acceleration, piezoresistive force and thermal sensors. For each finger the acceleration sensor is attached to the top of the fingertip, the force sensor is attached under the bone, and the thermal sensor is attached to the finger cover with a thin elastic film. This design allows for precise measurements while improving the grasping ability [11].

The operator gloves are equipped with counterparts to reproduce the measured sensations. To achieve this, a vibro-

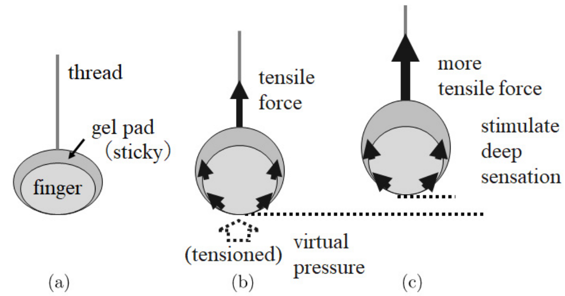

Fig. 4. A force representation system for fingers utilising tensile force by strings [11]. As the thread is pulled, the skin is deformed, creating the sensation of pressure. When the applied tensile force exceeds the skin deformation range, the finger is lifted.

thermal presentation module and force-representation system are installed on the control gloves [11]. As these systems are in addition to the active and passive motion tracking points, as well as the IMUs, the space for additional parts is strictly limited. Vibro-thermal presentation modules are rather small and don't take up more space than their housing [45]. They are therefore compact and available - easy to install and replace. The force-representation, on the other hand, is more challenging. As shown in Figure 4(a), the fingertip is enveloped in a sticky gel pad [11]. To reduce glove wear, the sticky gel pads can be replaced by C-shaped elastic rings, that grip the fingers from both sides. Attached to the gel pad or elastic ring is a thread that is contracted by a motor placed on the back of the hand. The thread passes through a thread column on the back of the fingers to reach the fingertip. As the string is pulled, it deforms the skin, creating a sensation of pressure (see Figure 4(b)). When enough pressure is applied, the skin stops deforming and the fingertip is lifted, stimulating a deep sensation (see Figure 4(c)). This presentation system allows for a continuous force representation from weak to strong intensity. The resulting master glove, which reproduces a wide range of haptic sensations, weighs approximately 0.3 kg [11].

B. UPPER BODY

For many problems it is sufficient to manually operate the upper body of a humanoid robot [34], [46], [47]. This control is achieved by mapping the operator's upper body onto the target robot. Meanwhile the lower body is automatically balanced. However, from the point of view of the device, upper body teleoperation might be interpreted as a partial application of whole-body teleoperation (see section IV-D).

TELESAR VI represents an interesting compromise between upper body and whole body teleoperation [11]. Although the robot models a whole body, it is intended to be operated from a seated position. This restriction is due to its design focus on telexistance. Many human tasks are performed sitting down and with manual manipulation, e.g. writing. Therefore, the focus of TELESAR VI is on upper body movement, body language transmission, and haptic telexistance. Furthermore, bipedal movement presents its own unique set of challenges, as seen in section IV-C.

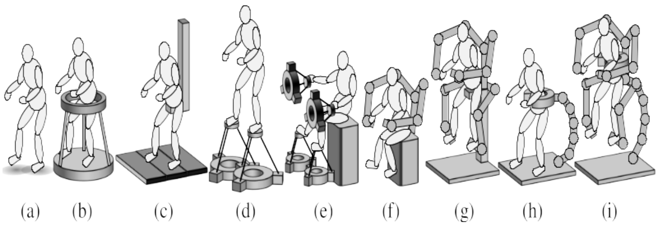

Fig. 5. A wide variety of whole body teleoperation designs, from motion tracking to full body exoskeleton cockpits [8].

C. BIPEDAL MOVEMENT

Bipedal movement is a challenging area of research [48]. Balancing a robot independent of the operator's control might be extremely difficult. Therefore, a common approach is to limit the operator's direct involvement in the bipedal movement depending on the task requirements [46], [47]. Generally speaking, the more complex the environment and in particular the terrain to be navigated, the finer the operator's control over the balance has to be or the more powerful the assistance needs to be [49], [50]. And the finer the operator's control has to be, the more mental resources he has to divert just to maintain stability [50]. Apart from that, bipedal movement can be seen as a partial application of whole body teleoperation, which is explored further in section IV-D.

Nonetheless, an especially interesting approach is to provide task-relevant haptic feedback [51]. The idea is to give the operator haptic cues about the impact of his proposed movement on the stability of the target robot. This notification is provided by a separate controller governing the leg movement, while the operator only actively controls the hands and arms. These cues are rather high-level and aim to provide feedback to the operator, while the underlying controller autonomously balances the robot's stability. However, so far this approach doesn't take into account the dynamics that are needed for guidance, e.g. when moving.

D. WHOLE BODY

Finally, the most complex body mapping is for whole body teleoperation, as it has the largest number of possible DOFs to map between operator and robot. Some of the most common interface designs are shown in Figure 5.

The most popular and simplest interface choice in terms of hardware is motion capture, as shown in Figure 5(a) [8], [46]. Haptic feedback is often provided by gloves and is usually paired with VR goggles [11], [52], [53]. It is best suited for unilateral teleoperation, as the mechanisms for providing direct feedback to the operator's movements are limited. However, movement can be difficult or disorientating for the operator, as anyone who has tried a basic VR game can attest. Furthermore, motion tracking might suffer from visual occlusion [11]. In general, motion tracking can be used on its own or in combination with any of the other designs presented in the rest of this section.

