IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 8, 2020, accepted October 19, 2020, date of publication November 9, 2020,
date of current version November 19, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3036596

Review of Control Methods for Upper Limb Telerehabilitation With Robotic Exoskeletons

GEORGETA BAUER, (Graduate Student Member, IEEE), AND YA-JUN PAN, (Senior Member, IEEE)
Department of Mechanical Engineering, Dalhousie University, Halifax, NS B3H 4R2, Canada

Corresponding author: Ya-Jun Pan (yajun.pan@dal.ca)

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC), in part by the Nova Scotia Graduate Scholarship (NSGS), in part by the Killam Trusts, and in part by the Dr. Eliza Ritchie Doctoral Scholarship, Canada.

ABSTRACT Given the escalating unmet demand for physical rehabilitation due to the growing global aging population and the effects of the coronavirus COVID-19 including increased incidents of stroke, hospital bed shortages, and clinics closures, robotic telerehabilitation is an emerging, timely, and crucial technology. Rehabilitating the upper limbs of affected patients is of upmost importance for restoring physical function and lighten the societal burden due to disabilities. So far, the majority of the research in robotic telerehabilitation for upper limbs has been performed with end-effector-type assistive robots; however, the use of robotic exoskeletons has significant and distinctive benefits. Although there are surveys written about control methods for upper limb robotic exoskeletons and other surveys written about bilateral teleoperation control methods, there are no surveys written specifically about telerehabilitation control methods for upper limbs using robotic exoskeletons. As a result, this article reviews the state-of-the-art control strategies including various advanced linear and nonlinear control approaches for upper limb rehabilitation robotic exoskeletons, bilateral teleoperation, and several state-of-the-art telerehabilitation applications with upper limb robotic exoskeletons. The benefits, drawbacks, challenges, and future directions of existing methodologies are extensively discussed. This article offers a comprehensive overview and insight for new researchers in the area of telerehabilitation robotic exoskeletons.

INDEX TERMS Bilateral teleoperation, robotic exoskeleton control, rehabilitation, delay.

I. INTRODUCTION

The worldwide senior population is expected to more than double in the next three decades [1] and with this increase, an unprecedented surge is predicted in aging-related motor-impairment diseases such as stroke, injuries and myriad neurological disorders causing – among other things - upper-limb mobility disfunctions requiring physical rehabilitation. Stroke is the largest cause of disability in the USA [2], [3] and one of the leading causes of long-term disability worldwide [4]. Predicted current demand for physical rehabilitation in the USA is 17% greater than what medical professionals can provide [5] and this disparity is expected to grow to 36% by the year 2030 [6]. Breaking news reveals that there is a newly-discovered correlation between the mildly-symptomatic coronavirus COVID-19 patients and incidence of major stroke [7], [8] which, if they survive, will most likely require physiotherapy – further adding to the escalating demand for physical therapeutic service. However, due to the surge in critically ill COVID-19 patients requiring hospitalization, there is a scarcity of available hospital beds for patients suffering from other illnesses, such as stroke. In fact, earlier this year hospitals in New York City have discharged patients and stopped accepting new ones in their acute inpatient rehabilitation units [9]. Furthermore, in order to mitigate transmission of the virus, physiotherapist need to wear personal protective equipment (PPE); however, there are many places around the world where inadequate PPE or the lack of PPE for the physiotherapist puts them at unacceptable risk while performing their jobs [10], [11]. Many clinics around the world are closing due to mandated social distancing restrictions and physiotherapists are left with providing support and instructions via a telephone helpline or video-consultations [12], [13]. However, as one of the commentators about the article [12] remarked: “What’s the value of physical therapy without physical contact?”. Clearly alternative solutions are required.

Having patients use assistive robotic devices at a remote site such as an assisted-living facility or their own home while a healthcare professional monitors and physically interacts

The associate editor coordinating the review of this manuscript and approving it for publication was Kang Li.

with them to deliver rehabilitation services from another site such as a hospital, clinic, or their own home is called robotic telerehabilitation [14]. Robotic tele-rehabilitation can be used to address the need for a physiotherapist to deliver physical guidance and interaction in order to assist patients with compromised mobility during the current pandemic and to address the preexisting escalating demand for physiotherapy [15]. This technology is also ideal for patients who are house-bound or live in remote areas where there are no rehabilitation clinics [16]. Another advantage of telerehabilitation is that one therapist could potentially train multiple patients at the same time by having each patient interacting with their own robotic exoskeleton at their own remote locations [17]. Furthermore, using assistive devices allows for smaller forces to be exerted by the therapist on their exoskeleton which can then be amplified to produce the required forces on the patient's side. As a result, the therapist's fatigue is lessened compared to the conventional one-on-one forceful physical manipulation of the patient's arm allowing them to deliver rehabilitative services to more patients.

Assistive robotic devices can provide consistent, intense training with the added benefit of collecting performance data for assessing and measuring progress. Furthermore, the control methods can provide customized rehabilitation exercises that adapt to the patient's performance and modify the intensity in real time depending on the patient's goals, training, and stage in the rehabilitation journey [18]. Assistive upper limb robotic devices usually consist of two types: end effector or exoskeletons [19]. The connection between a patient and the end-effector-type robot is at a single interface where the patient grasp a handle, which is the end effector of the robotic manipulator [20]. Typically there is no consideration to the individual joint motion of the patient's affected limb [21]. This sole connection is the only point where any forces and assistance is applied to the patient [22]. One of the main advantages of using end effector type devices is that typically they are simpler to design and build than exoskeletons. Furthermore, the end effector type devices are easier to integrate with the patient considering the single-point contact between the two entities, thus they are the more popular type of assistive devices [20]. A disadvantage of end-effector type devices is that it is not possible to assess the function of patient's individual joints. Additionally, the main disadvantages of using end-effector-type robots in rehabilitation is that the movement of the patient's joint cannot be independently controlled nor targeted and thus the patient can actually recruit the use of other unaffected muscles in the body or move their arm in unnatural ways to complete a task – deeming the exercise counterproductive or even resulting in injury [17]. For example, it is not uncommon for patients to attempt to and succeed in using their torso to perform a manipulation task when using end-effector-type assistive devices to compensate for the dysfunction in the affected muscles [23], [24].

On the other hand, exoskeletons are anthropomorphic devices which encapsulate the patient's arm and are typically fastened with adjustable straps or tight-fitting brackets at several points along the limb with the goal of having both the robot and patient links move together – typically with their joints aligned. The kinematic structure of the exoskeleton robot should be compatible with that of the patient's joints [25]. Exoskeletons being worn by the patient and thus physically coupled to the patient's limb, provide a targeted therapeutic experience which can exercise specific joints by controlling the motion of each joint individually. Therefore, robotic exoskeleton-based training provides enhanced retraining of the correct physiological skeletal-muscle synergies without allowing for undesirable or detrimental compensatory actions. However, the control of robotic exoskeletons and their teleoperation are more challenging than their end-effector-type counterparts since typically the motion and forces are controlled and/or monitored at every joint rather than just at the end effector.

The novelty and contributions of this article are that different from previous work, here we look at control methods used in upper limb telerehabilitation applications that are specifically using robotic exoskeletons. We first review and summarize methods used for single upper limb rehabilitation robotic exoskeletons, such as proportional integral derivative (PID) and adaptive control, and then examine methods used to control the effects of delays across a bilateral communication channel when operating robots remotely. Some of the presented methods include wave transformation, time domain passivity control (TDPC) and proportional-derivative-like (PD-like) control. Lastly, this article looks at how some research projects present in the literature have combined the two previously-mention types of control methodologies to achieve upper limb tele-rehabilitation with robotic exoskeletons.

The paper is organized as follows. Section II presents the literature search methodology. Section III, IV, and V discuss control methods for upper limb rehabilitation single rehabilitation robotic exoskeletons, teleoperation, and cases revealing upper limb robotic telerehabilitation applications, respectively. Section VI concludes the paper.

II. LITERATURE SEARCH METHODOLOGY

There are three distinctive control method applications studied in this article: upper limb rehabilitation robotic exoskeleton control methods, teleoperation control methods, and upper limb telerehabilitation robotic exoskeleton control methods.

A corresponding literature search was conducted and limited to publications between 2012 and 2020 in order to find the most recent and state-of-the-art developments in these control methodologies. The searches were performed in Engineering Village, which offers access to 12 engineering literature and patent databases in a single platform including Compendex which includes the IEEE Xplore Digital Library.

To obtain a good overview of control methods used for upper limb rehabilitation robotic exoskeletons, a search for survey and review papers was performed with the search words: ((review OR survey) AND robot AND control AND exo* AND upper). The most relevant and important findings from the 34 records found are presented in Section III.

Teleoperation control methods were next researched by searching for: (control AND bilateral AND robot AND delay AND tele*). 317 records were found and the most relevant findings are presented in Section IV.

For control methods used in upper limb telerehabilitation with robotic exoskeletons the used keywords were: ((upper OR arm) AND tele* AND robot* AND rehab* AND control AND exo*). Pertinent projects are presented in Section V.

It is important to note that although the searches were limited to papers from 2012-2020, numerous papers' references within the initially discovered papers were also studied and referenced in this article as necessary, regardless of the publication year.

III. UPPER LIMB REHABILITATION ROBOTIC EXOSKELETON CONTROL METHODS

Rehabilitation is performed to provoke motor plasticity [26] to accelerate motor recovery in a patient. During the acute stage, right after the stroke, injury, or surgery has taken place, the rehabilitation training mode is called 'passive'. During this stage, the patient's affected arm is unable to move voluntarily on its own. With the aid of the robotic exoskeleton and by analyzing the data collected by its sensors, the therapist can assess the muscle strength, range, and quality of the motion of the patient's joints of interest. The control methods implemented on the robotic exoskeleton during the passive mode command the motors to move the patient's limb through preset standard exercises. Once some of the patient's mobility returns, the active mode of training can be applied. Control strategies during the active mode take into consideration the patient's intention of motion. Furthermore, during this stage, the patient is expected to initiate the motion – a step which has been proven to be necessary in order to promote neural plasticity [27], [28]. The robotic exoskeleton control systems can be set to assist the patient to perform and complete training exercises in assist-as-needed types of therapy, in order to encourage and promote patient engagement. Eventually the control methods can be set to have the robotic exoskeleton resist the patient's motion for more advanced training.

Typically, the objectives for robotic exoskeleton control methods are to provide optimal force and position control necessary to safely and effectively implement either passive or active modes of training to the patient. The performance of a controller is evaluated based on the objectives of each specific application to achieve the desired dynamic responses over an expected range of operating conditions. Some of the most common performance parameters that researches evaluate are maximum overshoot, rise time, and settling time of the manipulated variable (such as position or velocity). In this section, the control methods addressed are those used during the passive mode. Fig.1 shows an overview of a generic motion-based upper limb rehabilitation robotic exoskeleton control block diagram. The desired reference motion on the left side of the diagram is specified by the therapist through routines stored in the computer. This reference motion information is compared to the actual motion measured by sensors on the robotic exoskeleton attached to the patient. The difference between the desired and the actual variables is called the 'error' in control theory. This error is fed back to the controller to calculate what voltage output should be instructed to the robotic exoskeleton's motors in order to minimize the difference between the desired and actual motion.

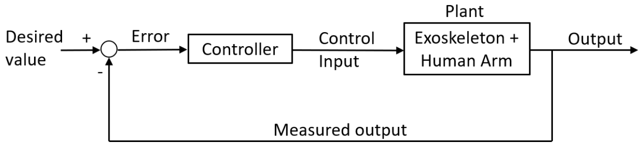


FIGURE 1. Block diagram of a generic feedback control.

Some of the more popular control methods for this type of applications are: Proportional Integral Derivative (PID) Control, Impedance Control, Admittance Control, Adaptive Control, and Sliding Mode Control (SMC). These methods are described in the following sections and summarized in Table 1.

