International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 12 (2017) pp. 3203-3213
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Review on Application of Haptic in Robotic Rehabilitation Technology

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Abstract

Haptic is a science of touch tactile or kinesthetic. It is an interaction with humans and machines.The review is conducted by looking at, the different catagories of haptic teleoperation systems, the channel control architectures, the different challenges in implementing haptic technology, and the area of interest in the application of haptic and non-haptic robotic rehabilitation technology. The review reveal that, haptic teleoperation constitute of unilateral, bilateral and multilateral teleoperation systems, the control architectures are two channel, three channel and four channel control architectures, Haptic challenges can be categorized in five problems the stability, transparency, determining the force methods, scalingand frequency bandwidth. Finally, the review summarizes haptic and non-haptic rehabilitation systems. As a result, it's been found that there are many rehabilitation systems but a few apply haptic. Haptic in rehabilitation is used in virtual haptic, but there are many opportunities can be benefit from haptic in real world rehab such as lower limb rehabilitation. In a conclusion, the gap in the area of haptic on robotic rehabilitation technology include, the limited attempt of applying haptic especially bilateral haptic control in robotic rehabilitation and particularly non for lower limb.

Keywords: Haptic, rehabilitation robots, haptic control. Haptic teleoperation, haptic control, acceleration based method.

INTRODUCTION

Haptic is a feeling of touch. The word haptic itself comes from Greek origin "hapto or haptesthai" which mean a common sense of touch. In a scientific manner, haptic means everything that is related to teleporting a sense of touch[1]. Haptic can be classified to haptic perception and haptic interaction. Haptic perception is tactile and kinesthetic. Tactile perception refers to how a person feels through his skin the objects in the environment around him. The kinesthetic perception refers to the movement and the position of the human[2]. Haptic interaction is the interface of human with machines in the real world or the virtual haptic. Both the real world haptic and virtual haptic are very active and promising fields. The virtual world is a computer simulation based on the real world environment. In other words, haptic is translating a touch to objects done by machines or by a person[3]. The combinations of human machine system contain four important aspects: the precognitive system, the actuating motors, sensory system and mechanical structure. The interface between robots and humans can described as exchanging mechanical energy between them[4].

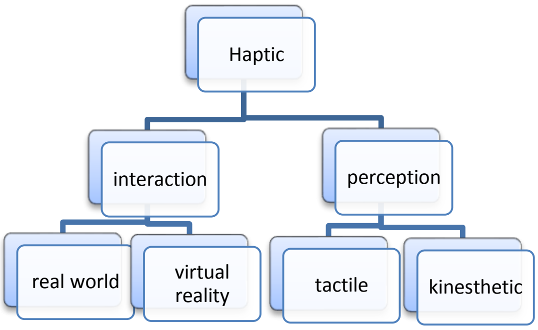

Figure 1: Haptic calassification

There are several applications in the haptic technology. The medical devices are one of the applications that use haptic[5][6]. Communication is the biggest area on haptic applications. Other areas such as video games, nuclear and hazardous environments and art apply haptic widely[7], and visual-motion navigation[8].Haptic is applied in rehabilitation robots for upper-limb and lower-limb of the body. Haptic virtual reality is also used in rehabilitation to encourage and motivate stroke patients as well as to evaluate improvement their physical state[9].Researching on strokes rehabilitation take a lead since strokes were ranked as the first cause for disability and the second cause of death globally after the heart disease [10].

This review paper focuses on haptic technologies and rehabilitation strategies. Section 1 is an introduction of haptic technology terminologies and classification. Section 2 reviews the haptic teleoperation methods. Section3, reviews the challenges in haptic teleoperation faced in previous work. Section 4 explains haptic control architectures. Section 5 is about haptic and non-haptic rehabilitation technologies. Lastly, section 6 is the review conclusion.

HAPTIC TELEOPERATION METHODS

Teleoperation in robotic is controlling a robot from a distance remotely by human operator. Haptic teleoperation involves an interaction between master and slave systems. Haptic future is directed more into real world haptic especially in the copying system of motion. The motion copying systems are new technologies to gather information from human user, store it in a system and reproduce it by machine operator system[11]. Copying the motion of one system and replicate it in other system without any mechanical connection between them. The reason of creating haptic teleoperation system is to provide assistance to human activities. It could provide visual or auditory assistance as well.