It is possible to alleviate the movement problem by adding an omidirectional VR treadmill, which is commercially available [9]. This is shown in Figure 5(b). Here, the operator moves by slip-walking on the hollow floor, which significantly reduces the disorientation caused by the movement. However, this design still only works for unilateral designs and cannot be extended from 2D to 3D locomotion [8]. The 2D treadmill shown in Figure 5(c) allows for more natural walking, but retains the other problems of Figure 5(b) [54].

Figure 5(d) demonstrates 3D locomotion by utilising position feedback devices under the operator's feet [55]. However, it is still difficult to provide force feedback for the rest of the body. Furthermore, this design is much more stressful for the operator, because of the standing position [8].

Figure 5(e) extends the force feedback of Figure 5(d) to the hands and arms [56]. It is operated from a seated position, which reduces the operator's workload. However, this design is not suitable for full-body bilateral teleoperation, as the posture of the operator and robot posture cannot be constantly matched.

The remaining designs Figure 5(f) to Figure 5(i) use an exoskeleton to varying degrees. Figure 5(f) uses it for dual arm feedback and is more typical for teleoperation [57]. It can be combined with slip-walking to model leg movement.

Figure 5(g) might be seen as an extension and is a whole body exoskeleton cockpit [8]. It offers to replicate remote 2D/3D ground surfaces and to provide force feedback for the whole body [8]. Additional software is used to assist the operator and prevent the robot from falling down [8]. However, because the centre of gravity is fixed, the operator, and therefore the robot, is limited to working in a near standing position [8].

The design in Figure 5(h) shows a coupling at the operator's centre of mass [58]. This coupling provides direct force feedback to the bipedal movement, which is captured along with other movements using motion capture.

Finally, the design in Figure 5(i) installs Figure 5(g) on a six DOF arm, similar to that in Figure 5(h) [8]. This design allows for more natural movement, including crawling and lying. However, this system requires a large installation space, a really strong connection between the exoskeleton and the ground, and substantial funds to build and operate.

In general, the designs from Figure 5(a) to Figure 5(i) except Figure 5(h) provide more force feedback, but also increase in costs and complexity. Therefore, the correct design must to be chosen based on the individual use case.

V. POTENTIAL APPLICATIONS

The potential for teleoperation is immense, and here are just a few possible areas of interest.

The first one is operation in hazardous environments [5], [59], [60]. These take many forms, including but not limited to chemical plants[58], buildings in danger of collapse [61], or even nuclear power stations [58]. In short, any environment that could be dangerous to humans entering it. In addition to the teleoperation requirements, such environments pose additional challenges for the target robot, such as radiation resistance or communication stability [5].

Apart from disasters, teleoperation could also be employed in research environments. One potential application is in clean rooms [62]. Teleoperation offers to significantly reduce the amount of external interaction and the risk of being compromised.

Another level of hazardous environments is space [7], [63]. Possible applications here include in-orbit satellite repairs, experiments, or space station maintenance [35], [63]. However, the operational requirements are even more demanding, ranging from improved reliability to severely limited communication channels [7], [35]. Even with perfect communication, there will inevitably be problems with delay due to the vast distances between the operator and the target robot. A compromise between autonomy and teleoperation is therefore likely to be the way to forward.

Another possible application could be the control of surgery robots [58]. This could be a renowned specialist operating on a patient on the other side of the world, or even in the same room, since teleoperation doesn't technically have a minimum distance requirement. Remote surgery allows expertise to be applied where it is needed, much more quickly than flying the specialist to the site. Surgical robots perform the movements more precisely and on a smaller scale than is humanly possible in minimally invasive procedures.

Finally, one potential application is telexistance - the feeling of being present anywhere in the world [11], [42], [64]. The COVID-19 pandemic demonstrated a potential market for this [5]. However, humanoid robots and the necessary interfaces for full immersion are not yet developed enough for inexperienced users. Therefore, telexistance is likely to be realised after the other applications mentioned.

VI. Conclusions

Teleoperation is a fascinating area of research with a multitude of facets. This work has focused on the interfaces that facilitate the operator's commands to the target robot and provide feedback to the operator. It has been shown that visual interfaces tend to use VR or, more rarely, AR goggles. There's a lot of potential for AR applications to improve operator performance by reducing motion sickness and increasing situational awareness. 3D displays however are virtually not utilised.

In terms of mappings between the operator and the target body, different parts of the human body have to be considered. In this work, particular emphasis has been placed on hand modelling, especially on the representation of cutaneous sensations. The haptic primary colour model is a great approach to increase the information modelled by haptic displays. This modelling helps to increase the operator's immersion and information, enabling more situational decisions. To date, haptics have rarely been used to model touch, but rather as an indicator, for example, of the potential impact of a proposed movement. Combining cutaneous sensations with AR could be an interesting approach to combine the enhanced immersion with increased awareness and reduced operator stress.

A number of designs for whole body teleoperation have been discussed. They can be summarised as follows: the more fine-grained control of the robot's movements is required, the more complex and expensive the operator hardware becomes. The right design has to be chosen according to the specific application. However, for most systems it is possible to enhance them with additional motion capture or sophisticated control gloves.

All in all, the right teleoperation interface will always depend on the application and the budget available.

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