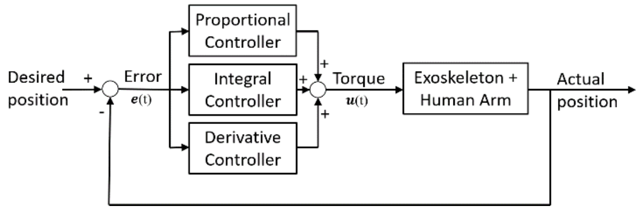


FIGURE 2. Block diagram of a PID controlled system.

A. PROPORTIONAL, INTEGRAL, AND DERIVATIVE CONTROL

PID control (Fig.2) does not require system modeling [18] and is relatively straightforward to implement. The PID control law is shown in (1) where $\boldsymbol{u}(t)$ denotes the control input (torque in this case), error $\boldsymbol{e}(t)$ represents the difference between the actual and desired position of joints, and $\dot{e}(t)$ is its derivative with respect to time. The Proportional gain K_P operates on the position error. The Integral gain K_I operates on the accumulated position error and the Derivative gain K_D operates on the velocity error.

$$\boldsymbol{u}(t) = \underbrace{K_P \boldsymbol{e}(t)}_{\text{Proportional Control}} + \underbrace{K_I \int_0^t \boldsymbol{e}(\tau)\, d\tau}_{\text{Integral Control}} + \underbrace{K_D \dot{\boldsymbol{e}}(t)}_{\text{Derivative Control}} . \tag{1}$$

While model-free control leads to simplicity in its implementation, a disadvantage of using this method is that tuning the gains to the current setup can be time-consuming. Another disadvantage is that since this control method is not model-based and only error-driven, if the exoskeleton becomes 'stuck', unwanted large torques could be commanded due to accumulated error [29], which could potentially damage the equipment and harm the patient if safety limits are not properly implemented in the system.

TABLE 1. Most common upper limb robotic exoskeleton control methods.

Control Method	Example References	Comments	Advantages	Disadvantages
PID Control	[30]	Reacts on the position and velocity errors, and the accumulated position error.	Model-free; No system identification required.	Requires gain-tuning which can be time consuming.
Impedance Control	[35]	Model-based Control; Measures position and controls force output.	Ideal for backdrivable robots; Stable dynamic interaction with stiff environments.	Not good at compensating for gravity and friction; Poor accuracy in free-space [32].
Admittance Control	[36]	Model-based Control; Measures force and controls position output; Needs to include a position controller.	Ideal for non-backdrivable robots; Accurate in free-space, soft environment.	Can be unstable during dynamic interaction with stiff environments.
Adaptive Control	[37]	Model-based control.	Good at compensating for time-varying system parameters.	Does not perform well with fast-changing parameters & disturbances.
SMC	[38]	Model-based Control; Works within the bounds of pre-known disturbances/uncertainties.	Good at rejecting bounded external disturbances and parametric uncertainties.	Chattering in the commanded signal requires smoothing approaches.

Controllers can be created which use a subset of the PID controller, such as P, PD, or PI. For example, the upper limb robotic exoskeleton ARMin III [17] uses a PD controller while EXO-UL7 [30] uses a PID controller. Furthermore, many researchers combine elements of the PID controller with advanced control methods (such as Robust Control, and Adaptive Control), and intelligent control methods (such as Neural Networks and Fuzzy Logic). For example, [31] combines PID Control with Robust Control and Fuzzy Logic based Control. Depending on the application, this type of control can lead to sufficiently acceptable system performance, without having to delve into the field of advanced control methods.

B. IMPEDANCE AND ADMITTANCE CONTROL

As opposed to PID control, impedance control is a model-based approach. There is some confusion in the literature as to the difference between Impedance and Admittance control. In this article, we use the explanation presented by Ott *et al.* in [32], Hogan in [33], and Hayward *et al.* in [34]. Lower case "impedance control" is the overall philosophy which establishes a dynamic relationship between the motion of a plant and the interactive forces between the plant and its environment. For example, in joint space this relationship could be expressed as:

$$\boldsymbol{\tau}_{\boldsymbol{ext}}(s) = (M_d s^2 + B_d s + K_d)\boldsymbol{e}(s), \tag{2}$$

where $\boldsymbol{\tau}_{\boldsymbol{ext}}$ is the external joint torque vector and $\boldsymbol{e}$ is the difference between the actual (measured) angular joint position vector $\boldsymbol{q}$, and the desired equilibrium (without external torque) angular joint position vector $\boldsymbol{q}_{\boldsymbol{o}}$. Parameters. M_d, B_d and K_d are selected to establish the desired mass-spring-damper relationship between $\boldsymbol{\tau}_{\boldsymbol{ext}}$ and $\boldsymbol{e}$.

According to Ott *et al.* in [32], lower-case "impedance control" can be implemented in two ways: upper-case "Impedance control" and "Admittance control". As shown in Fig.3 a) and described by Hogan [33] and Hayward and Maclean [34], systems that have "flow" (e.g. angular position) as input and "effort" (e.g. torque) as output are called impedances. Systems that have "effort" (e.g. torque) as inputs and "flow" (e.g. angular position) as outputs (Fig.3 b)), are called admittances. The "system" in these figures could be a controller or the plant (robot), or the environment, or a human in the system.

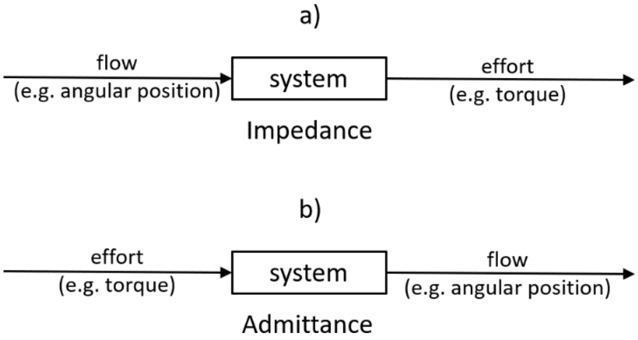


FIGURE 3. Control block diagrams of impedance and admittance control for impedance control.

Using these definitions for impedance control, in Ott *et al.* [32] the controller is an impedance system while the controlled plant (e.g. robotic manipulator) is an admittance system. Conversely, "Admittance control" features a controller that is an admittance system with the controlled plant (e.g. Robotic manipulator) as an impedance system. It is important to note that for both Impedance control and Admittance control the control objective is the same: determine the control torque τ, that provides the desired relationship between the measured external torque $\boldsymbol{\tau}_{\boldsymbol{ext}}$, and the deviation $\boldsymbol{e}$, from the equilibrium angular joint trajectory as shown in (2).

Fig.4 illustrates Impedance control where the impedance controller has motion as the input ([29], [39]) $\boldsymbol{q}$ and torque $\boldsymbol{\tau}$ as the output, and the controlled robotic exoskeleton and human arm have torque $\boldsymbol{\tau}$ as the input and measured motion $\boldsymbol{q}$ as the output in order to achieve the desired dynamic interaction between the robot and the environment [40].

Whereas PID controllers aim to minimize the position and velocity tracking errors, impedance control is an expansion of position control [39] with the objective of having the

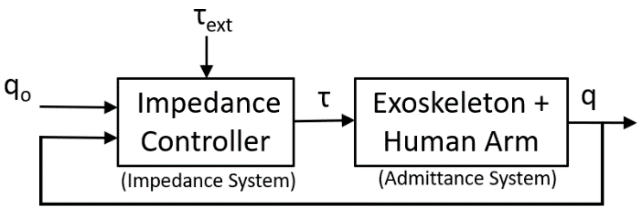


FIGURE 4. General impedance control block diagram.

position and velocity errors follow desired trajectories which depend on the human interaction (such as the relationship described by (2)) instead of rigidly following a given trajectory [41]. This method has been proven to produce stable interactions and is efficient for lightweight, backdrivable exoskeletons [32]. However, it has been shown to not be very good at compensating for gravity, and friction in the system [18] and other unmodeled dynamics in free-space (where the human user is allowed to move the exoskeleton without resistance). As a result, in these scenarios the accuracy and precision are compromised [42]. Using low-friction joints, direct drives and backdrivability [32], [43] can improve performance [26]; however, researchers have found that Impedance control can become unstable when the impedance is high [44]. Impedance control strategies perform well with stiff environments and enable the robotic exoskeleton-human assembly to move compliantly with deviations from a set trajectory [41]. Impedance control has been implemented in many research upper limb exoskeletons including the L-Exos [23] and SUEFUL-7 [35].

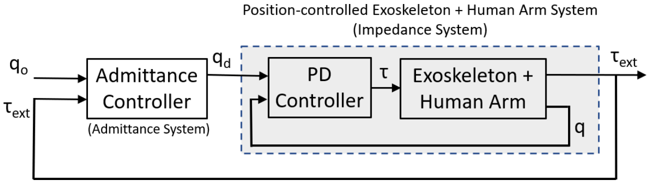


FIGURE 5. General admittance control block diagram.

Conversely, Fig.5 shows Admittance control where the admittance controller has the external (measured) torque $\boldsymbol{\tau}_{ext}$ as the input and produces a desired angular joint trajectory to follow $\boldsymbol{q}_d$ as the output (admittance system). The controlled robotic exoskeleton and human arm uses this desired angular joint motion $\boldsymbol{q}_d$ as input (via a position controller such as a PD controller) with the measured external torque $\boldsymbol{\tau}_{ext}$ as the output (impedance system). To clarify, $\boldsymbol{q}_d$ is what we want $\boldsymbol{q}$ (the actual (measured) angular joint position) to be so that $\boldsymbol{e}$ (which is equal to $\boldsymbol{q}-\boldsymbol{q}_o$) is as desired.

Admittance control is useful with stiff robots since forces need to be sensed at the interface between the robot and the human limb. One of the disadvantages of this method is that high admittance (low impedance) can destabilize the system [36]. This method requires high transmission ratios such as those provided by harmonic drives in order to achieve precise motion control with very little backlash [28]. An advantage of using a system without backlash is smooth movement, though the friction could make the environment feel non-realistic [18]. One commercial rehabilitation system that uses admittance control is the HapticMaster from Tyromotion. Two other systems that can also be controlled using admittance controllers are MGA [36] and ARMin III [17].

C. ADAPTIVE CONTROL

One of the disadvantages of impedance and admittance control is that they do not incorporate time-varying adjustments to the desired parameters [28] and may 'intervene incorrectly' if participants regain some of their strength and require less assistance. It is in these kinds of situations that adaptive control methods can help. Fig.6 shows a type of adaptive controller called Model Reference Adaptive Controller (MRAC) which adjusts for unknown variances of system parameters online based on ongoing operations. As can be seen in Fig.6, the controller parameter values are updated based on the difference between the measured sensor values $\mathbf{y}$ from the system and those from the reference model $\mathbf{y}_{\mathbf{ref}}$.

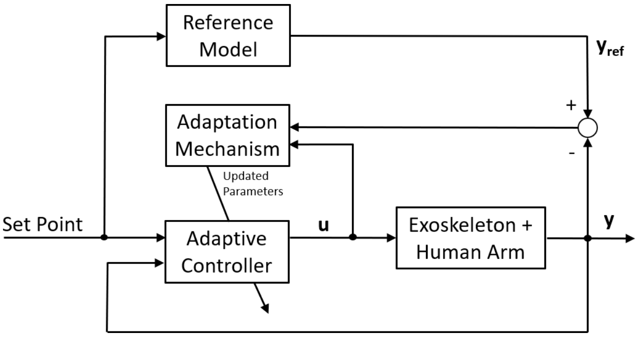


FIGURE 6. Model reference adaptive controller (MRAC).

