Journal of
Sensor and
Actuator Networks

MDPI

Review

Model Mediation to Overcome Light Limitations—Toward a Secure Tactile Internet System

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Received: 21 November 2018; Accepted: 25 December 2018; Published: 2 January 2019

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Abstract: Enabling haptic communication as well as voice and data over the future 5G cellular system has become a demand. Tactile Internet is one of the main use cases of the 5G system that will allow the transfer of haptic communications in real time. Latency, availability, reliability, and security are the main design challenges of the tactile Internet system and haptic based bilateral teleoperation systems. An end-to-end latency of 1 ms remains the main challenge toward tactile Internet system realization, not only for the processing and coding delays but mainly for the limitations of light. In this work, we analyze the key solutions to overcome the light limitations and enable the tactile Internet over any distances with the required latency. Building a virtual model or model mediated for the remote environment at the edge cloud unit near to the end user is the main solution. By means of AI, the virtual model can predict the behavior of the remote environment and thus, the end user can interact with the virtual environment with a high system experience. This literature review covers the existing work of the model mediated bilateral teleoperated systems and discusses its availability for the tactile Internet system. Furthermore, the security issues of tactile Internet system and the effect of model mediated system on the required security level of tactile Internet applications are discussed. Finally, a structure for the tactile Internet system, with the deployment of model mediation, is suggested.

Keywords: tactile Internet; model mediation; latency; security; haptic communication; teleoperation

1. Introduction

Tactile Internet is the future communication system that enables the communication of human sense of touch and actuation in a real time [1]. The conventional and traditional evolved communication networks fit a communication medium for transferring voice and data with certain performance. These systems represent either a form of human to human (H2H) communication or a machine to machine (M2M) communication; however, they do not cover the interaction between the human and the machine [2]. Tactile Internet provides a bilateral communication system able to transfer actuation and touch in a real time form between two distinct sides, mostly a human and a machine.

This presents a new form of communication, which is the human to machine communication (H2M) [3]. Haptic communications can be enabled over the tactile Internet and thus, moving from the traditional content delivery to skill delivery [4].

Tactile Internet as teleoperated systems can be viewed as three main domains; the master domain, the network domain, and the slave domain as illustrated in Figure 1 [5]. The first part is the master domain, which represents the human or the operator with one or more master devices. The master device is a haptic device with a certain degree of freedom (DoF). Haptic devices allow end users to feel, touch and manipulate objects in remote environment through an appropriate interface [6]. The sensation and interaction capabilities of the haptic device depend mainly on the DOF of the device. Haptic devices extract and track physical manipulations of the end user that represent the device inputs and fed the end user with real touch sensations as outputs. Haptic devices have inputs, such as position and orientation components, and outputs such as force and torque components. These devices differ in terms of DOF, mechanical bandwidth, workspace, possible inputs and outputs, interfaces, and maximum range of displayed force [7].

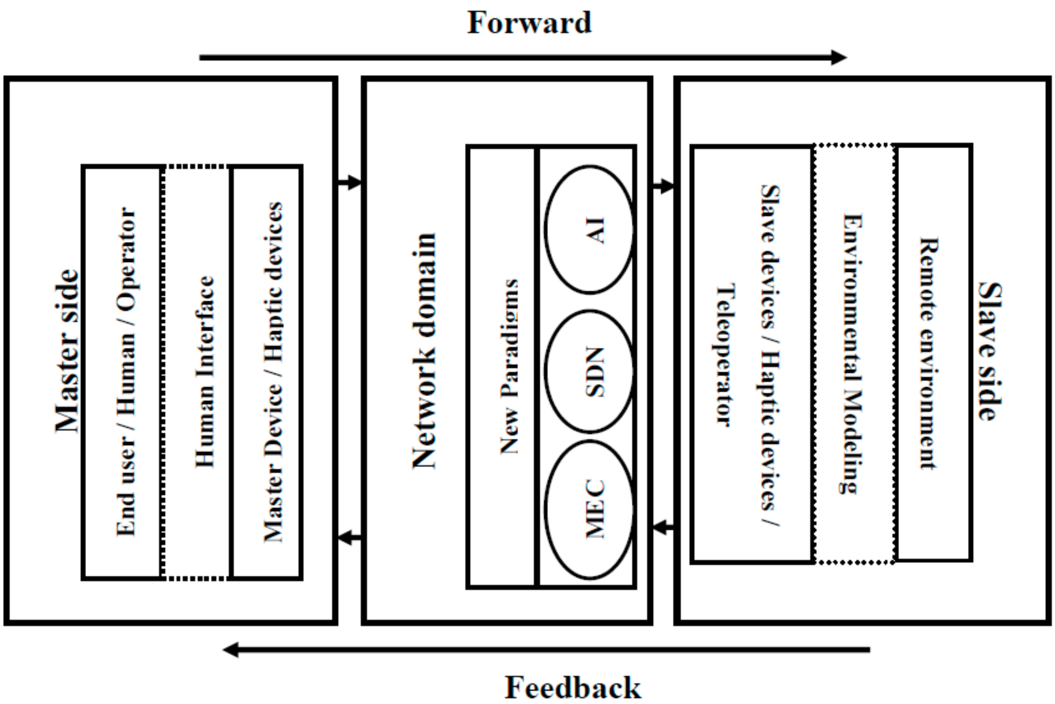

Figure 1. General structure of the tactile Internet system.

The second part is the slave domain, which is the remote domain that includes the slave device or the teleoperator operated in an environment. Remote environment may also deploy many slave devices that work together or independently to achieve common or different tasks [8]. Slave devices employ haptic devices with certain DoF, as well as the master devices. Table 1 introduces a list of common market available haptic devices with the main features and applications of each device. The mid domain is the network domain, which represents the medium for the haptic data to be transferred in a bilateral way. The network domain provides the infrastructure for transferring both haptic information data; kinesthetic and tactile data [9]. Kinesthetic data contains information about force and position, while tactile data contains touch information [10].

Table 1. Examples of available market haptic devices with their features and applications.