Transferring a touch need controlling system and the controlled system (the mater and the slave). It can be one way (unilateral) where the human operator controls a machine remotely without feedback of the reaction from the environment. Unilateral system allows teleporting information in single way from human to system or from system to human. However, bilateral system allows two directional teleporting human machine data.

There are three of haptic teleoperating systems illustrated in figure 2; unilateral, bilateral and multilateral. Unilateral system send position and force from master to slave. Bilateral system is two ways change of force and position between master and slave. The multilateral system

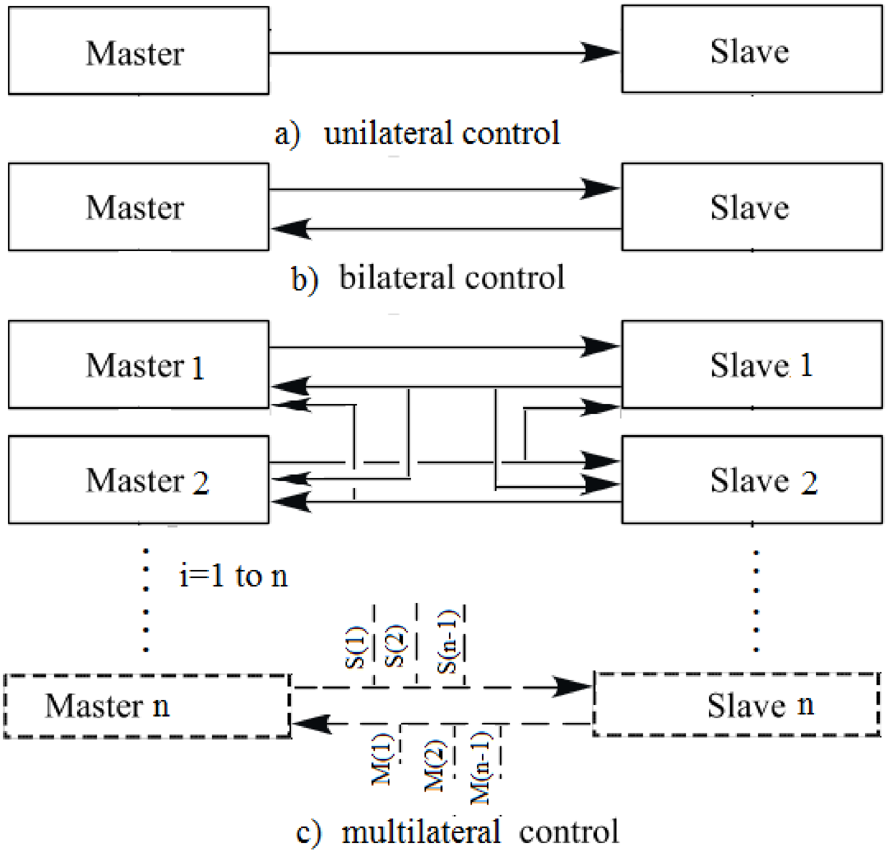

Figure 2: Haptic multilateral, bilateral and unilateral control

a) Unilateral Haptic

Unilateral teleoperation is direct commends send from mater device to slave device. The difference between unilateral and bilateral teleoperation is the feedback from the environment contacted the slave manipulator. In unilateral teleoperation the master is not affected by the environment from the slave manipulator. There is no force exerted on the master actuator from the slave feedback. For 1DOF master and slave unilateral systems, master manipulator controls the force and the position of the slave manipulator. If the slave manipulator hit an object that prevents it from reaching the desired position, it will continue trying to reaches the desired position until the all system is shutting down. That is because there is no force feedback to worn the user of master manipulator. As in [12] there is visual feedback in unilateral system. Auditory and visual teleoperation is considered as unilateral systems as figure 3 illustrated.