Another advantage of adaptive controllers is that they can compensate for modeling uncertainties. Additionally, adaptive controllers do not require *a priori* information about the limits of the uncertain or changing parameters as robust methods do. Adaptive methods, however, can neither handle fast-changing parameters nor systems that are exposed to external disturbances. Researchers have addressed the latter problem by combining adaptive controllers with other types of controllers including robust control methods to handle bounded external disturbances. An example of an upper limb rehabilitation robotic exoskeleton system that uses adaptive control is ARMin V [37]. Adaptive robust control is demonstrated in [45] and [46].

D. SLIDING MODE CONTROL

Sliding Mode Control (SMC) is a nonlinear robust method which handles bounded external disturbances [29] and parametric uncertainties. First, a switching controller is designed which forces the system state trajectories to converge onto a sliding surface in the state space in a finite amount of time. Then, the nominal controller is computed. These two controllers are shown in Fig.7, with their computed torques $\mathbf{u}_{\mathbf{sw}}$ and $\mathbf{u}_{\mathbf{nom}}$, respectively. The two torques are then added to produce the commanded torque sent to the robot [43]. One of the disadvantages of SMC is that the high frequency switching action could cause chattering in the commanded output resulting in wear or damage of the mechanical system as well as energy loss in the electrical system. However, there are many mathematical smoothing methods that could be implemented which may negate or mitigate this problem. Some systems that use SMC are described in Yun *et at.* [47] and Brahmi and Saad [38].

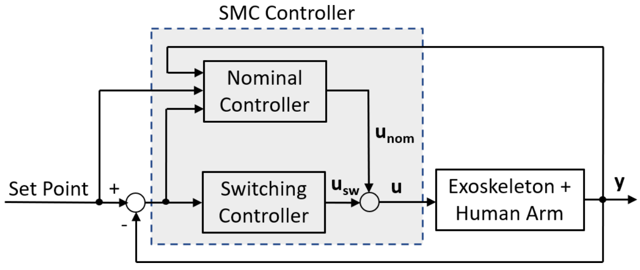


FIGURE 7. **SMC controller.**

E. OTHER CONTROL METHODS

There are myriad other control approaches which combine the above-mentioned methods together as well as others that also integrate intelligent control methods such as Neural Networks [48], Fuzzy Logic [49], and Machine Learning methods [50]. There are also approaches which use time-delay estimation [51] and iterative learning control for repetitive tasks [52]. Other controllers integrate the use of biosignals such as Electromyography (EMG) [53], [56] and Electroencephalography (EEG) [57], but these will not be covered in this study.

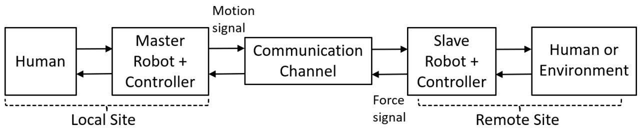


FIGURE 8. **Overview of a telerobotic system.**

IV. CONTROL METHODS FOR TELEROBOTIC SYSTEMS WITH TIME DELAYS

The methods discussed in the previous section can be used to control single upper limb rehabilitation robotic exoskeletons. In this section, we discuss control methods that allow humans to operate robotic system remotely in the presence of time delays. Fig.8 shows the block diagram of a generic teleoperation system which involves a master and a slave robotic device. Typically, a human operator moves the master robot at the local site with the goal of accomplishing a task using the slave robot at the remote site. As the human operator interacts with the master robot, its motion information is conveyed over a communication channel to the remote side, as a command signal, so that the slave robot imitates the master robot while interacting with the environment [58] or another human [59]. Additionally, if the teleoperation is bilateral, the interaction force between the slave robot and its environment (or the human) is measured and transmitted to the human operator at the local site. As a result, "the master robot not only measures motions but also displays forces to the user" [60] - simultaneously affecting the remote environment (or human) at the remote site while also perceiving the reflected force from that interaction [61]. The goal is for the interaction to be so immersive and natural that the "human operator is fooled into forgetting about the medium itself" [60]. However, when the communication channel has issues such as time delays, the stability of the system can be compromised resulting in undesirable, and even more critically, unsafe consequences for the humans in the loop.

There has been a lot of research over the years on telerobotics to develop control methods that adeptly compensate for time delays with the following three main objectives:

- **Stability:** the closed-loop system is stable regardless of the behaviour of the operator or the remote environment [62]
- **Tracking Performance:** how well the slave side follows the master side
- **Transparency:** the fidelity of the system [63]; how well "the operator feels that s/he is directly interacting with the remote environment" [64].

For perfect transparency and performance, the motion of the master robot needs to be mimicked exactly by the slave robot, and the forces sensed on the slave side have to be exactly reflected at the master side [65] as shown in (3):

$$\boldsymbol{v_m} = \boldsymbol{v_s} \wedge \boldsymbol{f_m} = \boldsymbol{f_s}, \tag{3}$$

where $\boldsymbol{v_m}$ is the velocity signal sent from the master side, $\boldsymbol{v_s}$ is the received velocity signal on the slave side, $\boldsymbol{f_m}$ is the received force signal on the master side, and $\boldsymbol{f_s}$ is the force signal sent from the slave side.

Having a human operator in the control loop is very desirable and advantageous in applications where the remote site interaction has unknown and unstructured characteristics [60]. Over the last sixty years, there have been increasingly more telerobotics applications in various fields such as space [58], underwater control [66], hazardous environments [67], forest fire detection [68], military [69], mobile robots [70], tele-driving [71], telemedicine such as telesurgery [72] and telerehabilitation [62].

This article only looks at communication over the internet. The main advantages of telerobotics over the internet are that the internet is widely available, inexpensive, and straightforward to use [73]–[76]. While limited bandwidth [58] and data loss are important issues for teleoperation over the internet, nondeterministic time delays across the internet can impair or threaten the stability of the system [61], [77] and as such are considered as the primary communication constraint over the internet in this article.

To illustrate what could happen when the communication delays are not addressed, Fig.9 portrays a hypothetical teleoperation system with the task of pushing a block towards a soft wall, with and without time delays across the communication channel. It can be seen how in the case where there is no delay, the motion and forces are relayed perfectly.

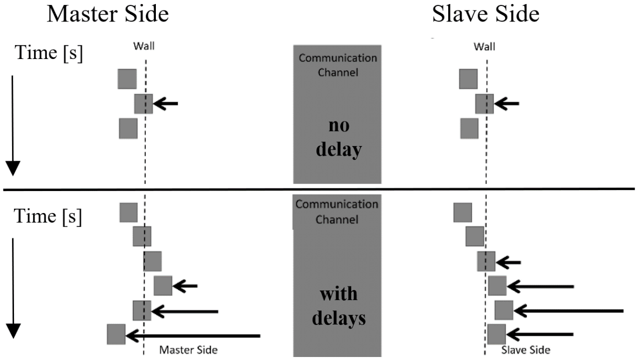


FIGURE 9. **Example of pushing on a soft wall, with and without time delays in bilateral teleoperation systems.**

In the case where delays do exist, they cause a phase shift in the position and force signals if not addressed. Due to the delays across the communication channel, the operator acts on old data and thus keeps moving the robot forward, believing that it has not yet reached the desired location. As a result, increasingly excessive forces are being applied on the slave side until the signal indicating that the robot went too far finally reaches the human operator. The operator tries to adjust but is also exposed to large forces pertaining to obsolete large displacement commands. This lack of synchronization of the motion and forces between the master and the slave side leads to instability and transparency degradation. The physical consequences can include injury to the humans in the loop and damage to equipment such as force sensors which are sensitive and expensive [78].

Besides issues due to the communication medium, such as internet latency, other challenges for bilateral control systems are modeling complexities and modeling uncertainties [72], parameter variations [79], and uncertain disturbances such as friction or payload variations [80]. Furthermore, safety and reliability are of paramount concern in telerobotics with human operators in the loop, and even more so when dealing with humans on the slave side as well. For example, in telesurgery, the slave robots are performing a task inside the human's body while in telerehabilitation – when using exoskeletons – the robotic device encapsulates part of the human body.

There are many surveys and reviews covering teleoperation in the literature [64], [72], [73], [80]–[83] and the following section summarizes succinctly the most commonly used control methods for telerobotic systems with more than one degree of freedom (n-DOF systems, n > 1).

A. PASSIVITY-BASED CONTROL METHODS

Passivity is based on the concept of energy transfer and power flow in a system. For stability, the system net power should be passive, meaning that the energy entering the system should be greater than the energy leaving the system – as expected considering that in real systems there is always some energy dissipated internally due to friction and other damping mechanisms [60], [82], [84]. Equation (4) shows this relationship:

$$\dot{E}_{stored} = P_{in} - P_{diss}, \tag{4}$$

where $\dot{E}_{stored}$ is the rate of change of the stored energy, P_{in} is the power entering the system, and P_{diss} is the dissipated power. For passivity to be ensured, P_{diss} must be positive [85]. When active elements exist in the system (eg. time delay across the communication channel, or a human at the slave side moving the robot), the control system can become unstable. However, passivity could be ensured by limiting the system energy, introducing boundedness for all the system variables [61] or applying damping agents [86] to remove the excess energy. It is important to note, however, that if a damping agent is too conservative, the performance of the system could be degraded [87].

A major advantage of using passivity-based methods is that the dynamic models of both the master and the slave systems are not required to be known [88]. As a result, passivity-based methods are ideal for systems with large uncertainties or multi-degrees of freedom systems which contain nonlinearities and complexities that are hard to model. These scenarios are typical of real physical environments [82]. Although passivity-based methods cannot guarantee the achievement of desired performance, stability can always be ensured. Five popular passivity-based methods and three non-passivity-based methods are described as follows.

1) WAVE TRANSFORMATION

Anderson and Song [89] were the first to combine the concepts of electrical network theory, scattering transformation, and passivity for telerobotic systems to ensure stability – regardless of the size of the constant time delays. They did so by treating the connection between the two robots like the equivalent of a virtual passive transmission line [14], and modeling the robots using (electrical components like resistors, capacitors, and inductors [90]. Two years later Niemeyer and Slotine [85] improved this method, while also making it simpler for mechanically-minded roboticists to understand. Instead of using electrical network modeling and the power variables $\{\boldsymbol{f}_m, \boldsymbol{v}_m\}$ and $\{\boldsymbol{f}_s, \boldsymbol{v}_s\}$, they implemented wave variables $\{\boldsymbol{u}_m, \boldsymbol{w}_m\}$ and $\{\boldsymbol{u}_s, \boldsymbol{w}_s\}$ which encode the velocity and force information from each side as shown in Fig.10 [91].

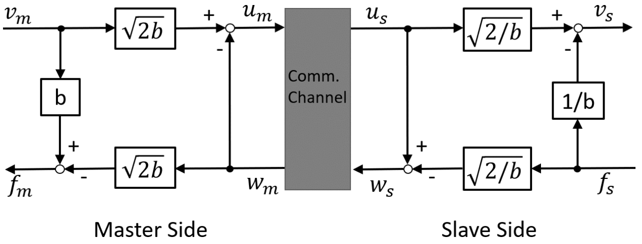


FIGURE 10. **Wave transformation.**

As can be seen in (5), wave variables do not have a physical meaning as they are a combination of velocity and force:

$$\boldsymbol{u}_m = \frac{b\boldsymbol{v}_m + \boldsymbol{f}_m}{\sqrt{2b}}, \quad \boldsymbol{w}_s = \frac{b\boldsymbol{v}_s - \boldsymbol{f}_s}{\sqrt{2b}}, \tag{5}$$

where $\boldsymbol{u_m}$ is the right-moving wave which travels from the master side to the slave side, $\boldsymbol{w_s}$ is the left-moving wave which is sent from the slave side to the master side and b is the characteristic wave impedance of the transmission line [82]. The wave impedance variable should be tuned according to the delay size. Furthermore, the wave impedance variable can be used to adjust the tradeoff between reflected inertia and stiffness, which can vary the feeling of the system from, for example, feeling light and flexible to feeling stiff and heavy.