Device	DoF	Maximum Force/Torque at Nominal Position	Stiffness X,Y,Z	Range of Motion	Characteristics	Applications
Touch [11]/ Geomagic Touch (Sensable Phantom Omni) [12]	6	3.3 N	1.26 N/mm 2.13 N/mm 1.02 N/mm	Hand movement pivoting at wrist	Positional sensing; Motorized device; High degree of flexibility with portable design; Compact footprint, removable stylus and two integrated buttons.	3D modeling and manufacturing; Medical surgery and rehabilitation; Artwork and sculpting; Gaming, Entertainment, and Virtual Reality; Training, simulation processes, and skills assessment; Robotic control and teleoperation processes; Collision detection and virtual assembly; Machine interface design; Nano manipulation.
Phantom Premium (Sensable Phantom Premium) [13]	6	8.5 N 37.5 N 22 N	3.5 N/mm 3.5 N/mm 1 N/mm	Lower arm movement pivoting at elbow; Full arm movement pivoting at shoulder.	Provides the largest workspaces and highest forces; Offers a broad range of force feedback; Various ranges of motion and varying stiffness; Maximum durability and simple PC connection via the parallel port (EPP) interface.	Mainly developed for academic and commercial research and development.
Virtuose 6D [14]	6	35N	8 N/mm 30 N.m/rad	Full arm movement	High force feedback with a large workspace; Passive weight balancing; Available with programmable buttons and a proximity sensor.	Medical surgery and rehabilitation; Industrial simulation; training; Virtual reality
omega.7 [15]	7	12 ± 8 N	14.5 N/mm	Hand centered rotation	Designed for superior performance with no plastic components; Produces minimal user fatigue, due to active gravity compensation; Has a rotational sensing extension that is fully gravity compensated and designed to avoid interference from parasitic torques generated by translational forces; Simple and flexible; Provides high precision active grasping capabilities with orientation sensing.	Medical applications including remote surgery; Safety-critical applications; Training; Video gaming; Nanotechnology researches with the Atomic Force Microscopes; Micromanipulation.
sigma.7 [16]	7	20 ± 8 N	unequal closed loop stiffness	Natural range of motion of the human hand; Compatible with bi-manual teleoperation console design.	High performance force-feedback; Highly ergonomic and distinctive design; High-fidelity torque feedback; Active gravity compensation; High precision active grasping capability; Designed for superior performance with no plastic components.	Advanced aerospace and medical industries; Safety-critical applications; Training; Developing of haptic applications.

Various applications in many heterogeneous fields can be allowed over the tactile Internet, which include the following [17,18]:

(a) Healthcare applications: Tactile Internet is expected to assist the human healthcare by introducing new applications and facilities that do not support by the traditional networks. These applications include remote rehabilitation, remote diagnosis, and remote surgery applications. These applications will make the rare medical expertise and physicians available anywhere, and break the location limitations. Furthermore, robots can perform complete complicated surgeries (e.g., neurological surgery and heart surgery) with a remote control by an expert surgeon over the tactile Internet [19].

(b) Virtual and augmented reality (VR/AR) applications: Tactile Internet will assist the dynamic augmentation instead of existing static solutions. VR can be considered as a form of haptic communications that will be delivered more collaboratively over the tactile Internet. Complete latency and reliability requirements of the VR/AR applications will be supported by the tactile Internet, which is expected to achieve a round trip latency of 1 ms far from that required by VR applications (i.e., 5 ms) [20].

(c) Industry automation applications: The closed loop control circuit of most of industry automated systems requires a per sensor end-to-end latency of 1 ms [17,21]. This can be achieved via the tactile Internet system and the current wired system would be turned to wireless or augmented systems. This will enable more automated process and enhance the automation of current processes.

(d) Robotics applications: Recently, robots have begun to take part in our daily life, and the number of developed robots and their market revenue increase daily [22]. Tactile Internet will take part in the human controlled robots; especially for remote control applications. The ultra-reliable latency and reliability required by remote controlled robots will be achieved by the tactile Internet [23].

(e) Vehicular applications: Tactile Internet is expected to assist the road traffic management through the vehicle sensors and driver assistance systems. Tactile Internet will facilitate and provide the medium for the vehicle to vehicle communication (V2V) and the vehicle to the road side infrastructure communication (V2I). Furthermore, the high mobility required by the vehicular applications will be supported by the tactile Internet [24].

(f) Smart grid applications: The main aim of the intelligent smart grid is to distribute the generated energy efficiently, with the required stability of power supply. The intelligent smart grid systems monitor the status of the power generators and transmission lines, and control the operation of both. Furthermore, the user consumptions and tariffs are monitored and controlled by the intelligent grid systems. Thus, such systems require ultra-reliability and low latency communication systems (e.g., the required end-to-end latency of a synchronous co-phasing of power suppliers is 1 ms) to convey the information among the network. Tactile Internet will support these systems by achieving an end-to-end latency of 1 ms with an ultra-high reliability (e.g., systems with packet loss probability of 0.001%) [25].

(g) Other applications: Tactile Internet will have many applications in various fields, which are not limited to the previous mentioned ones. Tactile Internet is expected to have applications in other vital fields such as education, culture, serious gaming, and unmanned aerial vehicles. Tactile Internet will assist developing applications that will help children as well as adults with difficulties in developing their education skills, recovery of skills after injury or having disabilities [17,26].

Serious games are games that combine fun with other motivations and problem-solving challenges [27]. These motivations represent the primary goal of the game; other than the fun and entertainment. Serious games have applications in all vital fields such as; education, simulation, training and health. Since, the end-to-end latency of communication systems supporting these games represents an important factor of limiting the development of game-mechanics; the tactile Internet will provide a great support for this kind of applications. Furthermore, tactile Internet will provide the communication medium for the human controlled unmanned aerial vehicle applications with the required latency, reliability, and system availability [28].

Powered by the recent advances and developments in the near future release of the fifth-generation cellular system (5G), researchers and industry groups begin to take real steps and put road maps toward tactile Internet system realization [29]. There are many requirements and constraints on designing, developing and realizing the tactile Internet systems, which include the high system availability, the very high reliability and the ultra-low latency [30]. The most important challenges among these design constraints include the following:

a- Latency: Tactile Internet is announced as an ultra-reliable low latency (uRLL) use case of the fifth-generation cellular system (5G/IMT2020) [31,32]. Tactile Internet system requires an end-to-end latency of 1 ms, which is far from the end-to-end latency of current applications and systems. Latest systems of fourth-generation cellular system (4G) handle a round trip latency of 15 ms, while the first release of 5G is expected to enhance the latency performance and achieve an end-to-end latency of 5 ms [33]. Tactile Internet will reduce this latency to 1 ms that will include all delays involved in the communication process. Section 3 discusses the 1 ms challenge in details.

b- Reliability: Tactile Internet system is required to achieve ultra-high reliability so that the packet loss will be less than 10^{-7} [34]. This is because higher packet loss probability, results in incorrect data at the slave side that leads to incorrect interaction with the remote side [35]. Current transmission protocols (e.g., UDP and TCP) cannot be used for the tactile Internet applications, especially for haptic based applications, because of the required reliability and latency. Thus, new protocols need to be developed.

c- Security: Heterogeneous communications over the tactile Internet requires different levels of security. The internet protocol security (IPSec) represents a sufficient framework for security issues associated with most of traditional communication applications, while for haptic communication applications and other applications (e.g., augmented reality (AR) and virtual reality (VR)), new security frameworks should be introduced since existing frameworks cannot be used [36,37]. This is because the implementations of current security methods for these systems affect the communication latency constraints by introducing much delay. Thus, security issues and the required security levels of tactile Internet applications should be considered for each kind or group of applications with the consideration of end-to-end latency constraints required by the system to achieve acceptable level of user experience [38].

The main challenge among these design constraints is the ultra-low latency, which represents the main obstacle toward system development and realization. Tactile Internet required an end-to-end latency of 1 ms, which means that all delays from the data transmission at the transmitter until the feedback reception at the transmitter should be at maximum of 1 ms to allow an acceptable experience [39]. The network domain of the tactile Internet systems should be designed in a proper way to achieve the requirements of the tactile Internet and as the 1 ms latency is a main requirement, the communication network should deploy new technologies to achieve this. 5G cellular systems will be proper but still far from 1 ms end-to-end latency [40].