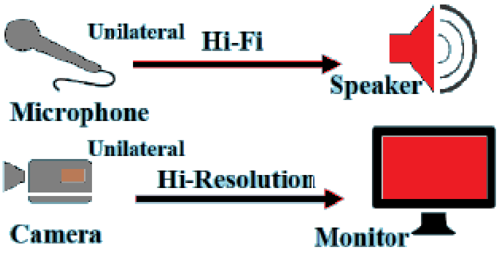

Figure 3: Unilateral teleoperation system

Controlling the unilateral system can be achieved by “Direct inverse dynamics” or “Feedback error learning control” according to[13]control methods. The inverse dynamics and neural network are applied to control the slave manipulator according to the following steps: the neural networks are trained using feed forward control from the master manipulator. The data can be gained from encoders. The plant input is fed to the neural network in order to drives an output to a desired value. The problem with this method control is that the only controller is the neural network in the loop, the closed loop of the system might be unstable in the beginning of the learning stages. Hence, it is required to provide initial estimates of the weights for the neural network.

b) Bilateral Haptic

The reason of introducing bilateral system is to feel the environment around the slave manipulator. Haptic bilateral teleoperation sends and receives information based on the action and reaction low[14]. So, gaining and transmitting haptic data, it is required to use bilateral system. Haptic bilateral teleoperation means that the operator controls a manipulator and feels the reaction from environment. Bilateral teleoperation system comprises of master device and slave device. Master system is always in contact to human-operator. Slave system copies the master motion in position and force. The slave system contacts the environment. Bilateral teleportation use acceleration based method as reliable control strategy. Four channel bilateral method produces stable and transparent teleportation[15].

c) Multilateral Haptic

Multilateral teleoperation is introduced based on bilateral teleoperation. Multilateral control has more than one master and slave systems. It can be many master and many slaves, many masters and one slave or one master and many slaves. In [16] the proposed system has 2 master manipulators systems and 1 slave system for broadcast a grasping operation. Multilateral control is more effective than other teleoperation types in haptic broadcasting.

CHANNELS CONTROL ARCHITECTURE

Haptic teleoperation is two port representations. One port represents the user / master manipulator and the other port represent the environment / slave manipulator. There are three types used in teleoperation researches; 2channels control, 3 channels and 4 channels control. The 2 channel architecture exchange position and forces information among master-slave manipulator. Specifically, the position of master is transferred to slave manipulator and the force of slave is sent back to master system. This method a high transparency[17]. The three channel architecture is used in micro macro haptic systems where there is a size difference between the master and slave manipulators. In the three channels control, the position and force are sent from master to slave system. Then, the force from slave is fed back to master system[18]. Moreover, the bilateral system performance shows improvement when 3 channel control is used[19][20].

The four channel control architecture in figure 4 is the most widely used in bilateral control[21][22]. This method exchange position and force based on the acceleration based method which consists of two modes; common mode is for control theforce and differential mode is for controlling the position. It contains outer loop that consist of system controllers and inner loop consist of disturbance observer / reaction force observer

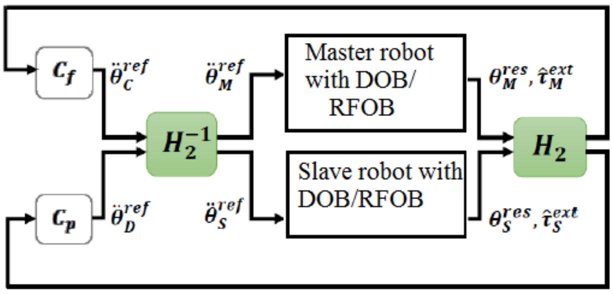

Figure 4: Four channel control architecture

CHALLENGES IN HAPTIC

Haptic challenges can be categorized in three problems the stability, transparency with time delay and without time delay.

A. Transparency

Transparency in bilateral haptic system is an important factor. Transparency indicates that the operator impedance from master device should be equal to the slave-environment impedance according action and reaction low[23]. Time delay makes the system instable and less transparent. According to the action and reaction low, the sum of master force and slave forces must be zero. The same concept is applicable to position, where the sum of master slave position have to be zero[24].Frequency bandwidth helps to achieve high transparency.