The advantage of using the wave transformation method is that neither the size of the time delay nor the model parameters need to be known to guarantee stable performance; however, the wave method has several disadvantages. i) Position drift, which is an intrinsic disadvantage, can occur when using only the velocity and force values [91]. One solution to compensate for position drift is to use a wave integral instead, which includes the position as well as the velocity and force in the single quantity of the wave variable [92]. ii) Another intrinsic disadvantage of the wave transformation method is that larger delay size can cause wave reflection. Wave reflection is information rebounded across the communication channel between the master and slave side leading to oscillatory behaviour, like an "underdamped resonance of the wave communication at its natural frequency" [82]. This manifestation produces an undesirable and significant settling time of the teleoperator [90]. Impedance matching can eliminate this issue, in addition to providing optimal tuning capabilities for the local and remote controllers [82]. iii) An additional disadvantage of the wave variable method is that spurious dynamics may interfere with normal operation [82]. These dynamics may be a problem if this method is used for telerehabilitation using robotic exoskeleton control with stroke patients as sometimes their affected arm can exhibit spurious behaviour due to spasticity in the muscles. iv) Additionally, this method on its own cannot ensure stability for time-varying delays, such as those that occur over the Internet. Extensions to the wave variable can be used however to guarantee passivity using energy-conserving dynamic filters to shape the wave responses [92].

2) WAVE PREDICTOR

A Wave Predictor [90] is a wave-based control method which predicts the incoming wave variable from the slave side to compensate for constant and variable delays [93] in the communication channel on the master side, and minimizes their effect. It does so by incorporating a modified Smith predictor, energy regulator (Fig.11) and a Kalman filter. This method is stable even with large modeling uncertainties of the remote system which is used in the predictor. Furthermore, a wave predictor uses a position-correcting input to minimize position errors. This method enforces passivity independent of constant delays and possibly even time-varying delays as well, provided that the slave robot dissipates sufficient energy. Rodriguez-Seda *et al.* [81], however, noted that it is difficult to predict how much energy should be dissipated. This method was validated using two 2-DOF mechanisms in [81].

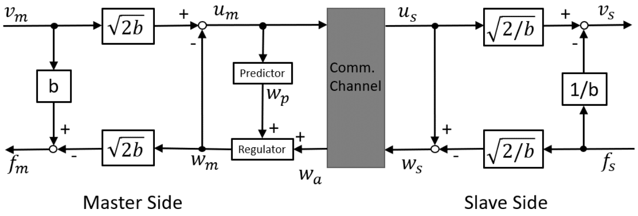


FIGURE 11. **Wave predictor incorporated inside the wave junction.**

3) TIME DOMAIN PASSIVITY CONTROL (TDPC)

TDPC is one of the most popular telerobotics control methods [62]. The main advantage of using TDPC for position-force architecture is that it is model-free and works with time-varying and unknown time delays. Since its performance only relies on measurements, it can be applied to many different systems. First introduced in [84], TDPC monitors the energy input and output into a system node in real time (Fig.12). The method uses Passivity Observers (POs) and dissipates the excess energy using Passivity Controllers (PCs) when the system shows an active behavior.

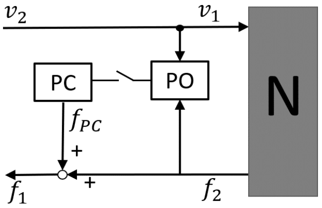


FIGURE 12. **Single port with passivity observer and passivity controller on the master side [73].**

One of the disadvantages of TDPC is that it can exhibit a jarring effect when the PC engages [87]. As a result, researchers have been expanding on this method by monitoring the power transfer between nodes instead of using a reference energy value. Improved stability and simplicity were observed in the new implementation [94]. Additionally, TDPC can suffer from the accumulation of energy dissipation. One solution is to reset the PO when the absolute value of the rendered force is less than a specified threshold for a set amount of time – meaning, when the slave robot is not interacting with the environment [95]. Another disadvantage of this method can occur when the velocity or force variables are close to zero or are zero since control failure can occur due to zero division behavior [96]. Consequently, researchers have devised estimations for the conventional TDPC method to overcome these issues. One example is Sheng *et al.*'s [96] switching dissipation controller which guarantees stability.

4) PASSIVITY-BASED ADAPTIVE CONTROL

Adaptive controllers which specifically compensate for communication delays are summarized in [97]. They can be applied to either linear or nonlinear systems. One method works by estimating an accurate environment model that gets updated in real-time. Another method suppresses uncertainties existing both in the master and the slave robot models. Chopra *et al.* [98] utilized a state-feedback control law which ensures the passivity for any constant time delays, initial offsets, and parametric uncertainties. This process is done using wave variables that contain the position, velocity, and force information [97]. Nuño *et al.* [99] devised a passivity-based adaptive control method that can work with variable and asymmetric time delays in both channels. During free motion, this method ensures that all signals are bounded and that the position errors and velocities diminish asymptotically and converge to zero.

5) PROPORTIONAL-DERIVATIVE-LIKE CONTROL

This method was introduced by Lee and Spong [100] and is a damping injection scheme. It treats the master and slave sides of the teleoperator as virtually connected via a spring and damper mechanism over the delayed communication channels with an added dissipative term at each side of the teleoperator. This method, which is sometimes expressed as PD+d, guarantees the passivity of the system with constant delays and parametric uncertainties. Although it requires a known upper bound of the round-trip delay, the delays can be asymmetric, and their exact estimates are not necessary. The advantage of this method is that the position is transmitted explicitly and that it passifies the communication and the control blocks altogether. Nuño *et al.* [101] showed that this strategy also provides position tracking for teleoperators with variable time-delays.

B. NON-PASSIVITY-BASED METHODS

1) FOUR-CHANNEL ARCHITECTURE

Lawrence [102] observed that velocity and force feedback should be used in the design of the control laws of the master and slave robot controllers to achieve perfect transparency. This 4-channel architecture requires the velocity and the force to be sent from the master to the slave and vice versa [61]. Although the 4-channel method achieves perfect transparency where there are no time delays, it loses passivity and robustness to delays [72]. Aziminejad *et al.* [103] addressed this shortcoming by combining the 4-channel method with the wave transformation. Another disadvantage of this method is that very accurate models of the master and slave robots are required to achieve perfect transparency.

2) SLIDING MODE CONTROL

SMC requires the design of a sliding surface based on the position and velocity errors. When applied to a single upper limb robotic exoskeleton, the error is between the desired and the actual positions and velocities. For teleoperated robots, however, the position and velocity errors are between those of the master and the slave robots. SMC has been used with success in telerobotics as it ensures robustness against uncertainties and time delays. For example, in [104], Park and Cho used an SMC controller on the slave side to track the master robot which utilizes an impedance controller. One of the main disadvantages of SMC is the chattering effect from the switching controller component but the use of numerous smoothing methods can be explored to improve performance.

3) ADAPTIVE ROBUST CONTROL

In the presence of parametric uncertainties and disturbances, a combination of adaptive and robust control methods was proposed in [105] which also addresses time-varying delays. The trajectory of the master was sent to the slave and estimated environmental torque parameters were sent to the master with simulation results.

The discussed telerobotics control methods are summarized in Table 2. Although there is still a lot of research taking place in telerobotics control methods dealing with delays, the most common and successful ones are passivity-based.

Having discussed some of the most popular teleoperation control methods in this section, the next section discusses several telerehabilitation projects which use upper limb robotic exoskeletons. The applications presented require the integration of control methods discussed in the previous section and those discussed in the current section.

V. CONTROL METHODS FOR UPPER LIMB BILATERAL TELEREHABILITATION WITH ROBOTIC EXOSKELETONS

An upper limb robotic exoskeleton-based telerehabilitation system consists of a therapist interacting with a robotic exoskeleton at the master side and a patient's arm fastened to a robotic exoskeleton arm at the slave side. In unidirectional teleoperation, kinematic information – such as position and/or velocity – is sent from the master side across a communication network to the slave side for the motion to be mimicked. In bilateral teleoperation, kinetic information – such as the force sensed on the slave side – is usually sent to the master side across the communication channel.

During the initial rehabilitation stage – when the patient cannot move the affected arm voluntarily – passive control is executed. For single exoskeleton-patient system, like those described in Section III, typically the motion of the exoskeleton is programmed in the software to performing standard upper limb rehabilitation and stretching exercises. In passive-control telerehabilitation, the therapist controls the motion of the master exoskeleton which is relayed to and mimicked by the slave robotic exoskeleton in order to move the patient's affected arm. The interaction during this passive control stage can additionally include the therapist assessing and improving the patient's muscle strength, range of motion, and quality of the motion of specific joints. The primary objectives for passive mode telerehabilitation are neural and muscular plasticity, improvement of range and reduction of muscle tone (spasticity) in the patient at remote locations. The control objectives are the same as those for a single exoskeleton, but in this case the slave robot's motion has the master's robot motion as the desired motion to follow. And in addition, the control system has to address effects of communication delays. The performance of the controllers is evaluated the same as for the single exoskeleton systems: by looking at the aximum overshoot, rise time, and settling time

TABLE 2. Telerobotics control methods with time delays in the communication channels.

Telerobotics Control Method	References	Handles variable-time delay	Doesn't require model	Comments
Passivity-based				
Wave Transformation	[85]	✓	✓	Requires filter to be used with time-varying delays; Impedance matching required to eliminate wave reflections if they occur.
Time Domain Passivity Control	[106]	✓	✓	Can accommodate many systems since its performance only depends on measurements; Can have switching effects.
Wave Predictor	[93]	✓		Requires the model of the slave and maybe the master system too.
Passivity-based Adaptive Control	[74][75]	✓		Nuno *et al.* [99] can deal with asymmetric and time-varying delays.
Proportional-Derivative-like Control	[100]	✓	✓	Position signals are transmitted explicitly; Passifies the communication and control blocks; Requires the known upper bound of the round-trip delays.
Not-Passivity-based Methods				
Four-channel architecture	[102]	✓		Achieve perfect transparency but loses passivity and robustness to time delays unless combined with other methods like wave variable-based method.
Sliding Mode Control	[104]	✓		Robust to modelling uncertainties and disturbance; Chattering requires smoothing schemes.
Adaptive Robust Control	[105]	✓		The trajectory of the master is sent to the slave and estimated environmental torque parameters are sent to the master with simulation results.

of the manipulated variable (such as position or velocity), which can be described as tracking performance.

Once some of the patient's mobility returns, active control strategies can be employed where the patient initiates the motion and the therapist can help the patient perform training exercises or even resist the patient's motion.

No comprehensive studies have been found in the literature describing upper limb telerehabilitation with robotic exoskeletons that include both an operator and a patient, and compensation for time delays. However, research projects were identified which contained a subset of the critical components and four are described as follows.

A. CASE STUDIES IN LITERATURE

1) TELEOPERATION OF 4-DOF EXOSKELETON USING TDPC

Buongiorno *et al.* [62] presented a project where upper limb robotic exoskeletons were used on both the master and the slave side of the teleoperation system with communication time delays between them. It was not a complete telerehabilitation system, however, since there was no human involved on the slave side for the performed experiments. A four degrees of freedom (4-DOF) upper-limb robotic exoskeleton called ALEx was used as the master robotic exoskeleton. This robot also had one passive degree of freedom and was a mechanically compliant, low-inertia device. All the joints were controlled using an impedance-like controller with the following control law:

$$\boldsymbol{\tau}_J + \boldsymbol{\tau}_J^G + \boldsymbol{\tau}_J^{VF} + J^T F_{EE}, \tag{6}$$

where $\boldsymbol{\tau}_J, \boldsymbol{\tau}_J^G, \boldsymbol{\tau}_J^{VF}, J^T,$ *and* F_{EE} are the vectors of the joint control torques, the feed-forward gravity compensation term, the feed-forward viscous friction compensation term, the transposed Jacobian matrix, and the renderized spatial force at the end effector, respectively.