In this work, we mainly consider the challenge of 1 ms and the associated security issues. In [41], we developed a multi-level edge computing framework for the tactile Internet system, which can be used to decrease the communication latency and achieves the 1 ms challenge, while the two communicated parts are in vicinity. The light speed limits the communication distance with the restriction of 1 ms delay. To this end, this work considers the main solutions to overcome the light speed limitations and provide a way toward tactile Internet realization. These solutions break these limitations and with the deployment of previous developed multi-level edge system, it can achieve the

1 ms end-to-end latency of the tactile Internet system; whatever the distances between the transmitter and the receiver.

Tactile Internet is expected to support and introduce many applications in different fields as previously introduced, however haptic communications will be the main applications run over the tactile Internet [37]. Thus, our main concern, in this work, is the haptic communication over the tactile Internet.

This work mainly considers the 1 ms latency constraint with consideration to light limitations and associated security issues. Furthermore, it introduces a literature review of model mediated systems that can be used to overcome light limitations and realize the tactile Internet system. Section 2 discusses the main features of the haptic communications as it represents the main application that will run over the tactile Internet. In Section 3, the reasons for the 1 ms end-to-end latency design constraint and light limitations for tactile Internet realization are discussed. Section 4 reviews the model mediated systems introduced for bilateral teleoperated systems and analyze them. Furthermore, methods for environmental modeling and main challenges associated with the design of model mediated system are introduced. Section 5 discusses the main security issues associated with the tactile Internet system and how the introduction of model mediation can solve these issues. In Section 6, we discuss how the model mediated can be used for the tactile Internet system with the introduction of artificial intelligent algorithms to overcome the problem of 1 ms latency and the light limitations, and to achieve the security levels for different tactile Internet applications. Finally, the work is concluded in Section 7.

2. Haptic Communications

Humans have five main senses; four of them are dedicated with centralized parts in the human's body. While, the sense of touch is distinct, since it is distributed over the entire human's body [42]. Our bodies contain main active tactile senses as the hands with different sensing sensitivities. Our human skin can distinguish four main sensation modalities; heat, cold, touch, and pain. Other sensations (e.g., vibration, roughness, softness, and moisture) can be characterized as a combination of two or more modalities from the four defined main sensation modalities [43].

The human can physically interact with a remote environment and controls a remote object by means of haptic communication. Haptic data are the information represents the human senses or the human sensory information [44]. The haptic data consists of two main senses: tactile and kinesthetic. The human skin employs mechanoreceptors that produce tactile inputs which allow the tactile perception of the surfaces [45]. Human muscles, joints, and tendons employ mechanoreceptors that generate kinesthetic inputs responsible for limb movement and position [46]. These two main mechanoreceptors relay sensory information to the human's central nervous system in the form of neural signals. We have an overall perception based on the gathered information from human audiovisual modalities with the neural signals [47]. Human interactions with others or with surrounding objects in the environment occur based on the involvement of tactile and kinesthetic senses.

Haptic communications can be classified into two main categories based on the type of the human interaction with the remote environment. The first category is the passive haptic communication networks, which refer to the haptic-based networks designed only for exploring remote environments and distributed objects in these environments [37].

This category mainly considers the perception rather manipulation of objects and surfaces in remote environments. This type represents an open loop haptic communication. The other category is the active haptic communication networks, which contains networks developed for both perception and manipulation of objects and surfaces in remote environments. Based on the application, the remote environment can be real or virtual [48]. Tactile Internet will provide the medium for the transmission of haptic information side by side with the audio and video data with the required latency and reliability constraints.

3. One Millisecond Challenge

The human senses interaction occurs in real time, only if the communication response is faster than the physiological time constant [49]. Table 2 indicates different physiological time constant for the different human senses [30]. For better understanding the problem of 1 ms, we consider the preliminary example introduced by GP Fettweis in [30]. When we move an object on a touch screen, the maximum latency that achieves an unobserved displacement between the moving object and the human finger is 1 ms. This can be interpreted as the 1 ms is the time duration a human finger can move a distance of 1 mm on a touch screen, since the average speed of the human finger on the touch screen is 1 m/s. The 1 mm is the maximum unobserved distance between any two displacements, and larger displacement will be noticeable.

Table 2. Physiological time constant of different human senses.

Human Sense	Time Constant
Muscular interaction	1 s
Auditory interaction	100 ms
Visual interaction	10 ms
Tactile interaction	1 ms

Signals suffer from different latencies among heterogeneous communication systems. Three main latencies can be defined; end-to-end latency, user plane latency, and control plane latency [50]. The end-to-end latency is the time delay from the start of transmission of a small data packet from the transmitter's application layer until the reception of the data by the receiver's application layer [51]. This represents all signal delays; queuing delay, processing delay, computing delay, transmitting delay, propagation delay, retransmissions delay and reception delay. The round-trip latency includes the previous delays with the feedback delay dedicated by the communication process. The round-trip latency mainly depends on the communication distance and the number of the network nodes involved in the communication process.

The 1 ms challenge puts high constraints on the communication network design. The current cellular network structure cannot be deployed, because the latest 4G network can achieve a communication with at least 20 ms end-to-end latency [52]. Future 5G cellular system is expected to deploy new technologies such as the software defined networking (SDN), the network function virtualization (NFV) and the mobile edge computing (MEC), which can reduce the communication delay but not to 1 ms [29]. MEC allows the end user to communicate with a cloud unit located at the cellular network edge (i.e., radio access network (RAN)) [53]. This offers all cloud computing capabilities one hop away from the end user, and thus reduces the communication latency. Many other benefits and other deployment scenarios of the MEC-based tactile Internet and 5G systems can be found in [41].

Due to light limitations; the maximum distance the light can travel in a 1 ms is 300 km, this implies that the distance between the transmitter and the receiver should be at maximum of 150 km. This is under the assumption that there are no other delays, which is a must. Speaking about haptic-based bilateral teleoperation/tactile system, this distance may be proper for minor applications but for the plurality this will be inappropriate and certainly for the tactile Internet. One way to overcome this limitation and break the distance is to build a model mediated system that brings the remote environment near to the user [54]. This can be achieved with the means of artificial intelligence (AI) algorithms that can assist the model mediated systems and develop tactile Internet systems with the required latency constraints. Such systems are referred to as the zero-delay communication systems [55].

4. Model Mediation

The model mediation concept appeared with the presence of the bilateral teleoperation systems; mainly to improve transparency and stability [56]. Bilateral teleoperation system is a system, which contains the main components of the tactile Internet system; master robot, slave robot, and a communication network and shares the main features with the tactile Internet system. Figure 2 illustrates the relation between the two systems. In bilateral teleoperation systems, the master robot or the human is able to manipulate, access and interact with a remote environment that contains a slave robot [57]. The system works via a closed loop communication system, where the master device must receive a feedback from the slave device to maintain the communion with an acceptable degree of experience, as illustrated in Figure 3.