B. Stability

Stability is another important issue in haptic which is difficult to achieve with transparency due to the uncertainties that exist in bilateral or multilateral systems. Both transparency and stability can be achieved by four channel acceleration based control method (which are master joint position, slave joint position, master forces and slave forces)[25]. The stability of hapticsystem is related to the method to measure the forces of the joints.

C. Determining forces

Forces in the manipulator joints and the reaction force from the environment need to be measured. There are two methods to measure these forces. The first method is to use force sensors[26] and the second is to use DOB[27]. Using force sensors is not suitable in haptic due to the drawbacks resulted from using it. Force sensors have narrow bandwidth which affects the transparency if the system is bilateral. The reading of force sensors has noise which leads to using filters to reduce the noise. Consequently, the filtered signal becomes narrower.

The second method to measure the manipulator joints force and the environment reaction force is by DOB and RFOB. Ohinshi develops disturbance observer to make acceleration method robust and accurate[28]. DOB is a system used to estimate external disturbance in the system as well as the system uncertainties. DOB output is friction under the motion of the system mechanism. The parameters of DOB can change the performance of the all system[29]. Increasing the value of Ktn in block diagram in figure 4, the system will be robust but less stable. The low pass filter in DOB affects the performance as well. Changing the order of low pass filter (LPF) gives two types of DOB (DOB and HODOB).

DOB normally has first order LPF. HODOB has second order LPF[30]. There are advantages and disadvantages of each type. For instant, the high order LPF improves DOB performance and shows better result in suppressing the disturbance. It work better in the low rate sampling systems[31] . However, with wide range of, a robust system con not be achieved. On the other hand, the first order DOB works better with wider range of bandwidth, but has limitation because of the first order LPF dynamic characteristics. The RFOB is DOB based tool used to detect forces from the contacted environment. There is no specific restricted design for RFOB. It basically depends on the designer. RFOB is superior to force sensors because of high bandwidth and improving the system stability[32]

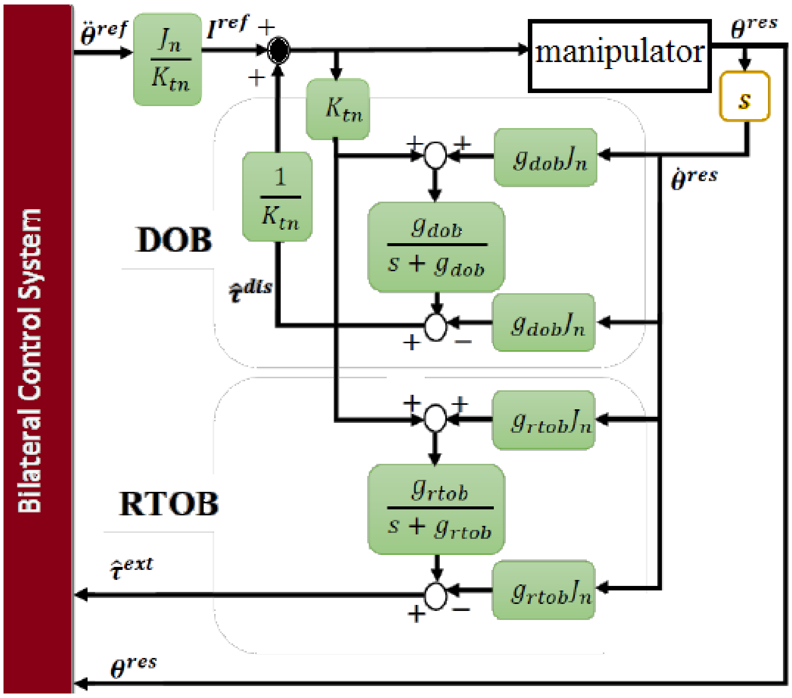

Figure 5: DOB/RFOB block diagram

D. Scaling

When the master system size is not identical to the slave system size, the scaling problem appears. In some applications, the size of master and slave systems must be different. In brain surgeries devices that are built on bilateral control, the slave system is small compared with master system.Scaling reduces the transparency of the bilateral control system. MS-DOB is proposed in[33]to eliminate the errors resulted from the size difference of master and slave systems. The acceleration based control method is hybrid of force and position controller. MS-DOB method is based on decompose force and position control hybridizing into two separate controllers.