An upper limb robotic exoskeleton called Rehab-Exos was used on the slave side. It has 4-DOF in a serial architecture isomorphic with the human arm kinematics. The Rehab-Exos was built with torque sensors at every joint. It also had high-ratio gear reduction built into the design to limit backdrivability. The controller on this robotic exoskeleton was admittance-based and the control law is as shown:

$$\boldsymbol{\tau}_J = \boldsymbol{\tau}^{dyn} + \boldsymbol{\tau}_J^G + K_P\left(\boldsymbol{q_o} - \boldsymbol{q}\right) - K_D\left(\dot{\boldsymbol{q}}_o - \dot{\boldsymbol{q}}\right), \tag{7}$$

where $\boldsymbol{\tau}^{dyn}$ is the dynamic compensation terms, and K_P and K_D are the proportional and derivative constants for the PD position controller. The desired and the actual joint positions are represented by $\boldsymbol{q_o}$ and $\boldsymbol{q}$, respectively.

The velocity from the master side was sent to the slave side and the force measured at the slave side was reflected to the master side. Since the two robotic exoskeletons were not kinematically identical, it was the end effector motion that the slave robot mimicked, rather than the motion of each of its joints. Additionally, even though the slave robotic exoskeleton was equipped with force sensors at every joint, only the force measured at the end effector was reflected across the communication channel to the master side.

To control the bilateral teleoperation across the communication channel, this project utilized the TDPC method. Furthermore, since it was the velocity that was sent from the master side, the implemented controller compensated for position drift. Additionally, the authors created a novel method to address the accumulation of energy dissipation – which is a known problem associated with TDPC. They did so by combining two other methods suggested in the literature: resetting the PO when the slave was not interacting with the environment [95], and also performing an energy resetting maneuver that resets the PO when the system was stable for a fixed amount of time [107].

The modified TDPC control method performed well during the tests described in the paper. In the future, it would be very useful to see how the control methods would perform – and what extensions would have to be made – when a human is included on the slave side. Furthermore, this study was based only on end-effector motion and force, thus it would be interesting to see this control method applied in joint-space to kinematically-comparable robotic exo-skeletons.

2) TELEOPERATION OF IMPEDANCE-CONTROLLED 6-DOF EXOSKELETONS WITH 'THERAPIST' AND 'PATIENT'

A study performed by Lanini *et al.* [108] in 2015 documented experiments performed with upper limb robotic exoskeletons and healthy human operators on both the master and the slave side of the teleoperation system. These experiments did not include time delays between the two systems, thus no teleoperation control method addressing delays had to be implemented. Although both unilateral and bilateral teleoperation was performed during this study, only the bilateral teleoperation case is discussed in this article.

On the master side, the authors used ARMin III, a 6-DOF grounded upper-limb rehabilitation exoskeletons which has position sensors at every joint. The master robot ARMin III joint angles were sent to the slave side. The device used on the slave side is ARMin IV, the next generation of ARMin III, a 6-DOF grounded upper-limb rehabilitation exoskeleton equipped with position sensors at every joint and three force/torque sensors placed in the two cuffs that envelop the user's upper arm and forearm. There was also a force/torque sensor in the hand module. The joint torques were measured on the slave ARMin IV and reflected to the master side for bilateral teleoperation. It should be noted that the measured torques were scaled and bounded by a safety limit before being applied to the robot-human system as the feedback torque on the master side.

There was no controller on the master side. The slave side exoskeleton had a compliance controller which was based on PD control with gravity compensation as shown below:

$$\boldsymbol{\tau} = K_P \boldsymbol{q}_e + K_D \dot{\boldsymbol{q}}_e + \boldsymbol{\tau}_G, \tag{8}$$

where $\boldsymbol{\tau}$ is the control torques, $\boldsymbol{\tau}_G$ is the estimated gravity torques, K_P is the gain for active stiffness on the joint angle error $\boldsymbol{q}_e$ between the desired and actual angles, and K_D is the gain for joint damping action operating on the velocity error $\dot{\boldsymbol{q}}_e$. If it is assumed that gravity torques can be estimated perfectly and that $\dot{\boldsymbol{q}}_e = \ddot{\boldsymbol{q}}_e = 0$, then:

$$K_P \boldsymbol{q}_e = J^T(\boldsymbol{q}) F_{int}, \tag{9}$$

where $J^T(\boldsymbol{q})$ is the transpose of the exoskeleton's Jacobian matrix and F_{int} is the interaction force between the human and the exoskeleton. Therefore, the interaction force acts on the human arm as a function of the joint angle error. Gain K_P allows each exoskeleton's joint stiffness to be adjusted separately. This method can be seen as an impedance controller with static model-based compensation.

To guarantee stability, the measured interaction torque sent to the master side from the slave side, $\boldsymbol{\tau}_{ef}(\boldsymbol{t})$, was constrained by the small gain stability requirements:

$$\boldsymbol{\tau}_{ef}(\boldsymbol{t}) = \begin{cases} \boldsymbol{\tau}_e(t), & if \ \ |\boldsymbol{\tau}_e(t)| < J_{arm}^T X(t) \\ \dfrac{\boldsymbol{\tau}_e(t)}{|\boldsymbol{\tau}_e(t)|} J_{arm}^T X(t), & otherwise \end{cases} \tag{10}$$

where J_{arm} is the Jacobian of the human arm and $X(t)$ is the permitted upper bound of the reflected torque.

Lastly, Lanini *et al.* [108] did not incorporate communication time delays, though they discussed the stability analysis of their system theoretically.

As a next step, it would be interesting to analyze the case with time delays between the master and the slave system and see which teleoperation control method would work best in addressing the delays. Furthermore, it would be useful to perform experiments in joint space to take full advantage of the hardware capabilities of these devices which are currently the most expensive and advanced upper limb rehabilitation robotic exoskeletons on the market.

3) TELEOPERATION OF AN END EFFECTOR ROBOT USING A 3-DOF EXOSKELETON

A paper written by Wei *et. al* in 2014 [109] documented a study performed using a custom-made upper limb robotic exoskeleton, ULERD [56], [110]–[113] on the master side and the PHANTOM Premium, an end effector robot on the slave side.

The PHANTOM Premium could provide the x, y, and z position values as well as the orientation of the end of the stylus about the three axis. Also, the force – which was motion-dependent and generated through the haptic rendering – was sent from the stylus.

The ULERD on the master side had 3-DOFs: elbow flexion/extension, wrist flexion/extension, and forearm pronation/supination. An MTx sensor, which tracks inertial orientation in 3-DOF (roll, pitch, and yaw), was installed 2 cm away from the wrist to track forearm flexion and extension.

In contrast to convention, in this study he 'therapist' handled the stylus on the PHANTOM Premium on the slave side and the 'patient' wore the ULERD on the master side. This study allowed active control from the patient side. Furthermore, when the patient moved the ULERD, the controller used a potential- field-of-virtual-force method that allowed customization and control over timing and the level of influence of the exert force. PID control was applied on the PHANTOM Premium in order to build the potential field of virtual forces. A desired position was specified to the PHANTOM Premium on the slave side and the programmed force that would send the robot towards this target position.

The test discussed in the study involved only the elbow flexion and extension motion by the patient on the master side inside the ULERD. Good following performance was achieved. As an extension, it would be beneficial to implement a teleoperation control method and perform tests with delays. One apparent limitation of this study is that the roles of both the 'therapist' and the 'patient' were performed by the same person at the same time. This setup is what is known as 'bilateral training', and it usually performed so that a patient's able arm can influence the rehabilitation of the patient's affected arm. As a result, this scenario uses another closed control loop through the patient and provides advanced and continuous knowledge about the intention, motion, and forces on both sides which can compromise the evaluation of the teleoperation system at hand. For telerehabilitation research, it is suggested that the same setup could be used but with different operators on the master and the slave side.

4) TELEOPERATION OF A 3-DOF EXOSKELETON USING A HUMAN-ARM-LIKE DEVICE, WITH 'THERAPIST' AND 'PATIENT'

Two papers have been written by researchers at the Department of Intelligent Mechanical Systems Engineering in Japan documenting aspects and stages of a project which involved using a human-arm-like device on the master side, and an elbow exoskeleton on the slave side [101], [102]. The master side incorporated an elbow Series Elastic Actuator (SEA) device to provide haptic feedback to the 'therapist'. A large reduction ratio gearhead was used in this device for minimal deflection of the elastic elements during passive training to provide high fidelity readings of the master side motion. The SEA was selected to also allow for adjustable impedances and to detect the force applied by the therapist during active training. An angle sensor and an inertia sensor (MTx) were used on the master device. This device was handled by the 'therapist' to perform elbow flexion and extension motion and the sensor data was sent to the slave side.

The same exoskeleton that was used in Study 3 [109] was used in this study as well on the slave side. Elastic elements were also incorporated in the design of the exoskeleton to allow for adjustable impedance since high joint impedance is required during the passive mode but near-zero impedance is required during the active mode. The patient's motion was tracked using an inertia sensor (MTx).

A closed-loop control strategy was applied on the master device which allowed for variable impedance by adjusting the deflection of the elastic elements. The robotic exoskeleton on the slave side was under PID control. The time lag during TCP/IP communication between the master and the slave had a maximum value of 15 ms. These delays were not compensated for and the 'patient' felt no obvious discomforts. The motion of the exoskeleton was observed to be smooth.

The exoskeleton's motor current was monitored for safety, as it could reveal the interaction force between the patient and the robotic exoskeleton. For extra added safety, and to compensate for delays, a mechanical torque-limiting component was also implemented in the exoskeleton.

B. DISCUSSIONS

Very few papers have been found in the literature that studied bilateral telerehabilitation with upper-limb robotic exoskeletons, as shown in this Section. Out of the four studies outlined in this article, only one utilized a teleoperation control method that addressed communication time delays. Furthermore, only one study included individual huma operators and robotic exoskeletons on both the master and the slave side; however, it did not consider communication delays. Two studies only used an upper limb exoskeleton on one side and an end effector type robot on the other. Another study used a SEA-based human-arm-like device that would require the 'therapis' to manipulate it similar to the way a therapist would handle a stroke patient's affected arm during rehabilitation training. Impedance control was used on the master side for two of the studies where a master side controller was used. Two of the studies used PID control on the slave side, one used Admittance control, and one used Impedance control.

Control methods for upper-limb telerehabilitation robotic exoskeletons have the advantage of being able to help in providing intensive, consistent, longer, programmable, and high-precision therapy compared to conventional physical therapies. They can objectively assess and monitor patients' performance using sensors. Furthermore, better outcomes than usual care can be achieved when combined with video games [116]. In the long run, robotic rehabilitation has the potential to reduce costs and increases patient throughput [117] and reduce therapist fatigue by using force-scaling [20], and facilitating multi-patient sessions [118]. In contrast with end-effector type robots, robotic exoskeletons are able to rehabilitate at the joint level and minimize compensatory movements that is common in systems using end-effector-type devices [119].

When electro-mechanical hardware is physically connected to the human limb, safety should be of paramount concern in order to prevent injury. Appropriate precautions should be taken in their design and operation by integrating software and hardware limits, torque limiters, saturation limits for local and reflected power signals, and emergency stop buttons that can be easily reached and operated by the patient.