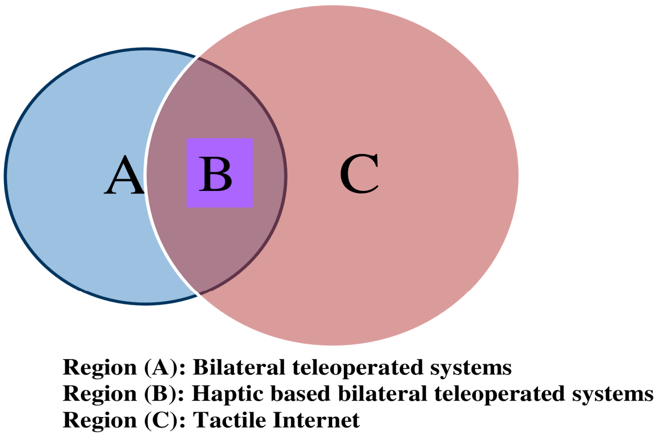

Figure 2. Tactile internet and bilateral teleoperation systems.

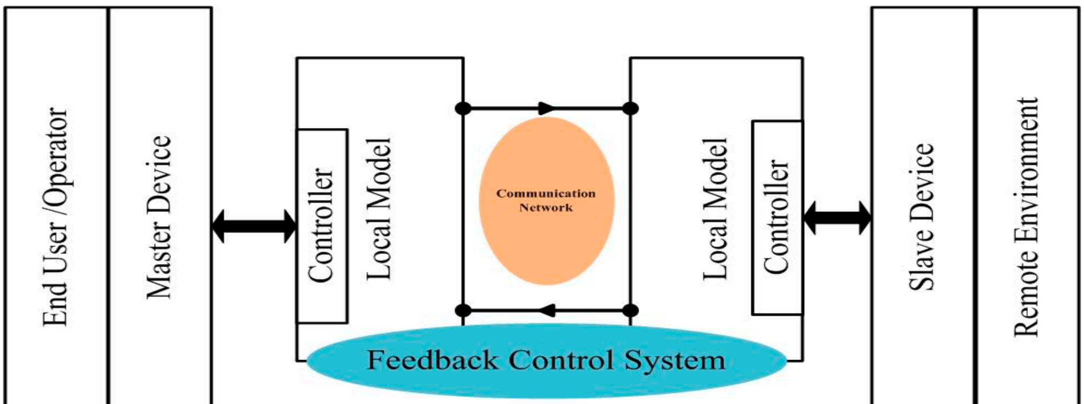

Figure 3. General view of the end-to-end system structure for the bilateral teleoperation systems.

The master device employs haptic devices through which the human can interact. The device transmits haptic data, which contains information about force and acceleration via the communication channel. The slave device is deployed in the remote environment, which interacts with the environment based on the received haptic data. The slave device must send a feedback to the master device contains visual, motion and force information, so as to make the user (operator, human) able to get a certain level of experience [58].

Bilateral teleoperation systems as well as the tactile Internet applications can be classified, based on the interaction level between master and slave devices and the communication latencies, into two main categories; mission-based control systems and direct control systems as illustrated in Figure 4. [37].

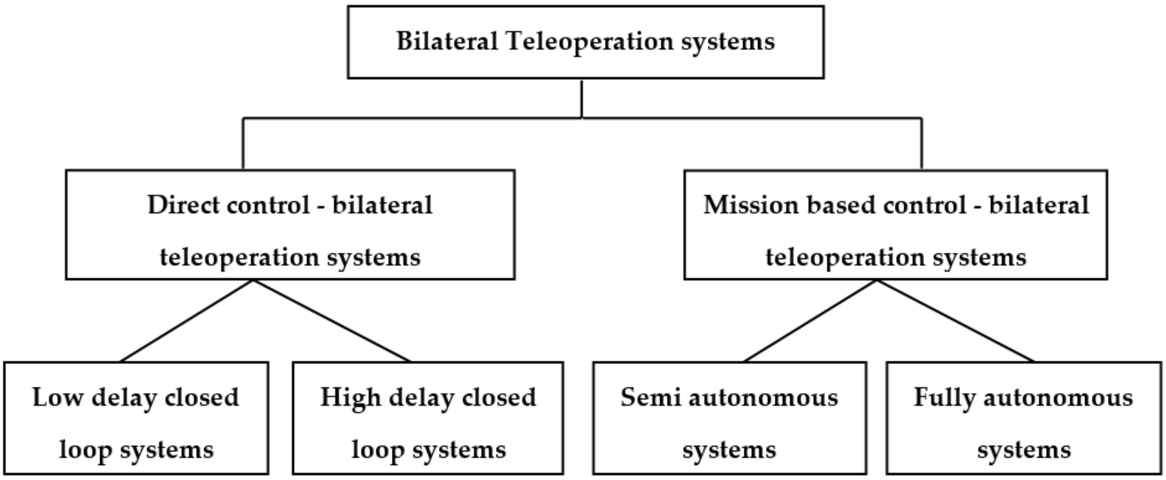

Figure 4. Classifications of bilateral teleoperation systems.

In direct control bilateral teleoperation systems, the master device (i.e., human) directly interacts with the remote environment in real time. This can be done by communication position and force signals between master and slave sides in real time. This group of teleoperation systems can be subdivided into two main subgroups; low delay closed loop systems and high delay closed loop systems. The low delay closed loop bilateral teleoperation systems are those with the negligible communication distance between master and slave domains. The propagation latency among communication channel for these systems is very small and can be neglected [59]. The other direct control subgroup is the high delay systems, in which the communication channel introduces high propagation delay due to the large distance between the master and the slave domains.

The other category is the mission-based teleoperation system, which is designed for a certain mission that requires the slave robot to be able to work independently. These systems can be divided into fully autonomous and semi-autonomous systems based on the interaction and transferred signals between master and slave sides [60].

The main design attribute of the bilateral teleoperation systems is the end-to-end to latency, which in case of haptic-based bilateral teleoperation systems should be less than or equal to 1 ms to get an acceptable level of experience. This represents the main design challenge of the tactile Internet. The end-to-end latency contains all delays involved in the communication process, in another way the time period from the start of communication process at master robot until the reception of the feedback [51]. Thus, the end-to-end latency mainly affected by the communication distance, and the number of intermediate communication nodes engaged in the communication process.

The model-mediated system provides a virtual version of the remote environment at the master side that can interacts with the master device with non-delayed force feedback, which make the haptic-based bilateral systems able to work under different communication network delays [61]. This virtual model interacts in real time with the end user based on a prediction model that can predict the reaction of the slave side including the remote environment and the slave robot. The virtual model at the master side is periodically updated based on the received feedback data from the slave side; however, this updating should be efficient to prevent the force disturbance [62]. Thus, tactile Internet can use such model mediated systems to overcome the light limitations and realize the system for any distances between the master and slave sides.