E. Bandwidth

Designing the bandwidth range is a one of the challenges of haptic. In fact, it is considered the biggest challenge in haptic data transmission[4]. It affects the other criteria such as transparency and stability[34]. The bandwidth is designed in the disturbance observer and the reaction force observer in a form of low pass filter. Increasing the DOB bandwidth will improve the system performance in terms of stability and robustness and suppress the system external disturbance[35]

HAPTIC AND NON-HAPTIC REHABILITATION TECHNOLOGIES

Virtual haptic is used in designing systems that motivate patients in their therapy treatment. The system in [9] is been designed based on virtual haptic to motivate stroke patients to move their hands. The data collected from actuators, sent to the computer where haptic rendering simulate the hand motion in the computer. Nonetheless, in some cases motivation is not enough to rehabilitate patient. That's lead to the use of exoskeleton. Exoskeleton robots have been used in widely in rehabilitation applications. One of the main applications is assisting patients to regain walking ability. A Self rehabilitation system in[36] is developed for arm rehabilitation. The system applies acceleration haptic method to control the arm. The patient can use the motion from the healthy arm to train the affected arm.

There are many rehabilitation devices that do not apply haptic. A research done by Hongchul Kim developed robot to help solders to walk normally under heavy loads. The system is equipped with hydraulic actuation system consist of hydraulic cylinders, sensors, motors, pump and valves. The authors introduce dual mode system as locomotion control method for the exoskeleton robot in both active and passive modes from this aspect, there are two actual controllers. The first controller is active in standing phases. The second control the leg during swinging phases. The system has two active DOF at the hip and the knee. The unactuated ankle has 3DOF[37]. Daewoo Company designed exoskeleton suit for construction workers to help them move heavy materials in the building[38]. NTU Wearable Exoskeleton proposed assistive human-like walking robot. The uniqueness of this robot is that it is designed with inner system and outer system. The inner system consists of encoders and links and controlling circuit. The encoders collect the data from the joints and use it to control the outer system. On the other hands, the outer system has separate structure which carry the weight and move as the wearer move. The device uses feedback controlling system with zero moment point method[39].

Rehabilitation is one of the most important applications of exoskeleton robots. Sai K.Banala proposed Alex (active-leg-exoskeleton) system which can be categorized as artificial neural network treadmill gait trainer. Alex one leg system is designed for hip joint and knee joint. The system uses linear actuation systems at the hip and the knee with supported motors and load-cells[40]. Tsukuba University developed a system designed to help people after strokes. The principle of HAL is that HAL observe and store the information of walking from the unaffected leg and apply it into the paralyzed leg. The system uses my electricity detection attached to human skin then amplifying the detected signal. It is also equipped with potentiometer sensors on the joints of the healthy leg to measure the angles of the hip, knee and ankle. FRF sensor is placed is the foot so it can measure the reactive force from the ground. Symmetry based controller is used to control HAL robot during support and swing phases[41], [42].

IMAMS system is developed as prototype in preliminary investigation on evolving lower limb rehabilitation exoskeleton, focusing more on clinical considerations. The prototype is actuated by DC motor at the ankle and pneumatic linear actuation system in the knee. The overall system in designed with considering minimum therapist interference[43]. Xiaonan Wang proposes training strategies for rehabilitation based on patient in charge system. The robot is trained in order to adapt the pattern of the motion. The system is controlled by fuzzy admittance control system encompass position, velocity and current controllers. The device is designed for both lift and right legs. Each legs is two degree of freedom(knee and hip)[44]. human walking vary in movements of the foot, leg , thigh and pelvis[45], connected with ankle, knee and hip. According to Y. Miao et al, four different type of movement was analyzed. The proposed design help people to carry payloads with no difficulties [46], different mode to find the particular action state for walking, running, jumping and squatting. From the Kamran Shamaei et al. analyses the effects of mass, joint and kinematic constraint on the walking motion. The system setup of the exoskeleton spring in parallel with knee joints[47].