With respect to telerehabilitation, some of the main advantages are that there would be cost reductions in hospital stays and cost reductions in travel for the therapists to go to clients' homes or remote community clinics. There would also be less need for patients to go to hospitals or clinics and therefore result in additional travel cost reduction. Even more cost savings could take place by having a therapist at a clinic, and conduct simultaneous rehabilitation sessions with multiple patients at several remote locations [117], [118]. Another advantage of telerehabilitation is that the same software and hardware systems could be implemented at different sites, providing consistency and reducing the learning curve for both therapist and patient [14]. Scaled forces between the master and the slave systems could be used to reduce fatigue for the therapist [20] and thus enable more patients to be serviced. Additionally, considering the reduced in-person physiotherapy services due to COVID-19, telerehabilitation should be seriously considered.

One of the main disadvantages of using assistive robotics is that it is an emerging technology and thus – not fully matured where it can be readily available to be implemented. Known current challenges for rehabilitation robots are the achievement of smooth interaction with the human limb and limited workspace [120], [121]. Furthermore, optimal control methods still need to be developed for this technology. Additionally, the cost of current systems is prohibitive to the general population [122]. One of the main disadvantages for telerehabilitation is dependability on the internet as service availability and reliability can limit its use in certain regions and its viability. When looking specifically at exoskeleton robots, the lack of flexible designs can be a deterrent to making them more widely integrated and used.

The control methods for upper limb robotic exoskeleton telerehabilitation have numerous challenges. First, there are system uncertainties [123] such as modeling uncertainties. There are also input uncertainties [80] such as unknown external disturbances and improperly measured, modeled [97], or time-varying human arm parameters. Accurate velocity and acceleration value estimates or measurements are required for many control methods – which can be challenging to obtain due to noise in the signal. Unreliable communication channels: delay and other degrading factors such as data loss, and limited bandwidth affect stability and transparency [108]. Furthermore, potential stability loss can happen due to the human operators injecting energy into the system which can result in failure of control and unsafe operation if not properly addressed.

For future rehabilitation robotic exoskeletons control systems, in order to deal with parametric uncertainties and unknown models, methods such as adaptive robust control, radial basis function-based approaches, and machine learning methods would be recommended. Furthermore, customizable impedance control is of great benefit to ensure and accommodate comfortable and adjustable interaction.

Robust teleoperation control methods that ensure boundedness of the reflected energy could possibly be the safest methods to be implemented.

Additionally, as telerehabilitation robotic exoskeleton systems advance to the later stages in research and to the clinical stage, key performance indicators, such as the Fugl-Meyer Assessment, should be used to assess the disease severity, motor recovery, and rehabilitation treatment of the patient's affected arm.

Perhaps the biggest reasons that there are so few studies and projects in this area is the cost and complexity of the robotic exoskeleton, as well as its control challenges involved with nonlinear systems and network communications. Possibly, as a first step, the focus should be placed on developing less expensive, simpler-to-integrate, and simpler-to-control robotic exoskeletons that would address only one or two degrees of freedom. Such systems could also be more portable and readily integratable into the homes of remote patients, as they would be more accessible.

VI. CONCLUSION

This article presents an overview of upper limb robotic exoskeleton control methods, telerobotics control methods, and four current upper limb robotic exoskeleton telerehabilitation studies. There are numerous papers found describing control methods for upper limb robotic exoskeletons and the most common methods were outlined in this article. There are also myriad control strategies in the literature for bilateral telerobotics and control methods used with multiple degrees of freedom that compensate for the time delay across the communication channel– the most common of which were summarized in this article. Lastly, there is very little research presented in the literature on telerehabilitation for upper limbs with robotic exoskeletons. It is expected that as the rapidly growing population of seniors around the world becomes more taxing on the medical system and the COVID-19 pandemic impeding the delivery of in-person physiotherapy services, tele-rehabilitation research, development, and implementation will become more crucial and prevalent.

REFERENCES

[1] *World Population Prospects 2019: Highlights, No. 141*, Dept. Econ. Social Affairs, Population Division, New York, NY, USA, 2019.
[2] H. I. Krebs, J. J. Palazzolo, L. Dipietro, M. Ferraro, J. Krol, K. Rannekleiv, B.T. Volpe, and N. Hogan, "Rehabilitation robotics: Performance-based progressive robot-assisted therapy," *Auton. Robots*, vol. 15, pp. 7–20, Jul. 2003.
[3] ASA. (2019). *About Stroke*. Accessed: Apr. 12, 2020. https://www.stroke.org/ en/about-stroke
[4] W. S. Organization. *Learn About Stroke*. Accessed: Apr. 22, 2020. [Online]. Available: https://www.world-stroke.org/world-stroke-day-campaign/why-stroke-matters/learn-about-stroke
[5] A. Lioulemes, "An intelligent multimodal upper-limb rehabilitation robotic system," Ph.D. dissertation, Texas Arlington Univ., Arlington, TX, USA, 2017.
[6] V. Lin, X. Zhang, and P. Dixon, "Occupational therapy workforce in the united states: Forecasting nationwide shortages," *PM&R*, vol. 7, no. 9, pp. 946–954, Sep. 2015.
[7] A. E. Cha. (Apr. 20, 2020). Young and Middle-Aged People, Barely Sick With COVID-19, Are Dying of Strokes. The Washington Post. Accessed: Apr. 25, 2020. [Online]. Available: https://www.washingtonpost.com/health/2020/04/24/strokes-coronavirus-young-patients/
[8] M. Wadman, J. Couzin-Frankel, J. Kaiser, and C. Matacic, "How does coronavirus kill? Clinicians trace a ferocious rampage through the body, from brain to toes," in *Proc. Amer. Assoc. Advancement Sci. (AAAS)*, 2020. Accessed: Apr. 25, 2020. [Online]. Available: https://www.sciencemag.org/news/2020/04/how-does-coronavirus-kill-clinicians-trace-ferocious-rampage-through-body-brain-toes
[9] I. Y. Balkaya, J. A. Fernandez, W. Gerguis, M. T. Kaner, M. Lamagna, A. Lekshminarayanan, H. Meng, S. M. M. Mohar, S. Randev, I. Sanchez, S. Brahmbhatt, M. Islam, M. Frankenthaler, P. T. Diamond, and E. L. Altschuler, "When physical medicine and rehabilitation became medicine-life in the time of COVID-19," *Amer. J. Phys. Med. Rehabil.*, vol. 99, no. 6, pp. 1–5, Jun. 2020.
[10] W. C. for P. Therapy. (2020). *WCPT Launches #PPE4PT Advocacy Campaign in Support of Access to Personal Protective Equipment for Physiotherapists*. World Confederation for Physical Therapy. Accessed: Apr. 26, 2020. [Online]. Available: https://www.wcpt.org/node/178216
[11] J. Kruger. (2020). *Jonathon Kruger, WCPT Chief Executive Officer, On WCPT's Advocacy Campaign #PPE4PT–YouTube*. World Confederation for Physical Therapy. Accessed: Apr. 26, 2020. [Online]. Available: https://www.youtube.com/watch?time_continue=117&v=AUcyLtZclsE&feature=emb_logo
[12] *Physiotherapy Consultations by Phone Available From Monday*, Times Malta, Birkirkara, Malta, 2020.
[13] *Support Helpline for Physiotherapy Outpatients Launched*, Times Malta, Birkirkara, Malta, 2020.

[14] C. R. Carignan and H. I. Krebs, "Telerehabilitation robotics: Bright lights, big future?" *J. Rehabil. Res. Dev.*, vol. 43, no. 5, pp. 695–710, 2006.

[15] C. Moro, S. Lin, G. Nejat, and A. Mihailidis, "Social robots and seniors: A comparative study on the influence of dynamic social features on Human–Robot interaction," *Int. J. Social Robot.*, vol. 11, no. 1, pp. 5–24, Jan. 2019.

[16] S. L. Wolf, K. Sahu, R. C. Bay, S. Buchanan, A. Reiss, S. Linder, A. Rosenfeldt, and J. Alberts, "The HAAPI (Home arm assistance progression Initiative) trial: A novel robotics delivery approach in stroke rehabilitation," *Neurorehabilitation Neural Repair*, vol. 29, no. 10, pp. 958–968, Nov. 2015.

[17] T. Nef, M. Mihelj, and R. Riener, "ARMin: A robot for patient-cooperative arm therapy," *Med. Biol. Eng. Comput.*, vol. 45, no. 9, pp. 887–900, Sep. 2007.

[18] T. Proietti, V. Crocher, A. Roby-Brami, and N. Jarrasse, "Upper-limb robotic exoskeletons for neurorehabilitation: A review on control strategies," *IEEE Rev. Biomed. Eng.*, vol. 9, pp. 4–14, Apr. 2016.

[19] R. C. V. Loureiro, W. S. Harwin, K. Nagai, and M. Johnson, "Advances in upper limb stroke rehabilitation: A technology push," *Med. Biol. Eng. Comput.*, vol. 49, no. 10, pp. 1103–1118, Oct. 2011.

[20] J. Laut, M. Porfiri, and P. Raghavan, "The present and future of robotic technology in rehabilitation," *Current Phys. Med. Rehabil. Rep.*, vol. 4, no. 4, pp. 312–319, Dec. 2016.

[21] R. A. R. C. Gopura, D. S. V. Bandara, K. Kiguchi, and G. K. I. Mann, "Developments in hardware systems of active upper-limb exoskeleton robots: A review," *Robot. Auto. Syst.*, vol. 75, pp. 203–220, Jan. 2016.

[22] J. Brackenridge, L. V. Bradnam, S. Lennon, J. J. Costi, and D. A. Hobbs, "A review of rehabilitation devices to promote upper limb function following stroke," *Neurosci. Biomed. Eng.*, vol. 4, no. 1, pp. 25–42, May 2016.

[23] A. Frisoli, F. Salsedo, M. Bergamasco, B. Rossi, and M. C. Carboncini, "A force-feedback exoskeleton for upper-limb rehabilitation in virtual reality," *Appl. Bionics Biomech.*, vol. 6, no. 2, pp. 115–126, 2009.

[24] S. S. Conroy, J. Whitall, L. Dipietro, L. M. Jones-Lush, M. Zhan, M. A. Finley, G. F. Wittenberg, H. I. Krebs, and C. T. Bever, "Effect of gravity on robot-assisted motor training after chronic stroke: A randomized trial," *HHS Public Access*, vol. 92, no. 11, pp. 1754–1761, Nov. 2011.

[25] A. Radman, W. Ismail, and M. Bahari, "Robotic devices for upper limb stroke rehabilitation: Potential research trends," in *Proc. IEEE Int. Symp. Robot. Intell. Sensors (IRIS)*, Oct. 2017, pp. 383–388.

[26] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," *J. Neuroeng. Rehabil.*, vol. 11, no. 1, pp. 1–29, 2014.

[27] I. M. Khairuddin and S. N. Sidek, "Assistive-as-needed strategy for upper-limb robotic systems?: An initial survey," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 260, no. 1, pp. 1–6, 2017.

[28] Q. Miao, M. Zhang, J. Cao, and S. Q. Xie, "Reviewing high-level control techniques on robot-assisted upper-limb rehabilitation," *Adv. Robot.*, vol. 32, no. 24, pp. 1253–1268, Dec. 2018.

[29] M. R. Islam, C. Spiewak, M. H. Rahman, and R. Fareh, "A brief review on robotic exoskeletons for upper extremity rehabilitation to find the gap between research porotype and commercial type," *Adv. Robot. Autom.*, vol. 6, no. 3, p. 2, 2017.

[30] W. Yu, X. Li, and R. Carmona, "A novel PID tuning method for robot control," *Ind. Robot, Int. J.*, vol. 40, no. 6, pp. 574–582, Oct. 2013.

[31] Q. Wu, X. Wang, F. Du, and Q. Zhu, "Fuzzy sliding mode control of an upper limb exoskeleton for robot-assisted rehabilitation," in *Proc. IEEE Int. Symp. Med. Meas. Appl. (MeMeA)*, May 2015, pp. 451–456.