4.1. Environmental Modeling

The modeling of a remote environment can be classified into two categories; parametric modeling and non-parametric modeling [58]. The first type is building a model based on a pre-defined parameters of the remote environment; this type of modeling is referred to as the parametric modeling. Parametric modeling defines the environment geometry and physical properties that can be extracted in real time [63]. The other type is the non-parametric modeling, which is used for blind environments. A blind environment is a remote environment with completely or partially unknown parameters, which means that there is no complete definition of the remote environment geometry. The non-parametric modeling firstly, defines the inputs and outputs of the slave device (i.e., velocity, position, and force). Then a linear or non-linear mapping algorithm is deployed to get the slave behavior [58]. This is much complicated than the parametric modeling, however this case is the common. This is because of, the certainty of the well know environment is hard as the slave device may be deployed in a pre-defined environment and after sometimes it moves to another unknown environment, or other likely situations.

For modeling the remote environment, the slave device should be able to capture and measure the geometry and the impedance in a real time [64]. The impedance term, used in the modeling process in any teleoperated system, always defines the physical properties of the slave side. These physical properties include inertia, surface friction coefficient, stiffness (resistance of deformation), and damping. While the geometry term, specifies the shape of the remote environment and the position of the slave device [65].

4.2. Model Mediated Systems

4.2.1. Early Birds

In 1975, Otto J. M. Smith developed the first predictor algorithm, which is referred to as the smith predictor [66]. The smith predictor was developed for the linear time-invariant (LTI) feedback control system, to enhance the system stability. No longer, the first predictor for a bilateral teleoperation system was developed [67]. It was a high-fidelity graphics model referred to as phantom robot that is used for controlling and monitoring a real robot with no delay. The graphics model aimed to make the phantom robot predict the real robot's motion and hence the real remote robot follows the phantom robot's motion on the computer with a counted time delay. The algorithm has been simulated for a PUMA arm and the experiments have indicated that the algorithm has boosted the task manipulation through the predictive display; however, the main disadvantage of the system was that the delay was large [68].

Many other models and different algorithms have been developed and introduced after the past works to enhance the predictor performance and overcome the large delay problems. At first, most of the attempts were just modifications to the previous two systems where predefined models and simplified geometry environments were deployed, and then a leap occurred [69,70]. The main point to be mentioned is that early works have considered a one degree of freedom (DoF) only; however there are methods that recently developed for high DoF systems. In the following, we consider the main works and most common model mediated algorithms developed for haptic-based bilateral teleoperated systems. Furthermore, recent developed model mediated systems are considered and the ability of these systems to serve for tactile Internet system is discussed. The last part of this section considers the security issues of the model mediated systems and how model mediated systems will increase the security of the tactile Internet system and prevent attacks.

4.2.2. Common Systems

In [68], authors developed a feedback predictive controller based on the recurrent neural network (RNN) for the dynamic bilateral teleoperation systems. The recurrent neural network controller is used to compensate for the time delay and result in a delay free system. The system employs the neural network predictor at the slave device side to predict its behavior; mainly for position-to-position teleoperation systems. This predictor is a non-linear one, which means that the relation between the slave inputs (i.e., position and velocity) and the slave outputs (i.e., force) is non-linear. The system employs another predictor at the master side, which is a linear predictor. The master side predictor is a modified smith predictor. Figure 5 illustrates the structure of the recurrent neural network-based bilateral teleoperation system with both predictors at the distant sides. The slave side also deploys a nonlinear compensator to compensate for the non-linearity and match both predictors at the distinct sides. The system uses a common non-linear environmental model at the slave side, which is the Hunt–Crossley model, for identifying input–output response of the remote environment [58]. The system achieves the stability requirements for the closed loop feedback control system.

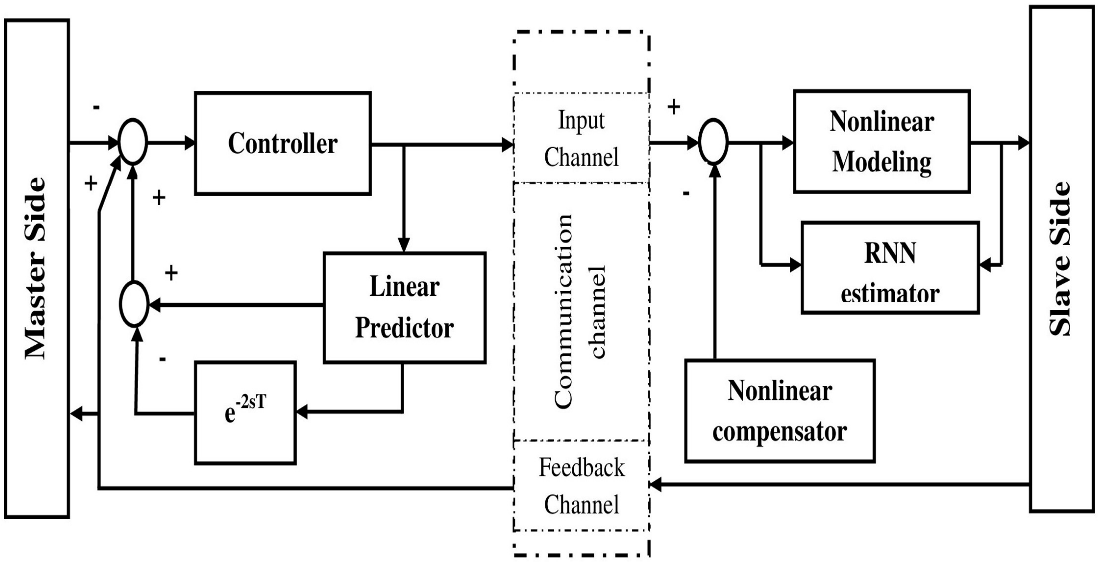

Figure 5. End-to-end system structure of the RNN-based model mediated bilateral teleoperated system developed in [68].

The main advantage of the system is that it assumes the nonlinearity relationship of the system parameters in environmental modeling, which enables the time varying behavior. Furthermore, the system deploys a compensator, which compensate for the miss match between both deployed predictors. The system does not require pre-defined environmental parameters, which can be considered as a great advantage. The system is suitable only for systems with constant time delay communication channel. In [71], a model mediated teleoperated system was developed based on linear predictor. The system is introduced mainly to reduce the packet rate of data exchanged between the master and the slave sides of the bilateral teleoperated systems without affecting the user experience of the system. Experimental measurements proved that the proposed algorithm can reduces the packet rate with 90% for systems with 3 DoF.

Employing traditional compression techniques for haptic data is not applicable; this is due to the large delay introduced by the building blocks of coding techniques. One way to reduce the number of transmitted packets is by making use of the properties of the human haptic perception. Thus, the system transmits only haptic events that a human being can perceive, based on the Weber's law for human haptic perception approximation [72]. Weber's law states that the relation between the human stimulus intensity (E) and the smallest change of the still perceivable stimulus intensity (ΔE) is linear.

$$\Delta E = CE \tag{1}$$

The constant (C) are referred to as the just noticeable difference (JND) or the differential stimulus threshold, which can be measured experimentally as a statistical value rather quantitative. Using JND, the system updates the haptic data and transmits it, only when the change of a haptic stimulus is detectable.

Figure 6 illustrates the structure of the system, where the system employs two linear coherent predictors on both network sides. These predictors not only help the master and slave devices to overcome the problem of communication delay associated with the haptic communication, but also used mainly to reduce the transmitted packets between both sides. Since the two predictors are coherent, the haptic data are transferred only if the actual data are different from the predicted ones. The system did not consider the deployment of a visual sensor or other impedance-based sensors in the slave side as the work is only a mathematical function-based algorithm, which is the main disadvantage of the work.