Lobes exoskeletons produce many designs for rehabilitation purpose. They use BWS (body weight suspension system) to limit the effect of gravity on the experiment result. The first prototype is 2D segment pelvis robotic leg. The exoskeleton leg has two revolute hip and / knee joints. The joints are controlled by impedance controller to permit mechanical interface between the patients and the robotic leg. The device has two modes: “patient- in-charge” and “robot-in-charge. EMG signal is used to control the robotic leg trajectories[45],[46]Lopes in 2011 studied velocity dependent trajectory approach using feed forward controlling system and impedance controller for 8 DOF robot. The experiment was not conducted using EMG signal as an input, instead they use trajectories reference. Trajectories reference were created for hip and joint angles. The patterns of the gait were measured from 12 different people with different walking speeds. The control system implemented using Feed-forward and Feed-back strategies. The Feed-forward is to predict the torques required to track the wanted trajectories. The inverse modelling was done by a double pendulum model. The feedback system is to confirm the impedance permitted a varied deviations from the desired trajectories[50]. The last Lobes system presents exoskeleton gait trainer for estimating the impedance for multi joint leg. Force controller is used with SEA (“series elastic actuation”) and Bowden cables[51] and end effector approach with parallel actuators[52].

Lokomat is position control device. It was developed with three different adaptive control algorithms. The first algorithm implemented using online minimization interaction torque between the machine and human and inverse dynamics. This method was developed to analysis the human machine interaction. If the patient follows lockomat motion the interacted torque should be zero. But the interacted torque will not be zero if the patient moves differently. The device uses force sensors to measure the overall torque. Lokomat system uses innovative way to estimate the patient torque of the next step of the walking using the previous measured torque. The second method is forward dynamics and estimating the gait pattern variation of acceleration. The third method used adaption of human gait walking cycle and impedance control. Lokomat can actively participate in controlling knee and hip motion. However, the design passively involves the ankle, but without any control of its motion[53], [54]. Biofeedback is added as new feature to the updated lokomat which allow patient to see their improvement[55], [56]. The updating also changes lokomat from position control device to force control to attain improved interaction between the patient and robotic leg[57].Another device designed by Jianxin Fang for lower limb rehabilitation. The device is controlled with a CPG (central pattern generator). The controlling process includes the using of Windows 7 computer, Visual C# and serial port communication. The actuation system uses servomotors in the joints to produce motion[58].

ANDROS exoskeleton is knee orthosis device developed in 2012. The actuation system is designed with pneumatic cylinder and brushless DC motor. The control method uses impedance model, admittance model and force feedback control[59]. Yuanchun Li develop similar control method using sliding mode impedance as feedback controller to control interaction force and position of lower limbs exoskeleton for people with disabilities. data are were collected using force sensor and encoder to measure the position of the patient leg [60]. Researchers of Human - Machine Cognition institute of Florida design 2DOF robotic leg for both left and right legs of the patients. The system was designed with four rotational motors for hip and knee to suit the user in flat grounds. A motor encoder is mounted on the motor to achieve high impedance position control. A simple PD controller is used to trajectory desired position. Torque control was done by PD controller too[61]. Trajectory generation is designed by using different methods to plan the path for exoskeleton motion[62][63]. Polynomials are a reliable trajectory generation. Quintic and cubic polynomials are the most applied trajectory methods. However, quintic polynomial is smoother than the cubic polinomial[64]

Yusuf Şahin and Fatih Mehmet Botsali research present two legs exoskeleton to help people carry extra loads. The team presented force feedback control system with PI controller. The exoskeleton is actuated hydraulic system consists of servo valves and hydraulic cylinders[65]. COWALK system is presented with new controlling method called “visibility guaranteed trajectories” to control the speed of the exoskeleton walking. The speed is controlled using the interaction forces. Admittance controller is used to find the walking speed. The intention of the patients to increase the speed is measured by EMG signal. The overall system consists of 14 DOF, 5DOF are passive and 9 DOF are active with linear actuators [66]. Table 1 shows several robotic rehab control strategies and actuation based on haptic and non-haptic systems.

