Faculty of Electrical Engineering

TORQUE SCALING OF BILATERAL CONTROL MASTER-SLAVE SYSTEM FOR EXTERNAL LOADS

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Master of Science in Mechatronic Engineering

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TORQUE SCALING OF BILATERAL CONTROL MASTER-SLAVE SYSTEM FOR EXTERNAL LOADS

SARI ABDO ALI MOHAMMED ALDABAS

A thesis submitted
in fulfilment of the requirements for the degree of Master of Science
in Mechatronic Engineering

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2019

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DECLARATION

I declare that this thesis entitled “Torque Scaling of Bilateral Control Master-Slave System for External Loads” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechatronic Engineering.

Signature : ………………………………..

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Date : ………………………………..

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DEDICATION

To my beloved father and in a memory of my mother

To my beloved wife

Thank you for your encouragement and support throughout the entire duration of the study.

To my supervisor and co-supervisor

Thank you for your guidance, support, advices and valuable information.

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ABSTRACT

In robotic field, haptics technologies are implemented to participate in increasing safety to human operators in many application fields such as medical devices, industrial manufacturing, and hazardous environments. Bilateral teleoperation is a part of real-world haptics that initiate two way of information teleoperation between two systems; the master system and the slave system. A person operates the master system to control a slave system that contact with the environment. The objectives of the experiments are conducted to investigate the effects of the variation of the bilateral controller parameters on the stability and the transparency, and to design and validate haptic bilateral controller to control the position and the torque when an external load is applied to the controller. The interaction between the slave system with the environment is fed back to the master system and the operator can sense it through the master system. The bilateral controller controls the position and the torques of the actuation motors. The bilateral control system contains PD controller for position control, force controller, disturbance observer and reaction torque observer. The disturbance observer reduces the disturbance of the system and the reaction torque observer estimates the external reaction torques. The bilateral controller is designed to make the slave system track the master system position trajectories so that the motion of the master and the slave motors are in synchronization. Furthermore, the master system and the slave system are built to have single link manipulator each. The effects of the external loads on the stability of the bilateral controller system have not been studied yet. If a load is attached to the bilateral controller on the slave side, the stability of the controller deteriorated. Additionally, the external load requires more operational force exerted by the human operator on the slave side. The contribution of the project is to propose torque scaling method to improve the stability and to reduce the effects of the load on the master side. The proposed method enables the operator to move the master manipulator and the slave manipulator will track the motion without more operational force. The proposed method scales up the master torque in order to be able to move the slave manipulator with the load on it. The proposed scaling factor is the ratio of load mass and the slave manipulator mass to the master manipulator mass the validation of the designed bilateral controller is done through experiments of free motion and through contact motion. The experiments showed that the position tracking of the deferential mode of the controller is improved. The error of the master manipulator position and the slave manipulator position is zero. The torque error of the common mode is 0.05. Throughout the experimentation, it showed that the scaling method succeeded in scaling the torque of the controller without affecting the accuracy of the position tracking.