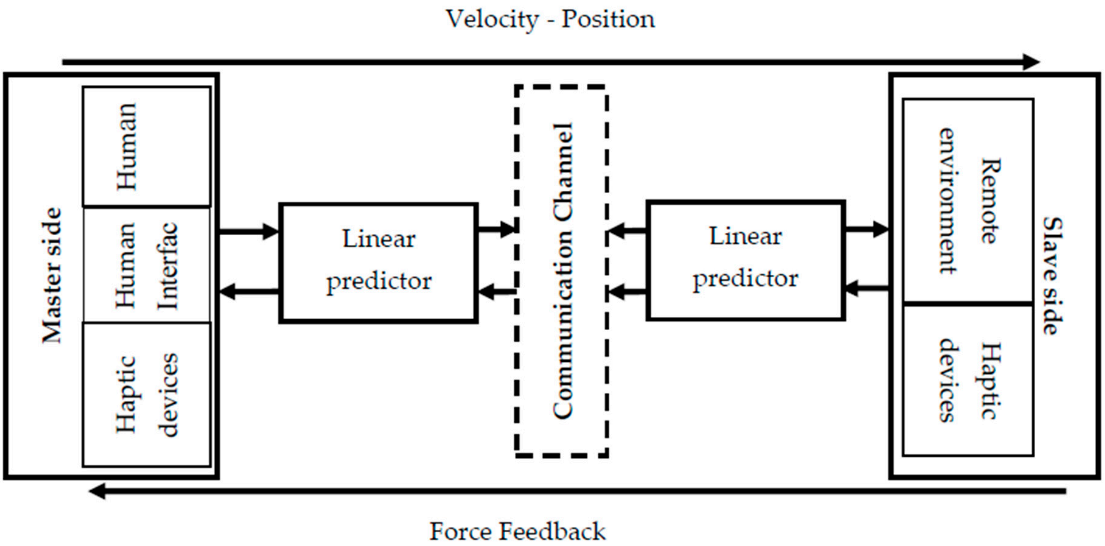

Figure 6. System structure of the model mediated bilateral teleoperated system with two coherent linear predictors developed in [71].

In [73], a haptic-based bilateral teleoperation system is introduced, based on a hybrid prediction mechanism. The predictor algorithm combines the signal-based prediction with the geometry-based prediction to facilitate the haptic data transfer and enable the user experience. The system employs two main modes for the signal-based prediction; linear first order mode and zero order mode, each of them identifies a prediction way. For the geometry-based prediction, the prediction is done based on the perceived tactile information about the surface includes, stiffness, friction, and position.

The future geometry parameters are predicted based on the current geometry parameters. This predictor is used for the rendering of haptic signals from remote environment. The system is experimentally tested using phantom desktop haptic devices and the CHAI3D computer interface [74]. The system achieved a high performance in terms of data reduction, nearly 69% reduction. In the other side, the system model mainly considered the stiffness and the surface geometry structure as the physical parameters and neglects other main parameters such as friction coefficient and inertia of the slave device. Also, the system model did not consider the communication delay and the effect of various communication delays on the system performance and stability.

In [75], authors proposed a point-cloud-based model mediated (Pcbmm) system for bilateral communication in a transparent and stable way. The system is developed for complex remote environments and these hard environments are modeled using point clouds rather simple geometry approximation. The slave device employs a time-of-flight camera that is used to capture the 3-D geometry of the environment [76]. The slave device uses the 3-D images with its position and measured forces to extract parameters of the environment model that are sent directly to the master side. These parameters are updated every 500 ms to consider any sudden changes that may occur. The master side uses these parameters to obtain or update the remote environment model and extracts the force feedback signal. One main considered component of the system is the updating controller, which is deployed to control the updates in the physical properties of the slave and the environment.

This enhances the force disturbance and reduces the packet rate transferred between the master and the slave sides.

The system is tested using master device of Omega.6 and a slave device of a KUKA lightweight arm, with a 6 DoF force sensor. The system achieves higher efficiency in terms of transparency and stability when experimentally evaluated. One more strong advantage of this system is the date reduction; the system achieves a 90% percentage reduction in haptic data. On the other side, the system does not consider movable and deformable objects in the remote environment modeling.

4.2.3. Recent Systems

In [77], authors developed a model mediated system based on an impedance controller. The model mediated is employed at the master side, which is responsible for building a virtual environment for the slave side‘s environment and interacting with the master device. This communication between the virtual model and the end user takes place with almost zero delay. Moreover, it sends command signals to the slave side via the communication network. The slave side deploys an impedance controller that is used mainly for ensuring the slave device stability when interacting with surrounded environment as it compensates for force disturbance and instability matters concerned with the slave side. The slave side is fed with a contact-force estimator as the model assumes a light weight slave device with no force sensors. The output of the estimator is used to update the virtual model at the master side and also to modify and adapt the impedance controller.

The system is experimentally tested for performance evaluation using a bilateral teleoperation system with a DoF of 3. The system employs a Novint's Falcon haptic device as the master device and a Geomagic's Phantom Desktop haptic device as the slave device [78,79]. The system indicates a high performance in terms of stability and tracking. The system is tested for various communication delays in the communication network and the results indicates that the system stability almost unaffected by the communication delay which can be considered one of the main achievement of this work over the past model mediated systems. Even with the existence of worse communication delay the proposed model through the impedance control prevent the master device from receiving excessive forces. The system can be deployed for a variety of applications especially for those with a gradually changing remote environment with unknown or variable communication delays. The main disadvantage with this system is the nonexistence of force sensors on the slave device. Another issue is the thoughtlessness of a high-quality visual sensor.

In [80], authors developed a model mediated system based on force updating algorithm and adaptive impedance controller. The force updating algorithm is introduced to overcome the force disturbance problem associated with the model updating, and thus achieves a higher level of system stability. The slave side employs an adaptive impedance controller, which can control the physical parameters of the slave side by comparing the expected model with the real environment. The system was mainly introduced to consider the stability issues associated with the teleoperated system and provide a stable human to machine interaction with acceptable experience. The system is experimentally tested to evaluate the controller performance, using a master device of a Geomagic Touch and the slave device of a translation parallel manipulator with a 3 DoF force sensor. The system is evaluated for 1 DoF with a constant delay of 5 s for different environmental materials. The controller achieves better efficiency intermesh of stability. The main limitation of this work is that it is dedicated only with one DoF tasks. The work also is tested for only a certain delay.

In [81], authors developed a nonlinear predictor-based model mediated bilateral teleoperation system for robot-assisted surgery applications. The system mainly considered the time varying communication channels and was developed to compensate for the delay. The system is composed of two main loops or subsystems; one for the slave side, which is responsible for parameter estimation and the other, is for the master side which is responsible for the prediction as indicated in Figure 7.