Table 1: Robotic rehabilitation technology

Title	Actuated body parts	Control	Actuation	Reference
Haptic Virtual Rehabilitation Exercises for Poststroke Diagnosis	The hand fingers	Haptic rendering simulator	Electric actuators	[8]
development of a haptic bilateral interface for arm self-rehabilitation	Arm	Acceleration control based method	Linear electrical motors	[33]
Hydraulic Lower Exoskeleton Robot	Hip, knee and unactuated ankle	Dual mode controller	Hydraulic actuators	[34]
NTU Wearable Exoskeleton	Hip, knee and ankle	Feedback control with the ZMP method	Electrical DC motors	[36]
Alex	Hip and knee	Feed forward forces controller, PI controller	Motors, hip and knee linear actuator systems	[37]
HAL	Hip and knee	Musculoskeletal model with impedance control, Symmetry based controller	Servo motors	[38-39]
iMAMS	Knee and ankle	-	DC motor at the ankle and pneumatic linear actuation system in the knee	[40]
“A Patient-driven Control Method for Lower-Limb Rehabilitation Robot”	Hip and knee	Fuzzy admittance control system	Linear actuators turned by DC motors	[41]
Lobes	2DOF hip and knee	Feed forward and impedance controllers, Force controller(2015)	Series elastic actuation and Bowden cables	[49]
Lokomat	Hip, knee and ankle	Adaption of human gait walking cycle and impedance controller	DC motor, helical gears	[50-51]
ANDROS exoskeleton	Knee orthosis	Impedance model, admittance model and force feedback control	Pneumatic cylinder and brushless DC motor	[56]
“Force Feedback Control of Lower Extremity Exoskeleton Assisting of Load Carrying Human”	Hip and knee	PI-controller for force control system	Servo-hydraulic actuators	[59]
COWALK	Hip, knee and ankle	Admittance controller,	Dashed circles in passive joints, active Joints are actuated by linear actuators.	[60]

From the rehabilitation systems listed above, there is a question of whether these systems can be benefit from haptics. From rehabilitation system review, it shows that not many rehabilitation system applying haptic. However, if haptic is used in designing, the design usually is using virtual haptic for simulation only. The table also shows exoskeleton systems of previous researches. Nearly 90% of the designed exoskeleton involves actuation on hip and knee joints. Whereas, small percentage of researches develop systems for single joint such as the ankle only. The drive of most of the proposed systems is for rehabilitation purposes. It is clear that most researches are using electrical linear actuators. The control methods can be categorized to impedance and admittance control with feedforward or feedback system. Moreover, the control strategies of these researches use impedance control with force sensors and load cells feedback systems. Using sensitive high resolution sensing systems make these systems expensive and more complex for usage. Haptic technology can replace the need of using force sensing system by using bilateral control to design exoskeleton. Bilateral system estimate joint forces without force sensors.

CONCLUSION

Haptic is defined as a science that studies the sense of touch. Haptic is classified to haptic interaction and haptic perception. The review concludes that there are three types of haptic teleoperation, unilateral, bilateral and multilateral teleoperation. uniltilateral teleoperation enable the system to send information from master to slave. The biltilateral teleoperation is two ways of information exchange, from master to slave and from slave to master. The multilateral teleoperation is based on bilateral system with more masters and slaves.

Unilateral systems face stability challenges, whereas bilateral and multilateral have more than stability problems. The biggest challenge for bilateral and multilateral teleoperation is transparency. There are other more challenges such as scaling problems when slave-master systems differ in size. The bandwidth and the force estimation method are significant challenges in haptic as well. Most of bilateral systems apply four channel control architecture because it result a high level of transparency. Haptic can be used significantly in rehabilitation, not only for virtual simulated haptic application, but also in the real interaction application. The application of haptic in robotic rehabilitation technology is limited to patient motivation in virtual haptic. Robotic rehabilitation tech has many areas in which haptic is beneficial especially lower limb and upper limb exoskeleton.

ACKNOWLEDGMENT

The authors would like to thank University Teknikal Malaysia Melaka (UTeM), UTeM Zamalah Scheme and RAGS/1/2014/TK03/FKE/B0054, Ministry of Higher Education Malaysia, for supporting this project.

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