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ABSTRAK

Dalam bidang robotik, teknologi haptik dilaksanakan untuk membantu dalam meningkatkan keselamatan kepada pengendali manusia dalam banyak bidang aplikasi seperti peranti perubatan, pembuatan industri, dan persekitaran yang berbahaya. Teleoperasi dua hala adalah sebahagian daripada dunia haptik sebenar yang memulakan dua cara teleoperasi maklumat antara dua sistem; sistem 'master' dan sistem 'slave'. Seseorang mengendalikan sistem 'master' untuk mengawal sistem 'slave' yang berinteraksi dengan alam sekitar. Interaksi antara sistem 'master' dengan persekitaran disuap balik kepada sistem 'master' dan operator dapat merasakannya melalui sistem 'master' Pengawal dua hala mengawal kedudukan dan daya kilas penggerak motor. Sistem kawalan dua hala mengandungi pengawal PD untuk kawalan kedudukan, pengawal kuasa, pemerhati gangguan (DOB) dan pemerhati reaksi daya kilas (RTOB). DOB mengurangkan gangguan sistem dan pemerhati daya kilas tindak balas menganggarkan daya kilas reaksi luar. Pengawal dua hala direka untuk membuat sistem 'slave' menjejaki trajektori kedudukan sistem 'master' supaya pergerakan 'master' dan motor 'slave' bersegerakkan. Selain itu, sistem 'master' dan sistem 'slave' dibina untuk mempunyai manipulator pautan tunggal. Objektif eksperimen dijalankan untuk menyiasat kesan variasi parameter pengawal dua hala terhadap kestabilan dan ketelusan, dan untuk merekabentuk dan mengesahkan pengawal dua haptik untuk mengawal kedudukan dan daya kilas apabila beban luaran digunakan pada pengawal . Kesan beban luar terhadap kestabilan sistem pengawal dua hala belum dipelajari. Sekiranya beban dipasang pada pengawal dua hala di sebelah 'slave', kestabilan pengawal merosot. Di samping itu, beban luaran memerlukan lebih banyak daya operasi yang dikenakan oleh pengendali manusia di sisi 'slave'. Sumbangan projek ini adalah untuk mencadangkan kaedah skala daya kilas untuk meningkatkan kestabilan dan mengurangkan kesan beban di bahagian 'master'. Kaedah yang dicadangkan membolehkan operator untuk menggerakkan manipulator 'master' dan manipulator 'slave' akan menjejaki gerakan tanpa lebih banyak daya operasi. Kaedah yang dicadangkan menaikkan daya kilas 'master' untuk dapat memindahkan manipulator 'slave' dengan beban di atasnya. Faktor penskalaan yang dicadangkan adalah nisbah jisim beban dan jisim manipulator 'slave' kepada jisim manipulator 'master' pengesahan pengawal dua hala yang dirancang dilakukan melalui percubaan gerakan bebas dan melalui gerakan hubungan. Eksperimen menunjukkan bahawa kedudukan penjejakan mod pengawal pengawal telah bertambah baik. Ralat posisi manipulator 'master' dan position manipulator 'slave' adalah sifar. Ralat kilasan mod biasa ialah 0.05. Sepanjang percubaan, ia menunjukkan bahawa kaedah penskalaan berjaya mengukur daya kilas pengawal tanpa menjejaskan ketepatan penjejakan kedudukan.

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LIST OF ABBREVIATIONS

ADC	-	Analog digital converter
ADRC	-	Active disturbance rejection controller
DAC	-	Digital analog converter
DOB	-	Disturbance observer
DOF	-	Degree of freedom
HODOB	-	High order disturbance observer
MATLAB	-	MATrix LABoratory
PD	-	Proportional derivative
PID	-	Proportional integral derivative
PI	-	Proportional integral
RTOB	-	Reaction torque observer
RFOB	-	Reaction force observer
WOB	-	Workspace observer

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LIST OF SYMBOLS

A_m	-	Motor gain
α	-	Position scaling factor
B	-	Viscous coefficient
β	-	Force scaling factor
C_f	-	Force controller
C_p	-	Position controller
$GDOB$	-	Cut-off frequency of disturbance observer
$GRTOB$	-	Cut-off frequency of reaction torque observer
J	-	Moment of inertia
J_{tn}	-	Motor nominal inertia
k_b	-	Back-EMF constant
k_t	-	Torque constant
K_p, K_d	-	The gain for proportional and derivative controller
k_s	-	Stiffness of the flexible link
L_a	-	Armature inductance
l	-	Length of the link
m	-	Mass of the link
M_m	-	Master manipulator mass
M_s	-	Slave manipulator mass

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R_a	-	Armature resistance
V_m	-	Motor input voltage
τ_L	-	Motor total torque
$\tau_{m,s}$	-	Master and slave torque
τ_{dis}	-	Disturbance torque
τ_{ext}	-	External torque
θ	-	Position of manipulator
$\theta_{m,s}$	-	Master and slave position
$\dot{\theta}$	-	Angular velocity produced by the motor
$\ddot{\theta}_{Dif}$	-	Differential mode acceleration
$\ddot{\theta}_{com}$	-	Common mode acceleration
ω_n	-	Natural angular frequency
δ	-	Damping coefficient

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Journal Publications

Ali, S.A., Miskon, M.F., Hj Shukor, A.Z., Mohammed, M.Q., 2018. The effect of parameters variation on bilateral controller. *Institute of Advanced Engineering and Science*, 9(2), pp. 648-659. (Published) (Scopus index)

Ali, S.A., Miskon, M.F., Hj Shukor, A.Z., Mohammed, M.Q., 2017. Single link bilateral haptics control with PD controller and geared DC-motor in robotic rehabilitation technology. *International Journal of Mechanical and Mechatronics Engineering*, 17(5), pp. 148-155. (Published) (Scopus index)

Ali, S.A., Miskon, M.F., Shukor, A.Z.H., Bahar, M.B., Mohammed, M.Q., 2017. Review on application of haptic in robotic rehabilitation technology. *International Journal of Applied Engineering Research*, 12(12), pp. 3203-3213. (Published) (Scopus index)