[32] C. Ott, R. Mukherjee, and Y. Nakamura, "Unified impedance and admittance control," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2010, pp. 554–561.

[33] N. Hogan, "Impedance control: An approach to manipulation," in *Proc. Amer. Control Conf.*, Jul. 1984, pp. 304–313.

[34] V. Hayward and K. Maclean, "Do it yourself haptics: Part I," *IEEE Robot. Autom. Mag.*, vol. 14, no. 4, pp. 88–104, Dec. 2007.

[35] K. Kiguchi and Y. Hayashi, "An EMG-based control for an upper-limb power-assist exoskeleton robot," *IEEE Trans. Syst., Man, Cybern., B (Cybern.)*, vol. 42, no. 4, pp. 1064–1071, Aug. 2012.

[36] C. Carignan, J. Tang, S. Roderick, and M. Naylor, "A configuration-space approach to controlling a rehabilitation arm exoskeleton," in *Proc. IEEE 10th Int. Conf. Rehabil. Robot.*, Jun. 2007, pp. 179–187.

[37] F. Just, K. Baur, R. Riener, V. Klamroth-Marganska, and G. Rauter, "Online adaptive compensation of the ARMin rehabilitation robot," in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2016, pp. 747–752.

[38] B. Brahmi, M. Saad, C. O. Luna, and M. H. Rahman, "Cartesian sliding mode tracking control of an exoskeleton robot based on time delay estimation," in *Proc. 14th Int. Multi-Conf. Syst., Signals Devices (SSD)*, Mar. 2017, pp. 817–822.

[39] K. Anam and A. A. Al-Jumaily, "Active exoskeleton control systems: State of the art," *Procedia Eng.*, vol. 41, pp. 988–994, Jan. 2012.

[40] C. Smith, Y. Karayiannidis, L. Nalpantidis, X. Gratal, P. Qi, D. V. Dimarogonas, and D. Kragic, "Dual arm manipulation—A survey," *Robot. Auton. Syst.*, vol. 60, no. 10, pp. 1340–1353, 2012.

[41] R. Riener, L. Lünenburger, and G. Colombo, "Human-centered robotics applied to gait training and assessment," *J. Rehabil. Res. Dev.*, vol. 43, no. 5, pp. 679–693, 2006.

[42] K. E. MacLean and V. Hayward, "Do it yourself haptics: Part II [tutorial]," *IEEE Robot. Autom. Mag.*, vol. 15, no. 1, pp. 104–119, Mar. 2008.

[43] H. S. Lo and S. Q. Xie, "Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects," *Med. Eng. Phys.*, vol. 34, no. 3, pp. 261–268, Apr. 2012.

[44] R. Riener, L. Lunenburger, S. Jezernik, M. Anderschitz, G. Colombo, and V. Dietz, "Patient-cooperative strategies for robot-aided treadmill training: First experimental results," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 3, pp. 380–394, Sep. 2005.

[45] H.-B. Kang and J.-H. Wang, "Adaptive robust control of 5 DOF upper-limb exoskeleton robot," *Int. J. Control, Autom. Syst.*, vol. 13, no. 3, pp. 733–741, Jun. 2015.

[46] B. Brahmi, A. Brahmi, M. Saad, G. Gauthier, and M. H. Rahman, "Robust adaptive tracking control of uncertain rehabilitation exoskeleton robot," *J. Dyn. Syst., Meas., Control*, vol. 141, no. 12, pp. 121007–121015, Dec. 2019.

[47] D. Yun, A. M. Khan, R.-J. Yan, Y. Ji, H. Jang, J. Iqbal, K. M. Zuhaib, J. Y. Ahn, J. Han, and C. Han, "Handling subject arm uncertainties for upper limb rehabilitation robot using robust sliding mode control," *Int. J. Precis. Eng. Manuf.*, vol. 17, no. 3, pp. 355–362, Mar. 2016.

[48] C. Yang, Y. Jiang, Z. Li, W. He, and C.-Y. Su, "Neural control of bimanual robots with guaranteed global stability and motion precision," *IEEE Trans. Ind. Informat.*, vol. 13, no. 3, pp. 1162–1171, Jun. 2017.

[49] L.-J. Xu, C.-Y. Dong, and Y. Chen, "An adaptive fuzzy sliding mode control for networked control systems," in *Proc. Int. Conf. Mechatronics Autom.*, Aug. 2007, pp. 1190–1195.

[50] Q. Wu, X. Wang, B. Chen, and H. Wu, "Development of an RBFN-based neural-fuzzy adaptive control strategy for an upper limb rehabilitation exoskeleton," *Mechatronics*, vol. 53, pp. 85–94, Aug. 2018.

[51] B. Brahmi, M. Saad, C. Ochoa-Luna, M. H. Rahman, and A. Brahmi, "Adaptive tracking control of an exoskeleton robot with uncertain dynamics based on estimated time-delay control," *IEEE/ASME Trans. Mechatronics*, vol. 23, no. 2, pp. 575–585, Apr. 2018.

[52] H. Shokri-Ghaleh and A. Alfi, "Bilateral control of uncertain telerobotic systems using iterative learning control: Design and stability analysis," *Acta Astronautica*, vol. 156, pp. 58–69, Mar. 2019.

[53] B. Ugurlu, M. Nishimura, K. Hyodo, M. Kawanishi, and T. Narikiyo, "Proof of concept for robot-aided upper limb rehabilitation using disturbance observers," *IEEE Trans. Human-Machine Syst.*, vol. 45, no. 1, pp. 110–118, Feb. 2015.

[54] T. Kawase, T. Sakurada, Y. Koike, and K. Kansaku, "A hybrid BMI-based exoskeleton for paresis: EMG control for assisting arm movements," *J. Neural Eng.*, vol. 14, no. 1, Feb. 2017, Art. no. 016015.

[55] J. Rosen, M. Brand, M. B. Fuchs, and M. Arcan, "A myosignal-based powered exoskeleton system," *IEEE Trans. Syst., Man, Cybern. A, Syst. Humans*, vol. 31, no. 3, pp. 210–222, May 2001.

[56] M. Pang, S. Guo, and Z. Song, "Study on the sEMG driven upper limb exoskeleton rehabilitation device in bilateral rehabilitation," *J. Robot. Mechatronics*, vol. 24, no. 4, pp. 585–594, Aug. 2012.

[57] D. Simonetti, L. Zollo, E. Papaleo, G. Carpino, and E. Guglielmelli, "Multimodal adaptive interfaces for 3D robot-mediated upper limb neuro-rehabilitation: An overview of bio-cooperative systems," *Robot. Auto. Syst.*, vol. 85, pp. 62–72, Nov. 2016.

[58] X. Zhong and Y. ShiQiang, "A review of on-orbit servicing robot teleoperation control system," *Int. J. Signal Process., Image Process. Pattern Recognit.*, vol. 9, no. 11, pp. 83–92, Nov. 2016.

[59] M. Ferre, M. Buss, R. Aracil, C. Melchiorri, and C. Balaguer, "Introduction to advances in telerobotics," in *Advances in Telerobotics*. Berlin, Germany: Springer, 2007, pp. 1–7.

[60] G. Niemeyer, C. Preusche, and G. Hirzinger, "Telerobotics," in *Handbook Robotics*, Cham, Switzerland: Springer, 2008, pp. 741–757.

[61] S. Hirche, M. Ferre, J. Barrio, C. Melchiorri, and M. Buss, "Bilateral control architectures for telerobotics," in *Advances in Telerobotics*. Cham, Switzerland: Springer, 2007, pp. 163–176.

[62] D. Buongiorno, D. Chiaradia, S. Marcheschi, M. Solazzi, and A. Frisoli, "Multi-DoFs exoskeleton-based bilateral teleoperation with the time-domain passivity approach," *Robotica*, vol. 37, no. 9, pp. 1641–1662, Sep. 2019.

[63] I. Nisky, F. A. Mussa-Ivaldi, and A. Karniel, "Analytical study of perceptual and motor transparency in bilateral teleoperation," *IEEE Trans. Human-Machine Syst.*, vol. 43, no. 6, pp. 570–582, Nov. 2013.

[64] R. Muradore and P. Fiorini, "A review of bilateral teleoperation algorithms," *Acta Polytech. Hung.*, vol. 13, no. 1, pp. 191–208, 2016.

[65] Y. Yokokohji and T. Yoshikawa, "Bilateral control of master-slave manipulators for ideal kinesthetic coupling," *Trans. Soc. Instrum. Control Eng.*, vol. 27, no. 1, pp. 56–63, 1991.

[66] M. Serna, L. G. Garcia-Valdovinos, T. Salgado-Jimenez, and M. Bandala-Sanchez, "Bilateral teleoperation of a commercial small-sized underwater vehicle for academic purposes," in *Proc. OCEANS-MTS/IEEE Washington*, Oct. 2015, pp. 1–5.

[67] W. Wei and Y. Kui, "Teleoperated manipulator for leak detection of sealed radioactive sources," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Apr. 2004, pp. 1682–1687.

[68] H. Sun, G. Song, Z. Wei, Y. Zhang, and S. Liu, "Bilateral teleoperation of an unmanned aerial vehicle for forest fire detection," in *Proc. IEEE Int. Conf. Inf. Autom. (ICIA)*, Jul. 2017, pp. 586–591.

[69] D. Lee, A. Franchi, P. R. Giordano, H. I. Son, and H. H. Bulthoff, "Haptic teleoperation of multiple unmanned aerial vehicles over the Internet," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2011, pp. 1341–1347.

[70] E. Slawiñski, V. Moya, D. Santiago, and V. Mut, "Force and position–velocity coordination for delayed bilateral teleoperation of a mobile robot," *Robotica*, vol. 37, no. 10, pp. 1768–1784, Oct. 2019.

[71] Y. Dong and N. Chopra, "Passivity-based bilateral tele-driving system with parametric uncertainty and communication delays," *IEEE Control Syst. Lett.*, vol. 3, no. 2, pp. 350–355, Apr. 2019.

[72] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, Dec. 2006.

[73] P. M. Kebria, H. Abdi, M. M. Dalvand, A. Khosravi, and S. Nahavandi, "Control methods for Internet-based teleoperation systems: A review," *IEEE Trans. Human-Machine Syst.*, vol. 49, no. 1, pp. 32–46, Feb. 2019.

[74] K. Goldberg, S. Gentner, C. Sutter, and J. Wiegley, "The mercury project: A feasibility study for Internet robots," *IEEE Robot. Autom. Mag.*, vol. 7, no. 1, pp. 35–40, Mar. 2000.

[75] Q. Wang, P. Markopoulos, B. Yu, W. Chen, and A. Timmermans, "Interactive wearable systems for upper body rehabilitation: A systematic review," *J. NeuroEngineering Rehabil.*, vol. 14, no. 1, pp. 1–21, Dec. 2017.

[76] A. J. Alvares and L. S. J. Romariz, Jr., "Telerobotics: Methodology for the development of a through-the-Internet robotic teleoperated system," *J. Brazilian Soc. Mech. Sci.*, vol. 24, no. 2, pp. 1–10, 2002.

[77] T. B. Sheridan, *Telerobotics, Automation, and Human Supervisory Control*. Cambridge, MA, USA: MIT Press, 1992.

[78] D. Richert, C. J. B. Macnab, and J. K. Pieper, "Adaptive haptic control for telerobotics transitioning between free, soft, and hard environments," *IEEE Trans. Syst., Man, Cybern. A, Syst. Humans*, vol. 42, no. 3, pp. 558–570, May 2012.

[79] Z. Chen, Y.-J. Pan, and J. Gu, "Integrated adaptive robust control for multilateral teleoperation systems under arbitrary time delays," *Int. J. Robust Nonlinear Control*, vol. 26, no. 12, pp. 2708–2728, Aug. 2016.