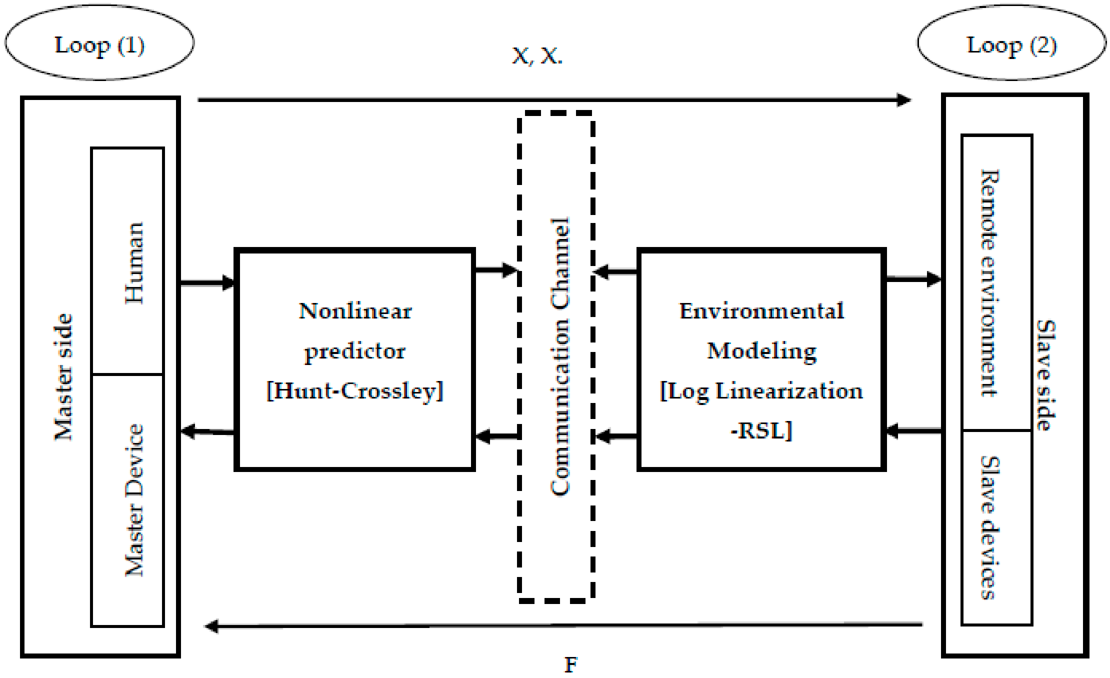

Figure 7. System structure of the model mediated bilateral teleoperated system developed in [81].

The environmental parameters are calculated in real time using log linearization technique and recursive least squares (RSL) method. The master side deploys the common Hunt–Crossley nonlinear predictor, which receives the force and position signals from the communication channel and from the end user as well and produces an output signal that represents the force feedback.

The stability of the proposed system has checked by analyzing the dissipation energy. The master device has been considered as a cascaded three systems (i.e., human, master device, and Hunt–Crossley predictor) and decoupled from the slave domain. The human and the master devices have a passive impedances and authors proved that the approximation of Hunt–Crossley predictor also possess a passive impedance. The slave device has been proved to have passive impedance as well and thus, the stability has been ensured for the overall system. The system has been simulated for both constant and varying environments and simulation results have indicated that the system has achieved faithful force interaction and the matching between perceived and real environment dynamics was accurate. The system did not consider the DoF of haptic devices employed in master and slave sides, which represents the main weakness.

4.3. Challenges

Designing a model mediated system for haptic-based bilateral teleoperation systems faces a lot of challenges; we consider the main challenges in the following points [82,83].

1- Transparency: is a measure of fidelity. It measures the degree of sense that the master device feel when interacting with a remote environment [84]. For a high transparency, the virtual model should provide the physical properties of the environment with no distortions. The degree of matching between the actual environment physical parameters and that of the virtual environment is a measure of the transparency [85].
2- Stability: is an important parameter that must be considered when designing a model mediated system. The stability of haptic rendering must be ensured for haptic communication systems especially for long distance communication [86]. The main reason affecting the stability of the model mediated systems is the force disturbance. As the hardware on either side may be affected—or worse, damaged—when fed with an excessive force or a vibrating one [87].

3- Consistency: this property insures that all users share the same virtual environment have the same experience. This property is considered only for a system with distributed users in either one side. The consistency is mainly affected by the delay between user and the virtual environment [88].

5. Security Issues

Security represents an important issue for the tactile Internet applications and also haptic-based bilateral teleoperation systems, this because of the diversity of applications with the delay, availability, and reliability constraints [89].

In the existing communication systems, the security is ensured via classical encryption techniques and other security algorithms that are implemented separately from the transmission [90,91]. Current security algorithms are implemented at the higher layers of the communication protocol, which adds more delay to the end-to-end latency. Thus, traditional security and encryption methods cannot be used for the tactile Internet applications. Instead, security algorithms for the tactile Internet must be fed to the physical transmission and should be implemented with low computational complexity so as to work against attackers and eavesdroppers with ensuring very low end-to-end latency as required. New coding techniques and security algorithms will be developed for tactile Internet applications so that only legitimated receivers can decode the secured messages even with finite computational power [27].

The maximum transmission rates of secure data, with the absolute rate of generation of secure keys represent main performance metrics of recent communication systems and as well, will be tactile Internet. This gives the priority to the technical security of transmission than classical coding, while designing the tactile Internet [17]. Dedicated hardware can be used for implementing such kind of coding and security methods with the transmission, these devises are such as the biometric fingerprints [27]. Furthermore, tactile Internet raises another security issue, which is user identification.

The introduction of mediated systems to support the tactile Internet system will also help in solving security issues; since it breaks through the delay constraints and even if the traditional coding scheme is used it will be prober for a part of applications.

6. Tactile Internet System with AI Model Mediated

Using model mediated system; a virtual model for the remote environment can be built on the edge cloud unit that is one communication hop away from the master device. The user interacts with the virtual environment and thus the delay is reduced to the distance between the edge computing unit and the end user. Figure 8 illustrates the structure of the tactile Internet system with the model mediated deployment. Figure 9 illustrates a time chart of the system, where τ_1 is system delay when the MEC unit is not deployed, τ_2 is the presence delay which is sensed by the master device, and τ_3 is the communication delay between the model mediated and the slave device.

The model mediated system employs a predictor, which by some means of artificial intelligence (AI) can predict the behavior of the actual remote environment and be able to receive the haptic feedback information and use it to update the model [27]. The end user interacts directly with the virtual model on the edge cloud in a haptic/tactile form with an acceptable delay. Consequently, the user can get a real time experience of the remote environment through the AI-based model mediated deployed at the edge cloud unit. Since the tactile Internet requires a very high reliability, the model mediated system must employ a very high accuracy predictor and transparent modeling algorithms. As an initial step toward tactile Internet realization IEEE organization releases the IEEE 1918.1 standards group to standardize the tactile Internet [92]. The IEEE P1918.1.2 is a subgroup dedicated with the AI for enabling tactile Internet [93].