Ali, S.A., Annuar, K.A.M., Miskon, M.F., 2016. Trajectory planning for exoskeleton robot by using cubic and quintic polynomial equation. *International Journal of Applied Engineering Research*, 11(13), pp. 7943-7946. (Published) (Scopus index)

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CHAPTER 1

INTRODUCTION

1.1 Background

Haptic studies transporting a sense of touch. It deals with human machine interaction. Haptic is divided into virtual haptic and real world haptic. Virtual haptic associates human and virtual computer environment. The real world haptic is related to the real physical environment. Haptic expands the limits for mechatronics and robotic application from medical devices to hazardous environments. Robotic systems apply teleoperation in environments where a human operator cannot be present. Teleoperation systems enable people to operate in unclear plants and hazardous environment without putting themselves in danger. Haptic also is used in designing surgical devices that conduct operations on human body.

A human operator can control a robot in the hard environment and feel the reaction from the environment through a teleoperation system. Teleoperation indicates operating a system or machine at distance. It is similar in meaning to the phrase remote-control. Haptic is direct teleoperation where the operator manipulates haptic interface to control real objects. The teleoperation system that enables an operator to sense the feedback from the environment is bilateral teleoperation. Bilateral control consists of two systems; master system and slave system. The master is operated by human operator and the slave system copies the master motion. The slave system gives a feedback from the environment reaction to the human operator. Master-slave systems have the same link’s size. If the size is not the same, the bilateral controller requires scaling system. In some applications like surgeries,

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it is difficult to obtain the reaction from the environment because the reaction is small. The scaling systems amplify the reaction to a level that can be felt by the operator.

1.2 Motivation

The project's finding is to develop a bilateral controller that adapts the change in the weight applied to it. The motivation behind the project is to be used in exoskeleton rehabilitation system. The device will help stroke patients who are half paralyzed. The system is designed so that the patient can train by himself without the need of therapist. The challenge here is on how to control the robotic leg so that it will track the patient movements and provide power to the patient effected part, using a system that can estimate the forces and track position without using highly sensitive sensors and load cells. This is to make the system accurate, inexpensive and affordable. The current exoskeletons designed to perform human walking are programmed with trajectories of walking. Preprogrammed trajectories exoskeletons cannot adapt any change in walking. Moreover, these exoskeletons are equipped with load cells and sensors in order to perform walking and track the angles of the joints and to measure the forces in the joints. Using force sensors result noises and narrow the bandwidth of the teleoperation (Katsura et. al., 2007). It is more feasible to use a system which provides the same performance and does not require sensors or load cells to achieve high position accuracy and transparent force teleoperation. Sensors and load cells have narrow bandwidth that result error in bilateral control system.

This study proposes a controller for guided rehabilitation device based on master system and slave system attached to lower limb. The device is controlled by haptic bilateral controller to copy the data from the master system to the slave system. The master system is attached to the healthy leg of the patient and the slave system is attached to the patient effected leg. In coming years, the trend shows that the advancements in the development

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of lower body exoskeleton robot for many purposes such as physical assistance and rehabilitation therapy. According to the statistics, the number of aging population and lower limb injury are always increasing. Therefore, many therapists are required to help overcome this problem. A lot of researchers are involved in rehabilitation robotic development due to the increasing number of patients. According to the American heart association report collected from 190 countries around the world, which stated that the number of strokes patients increased to 33 million in 2010. The report stated that the stroke is ranked as the second cause of death globally after the heart disease (Mozaffarian et. al., 2014). The invented systems have functions treated people in different poses and ways. The rehabilitation devices can be stationary or movable. The patients go through foot gate training, ankle training, over ground training, stationary and treadmill training (Díaz et. al., 2011). The exoskeleton device must be accurate, precise and beneficial for patients. Rehabilitation robots are checked by clinical community to validate it and prevent any use of devices that might harm the patients. Stroke patients have difficulties to regain walking due to the expensive therapy process. The existed rehabilitation robots are costly. New technologies offer simple rehabilitation system that can be affordable to all patients because it is cheaper and less complicated which is used be the patient without the need of expert to use it.

1.3 Problem statement

Bilateral teleoperation attracts significant interest in the industry because it transmits and receives a haptic touch to remote environment. The bilateral controller has challenges that must be solved to be suitable to improve the system for real time applications. The studies conducted by (Sariyildiz and Ohnishi, 2013c) (Sariyildiz and Ohnishi, 2015b) improve stability and performance of the bilateral control system. However, the external

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