[80] S. Tzafestas and A.-I. Mantelos, "Time delay and uncertainty compensation in bilateral telerobotic systems: State-of-art with case studies," in *Engineering Creative Design in Robotics and Mechatronics*. Hershey, PA, USA: IGI Global, 2013, pp. 208–238.

[81] E. J. RodrIguez-Seda, D. Lee, and M. W. Spong, "Experimental comparison study of control architectures for bilateral teleoperators," *IEEE Trans. Robot.*, vol. 25, no. 6, pp. 1304–1318, Dec. 2009.

[82] G. Niemeyer and J.-J.-E. Slotine, "Telemanipulation with time delays," *Int. J. Robot. Res.*, vol. 23, no. 9, pp. 873–890, Sep. 2004.

[83] P. Arcara and C. Melchiorri, "Control schemes for teleoperation with time delay: A comparative study," *Robot. Auto. Syst.*, vol. 38, no. 1, pp. 49–64, Jan. 2002.

[84] B. Hannaford and J.-H. Ryu, "Time-domain passivity control of haptic interfaces," *IEEE Trans. Robot. Autom.*, vol. 18, no. 1, pp. 1–10, Aug. 2002.

[85] G. Niemeyer and J.-J.-E. Slotine, "Stable adaptive teleoperation," *IEEE J. Ocean. Eng.*, vol. 16, no. 1, pp. 152–162, Jan. 1991.

[86] M. D. Duong, K. Terashima, and T. Miyoshi, "A novel stable teleoperation with haptic feedback by means of impedance adjustment via arbitrary time delay environment for rehabilitation," in *Proc. IEEE Int. Conf. Control Appl.*, Jul. 2009, pp. 1744–1749.

[87] J. R. Ware, "Power based time domain passivity control and its application to bilateral teleoperated robotic vehicles," M.S. thesis, Dalhousie Univ., Halifax, NS, Canada, 2010.

[88] J. Ware and Y.-J. Pan, "Realisation of a bilaterally teleoperated robotic vehicle platform with passivity control," *IET Control Theory Appl.*, vol. 5, no. 8, pp. 952–962, May 2011.

[89] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," *IEEE Trans. Autom. Control*, vol. 34, no. 5, pp. 494–501, May 1989.

[90] S. Munir and W. J. Book, "Wave-based teleoperation with prediction," in *Proc. Amer. Control Conf.*, 2001, pp. 4605–4611.

[91] D. Sun, F. Naghdy, and H. Du, "Application of wave-variable control to bilateral teleoperation systems: A survey," *Annu. Rev. Control*, vol. 38, no. 1, pp. 12–31, 2014.

[92] G. Niemeyer and J.-J.-E. Slotine, "Towards force-reflecting teleoperation over the Internet," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 1998, pp. 1909–1915.

[93] S. Munir and W. J. Book, "Internet-based teleoperation using wave variables with prediction," *IEEE/ASME Trans. Mechatronics*, vol. 7, no. 2, pp. 124–133, Jun. 2002.

[94] Y. Ye, Y. J. Pan, and Y. Gupta, "A simplified time domain passivity control of haptic interfaces," in *Proc. Int. Conf. Intell. Syst. Control (IASTED)*, 2008, pp. 215–219.

[95] Y. S. Kim and B. Hannaford, "Some practical issues in time domain passivity control of haptic interfaces," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, vol. 2, 2002, pp. 1744–1750.

[96] L. Sheng, U. Ahmad, Y. Ye, and Y. J. Pan, "A time domain passivity control scheme for bilateral teleoperation," *Electronics*, vol. 8, no. 3, pp. 325–338, 2019.

[97] L. Chan, F. Naghdy, and D. Stirling, "Application of adaptive controllers in teleoperation systems: A survey," *IEEE Trans. Human-Machine Syst.*, vol. 44, no. 3, pp. 337–352, Feb. 2014.

[98] N. Chopra and M. W. Spong, "Adaptive coordination control of bilateral teleoperators with time delay," in *Proc. 43rd IEEE Conf. Decis. Control (CDC)*, vol. 5, Dec. 2004, pp. 4540–4547.

[99] E. Nuño, I. Sarras, and L. Basañez, "An adaptive controller for bilateral teleoperators: Variable time-delays case," *IFAC Proc. Vols.*, vol. 47, no. 3, pp. 9341–9346, 2014.

[100] D. Lee and M. W. Spong, "Passive bilateral teleoperation with constant time delay," *IEEE Trans. Robot.*, vol. 22, no. 2, pp. 269–281, Apr. 2006.

[101] E. Nuño, L. Basañez, and R. Ortega, "Passivity-based control for bilateral teleoperation: A tutorial," *Automatica*, vol. 47, no. 3, pp. 485–495, Mar. 2011.

[102] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Trans. Robot. Autom.*, vol. 9, no. 5, pp. 624–637, Oct. 1993.

[103] A. Aziminejad, M. Tavakoli, R. V. Patel, and M. Moallem, "Transparent time-delayed bilateral teleoperation using wave variables," *IEEE Trans. Control Syst. Technol.*, vol. 16, no. 3, pp. 548–555, May 2008.

[104] J. H. Park and H. C. Cho, "Sliding-mode controller for bilateral teleoperation with varying time delay," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, Sep. 1999, pp. 311–316.

[105] M. Zou, Y.-J. Pan, S. Forbrigger, and U. Ahmad, "Adaptive robust control for bilateral teleoperated robotic manipulators with arbitrary time delays," in *Proc. 2nd Int. Conf. Robot. Artif. Intell. (ICRAI)*, Nov. 2016, pp. 105–111.

[106] K. Kawashima, K. Tadano, G. Sankaranarayanan, and B. Hannaford, "Bilateral teleoperation with time delay using modified wave variables," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2008, pp. 424–429.

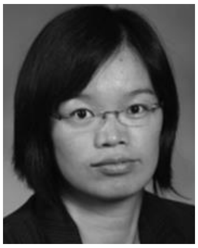
[107] J. Ryu, "Bilateral control with time domain passivity approach under time-varying communication delay: Resetting scheme," *J. Inst. Control Robot. Syst.*, vol. 14, no. 11, pp. 1124–1129, 2008.

[108] J. Lanini, T. Tsuji, P. Wolf, R. Riener, and D. Novak, "Teleoperation of two six-degree-of-freedom arm rehabilitation exoskeletons," in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, Aug. 2015, pp. 514–519.

[109] W. Wei, W. Zhang, S. Guo, X. Zhao, and Y. Wang, "Development of an upper limb rehabilitation robot system for bilateral training," in *Proc. IEEE Int. Conf. Mechatronics Autom.*, Aug. 2014, pp. 930–935.

[110] Z. Song and S. Guo, "Design process of exoskeleton rehabilitation device and implementation of bilateral upper limb motor movement," *J. Med. Biol. Eng.*, vol. 32, no. 5, pp. 323–330, 2012.
[111] W. Wei, S. Guo, W. Zhang, J. Guo, and Y. Wang, "A novel VR-based upper limb rehabilitation robot system," in *Proc. Int. Conf. Complex Med. Eng. (ICME)*, vol. 5, May 2013, pp. 302–306.
[112] S. Guo, W. Zhang, W. Wei, J. Guo, Y. Ji, and Y. Wang, "A kinematic model of an upper limb rehabilitation robot system," in *Proc. IEEE Int. Conf. Mechatronics Autom.*, Aug. 2013, pp. 968–973.
[113] S. Zhang, S. Guo, M. Qu, and M. Pang, "Development of a bilateral rehabilitation training system using the haptic device and inertia sensors," in *Proc. IEEE Int. Conf. Mechatronics Autom.*, Aug. 2014, pp. 606–611.
[114] S. Zhang, S. Guo, B. Gao, H. Hirata, and H. Ishihara, "Design of a novel telerehabilitation system with a force-sensing mechanism," *Sensors*, vol. 15, no. 5, pp. 11511–11527, May 2015.
[115] S. Zhang and S. Guo, "Performance evaluation of a novel telerehabilitation system for the elbow joint training," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, Aug. 2015, pp. 420–424.
[116] L. Piggott, S. Wagner, and M. Ziat, "Haptic neurorehabilitation and virtual reality for upper limb paralysis: A review," *Crit. Rev. Biomed. Eng.*, vol. 44, nos. 1–02, pp. 1–32, 2016.
[117] H.-S. Park, Q. Peng, and L.-Q. Zhang, "A portable telerehabilitation system for remote evaluations of impaired elbows in neurological disorders," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 3, pp. 245–254, Jun. 2008.
[118] A. Song, C. Wu, D. Ni, H. Li, and H. Qin, "One-therapist to three-patient telerehabilitation robot system for the upper limb after stroke," *Int. J. Social Robot.*, vol. 8, no. 2, pp. 319–329, Apr. 2016.
[119] M. Cortese, M. Cempini, P. R. de Almeida Ribeiro, S. R. Soekadar, M. C. Carrozza, and N. Vitiello, "A mechatronic system for robot-mediated hand telerehabilitation," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 4, pp. 1753–1764, Aug. 2015.
[120] A. Schiele and F. C. T. van der Helm, "Kinematic design to improve ergonomics in human machine interaction," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 14, no. 4, pp. 456–469, Dec. 2006.
[121] J. Corredor, J. Sofrony, and A. Peer, "Decision-making model for adaptive impedance control of teleoperation systems," *IEEE Trans. Haptics*, vol. 10, no. 1, pp. 5–16, Jan. 2017.
[122] M. J. Fu, J. S. Knutson, and J. Chae, "Stroke rehabilitation using virtual environments," *Phys. Med. Rehabil. Clinics North Amer.*, vol. 26, no. 4, pp. 747–757, Nov. 2015.
[123] M. Shahbazi, S. F. Atashzar, and R. V. Patel, "A systematic review of multilateral teleoperation systems," *IEEE Trans. Haptics*, vol. 11, no. 3, pp. 338–356, Jul. 2018.

GEORGETA BAUER (Graduate Student Member, IEEE) received the B.A.Sc. degree in mechanical engineering from the University of Waterloo, in 1994, and the M.A.Sc. degree in electrical and computer engineering from Dalhousie University, in 2000, where she is currently pursuing the Ph.D. degree in mechanical engineering. She was the Engineer-in-Residence and an Instructor of Mechatronics with the Mechanical Engineering Department, Dalhousie University. She has worked in a multitude of fields, including space, automotive, mining, and oceanography, and is a co-inventor of an automated inoculation robotic workcell. Her current research interests include assistive robotics, mechatronics, advanced control methods, and artificial Intelligence. She is a Student Member of the Canadian Society of Mechanical Engineering (CSME) and the Canadian Medical and Biological Engineering Society (CMBES) and has been a registered Professional Engineer of Nova Scotia, Canada, since 1998.



YA-JUN PAN (Senior Member, IEEE) received the B.E. degree in mechanical engineering from Yanshan University, in 1996, the M.E. degree in mechanical engineering from Zhejiang University, in 1999, and the Ph.D. degree in electrical and computer engineering from the National University of Singapore, in 2003. She held postdoctoral positions at CNRS in the Laboratoire d'Automatique de Grenoble (current name GPISA-Lab), France, in 2003, and the Department of Electrical and Computer Engineering, University of Alberta, Canada, in 2004. She is currently a Professor with the Department of Mechanical Engineering, Dalhousie University, Canada. Her research interests include robust nonlinear control, cyber-physical systems, intelligent transportation systems, haptics, and collaborative multiple robotic systems. She is a fellow of ASME, a member of CSME, and a registered Professional Engineer of Nova Scotia, Canada. She serves as an Associate Editor (AE) for the IEEE Transactions on Industrial Electronics, IEEE/ASME Transactions on Mechatronics, and IEEE Transactions on Cybernetics, the VP Atlantic of CSME, Canada, and has served as an AE for several other journals and conferences.

• • •