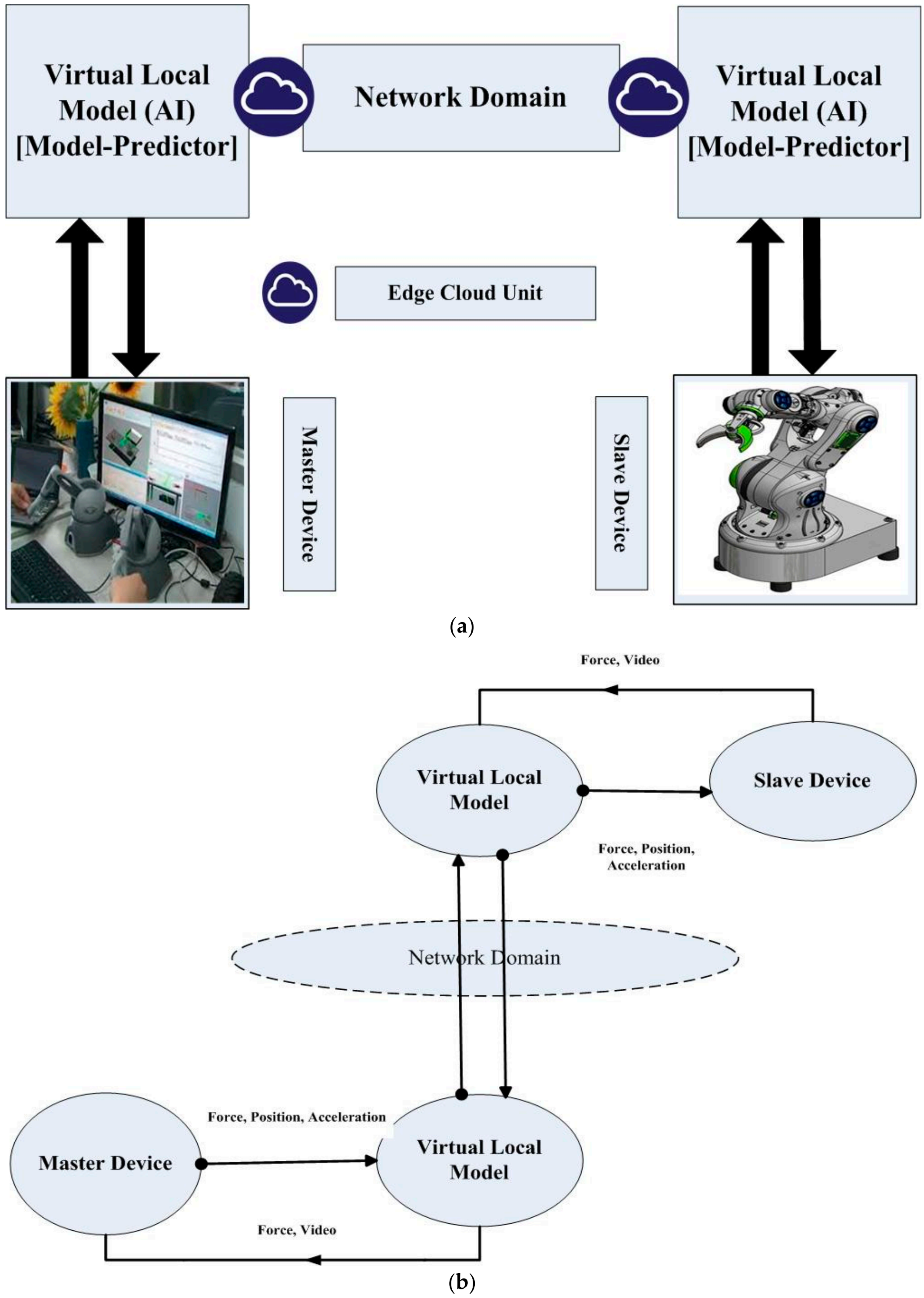

Figure 8. (**a**) End-to-end general structure for the tactile Internet with the AI model mediated. (**b**) Signaling diagram for the tactile Internet system.

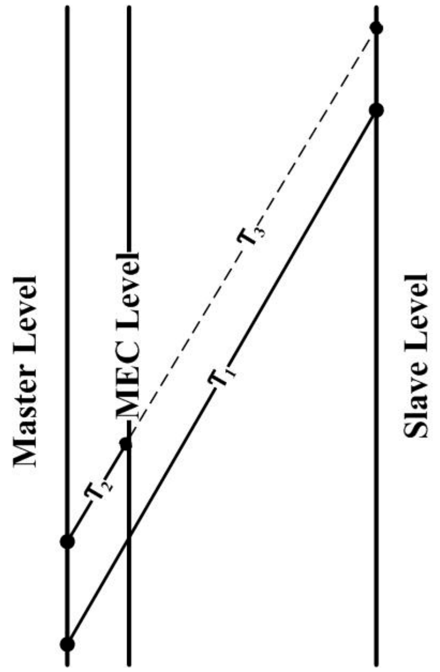

Figure 9. Time graph for the tactile Internet system.

Stability vs. Communication Delay

One main issue that must be considered in designing the tactile Internet system is the system stability. The stability is mainly affected by the delay happened in communication network between the master and the slave devices. The more delay via the communication channel the more system disturbance that may lead to the system instability [94]. The AI-based virtual model at the edge computing connected to the master device will be affected by long delayed versions of haptic feedback even kinesthetic or tactile, also the model update which may depend on the visual feedback will be affected.

Building an AI-based model mediated system for tactile Internet deployed on the edge cloud unit at the master side is the only way to overcome the light limitations and realize the tactile Internet system. The deployment of AI at the edge cloud leads to the perception of the near-zero delay networks as the master device will sense only the delay of the communication hop to the edge cloud. Many open research problems for such a system are concerned with the AI and the modeling of remote environment including physical properties and geometry.

7. Conclusions

Tactile Internet can overcome the limitations of the light by introducing a model mediated system. Building an AI-based virtual model at the edge cloud unit one hop away from the master side is a solution. The model is able to predict and act as the slave side, thus it can interact with the master device with an acceptable experience. This work reviews the model mediated system for haptic-based bilateral teleoperation systems. The model mediation bases are discussed and the challenges in modeling the remote side are introduced. Main developed systems are presented and validity of each to serve for the tactile Internet system is discussed. A general structure of the tactile Internet system with the model mediated is included; in this way, the 1 ms design challenge of the tactile internet system and also security issues will be solved even with the light limitations.

Author Contributions: Conceptualization, A.A.A., A.M. and A.K.; Methodology, A.A.A., Y.G. and I.G.; Formal Analysis, A.A.A., A.M., A.D.A. and A.A.; Investigation, A.A.A., A.M., A.V. and I.G.; Resources, A.D.A., A.A. and A.K.; Data Curation, A.K. and Y.G.; Writing-Original Draft Preparation, A.A.A., A.M.; Writing-Review & Editing,

A.A.A., A.V. and A.K.; Visualization, A.D.A., A.A. and A.M.; Supervision, A.K.; Project Administration, Y.G. and I.G.; Funding Acquisition, I.G.

Funding: The publication was supported by the Ministry of Education and Science of the Russian Federation (project no. 2.3397.2017/4.6).

Conflicts of Interest: The authors declare no conflict of interest.

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