Faculty of Electrical Engineering

SCALING OF MDOF MICRO-MACRO BILATERAL CONTROL TELEOPERATION SYSTEM USING STANDARDIZED MODAL SPACE

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

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DECLARATION

I declare that this thesis entitled “Scaling of MDOF Micro-Macro Bilateral Control Teleoperation System Using Standardized Modal Space” 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 candidature of any other degree.

Signature : ……………………………..
Name : …..... LEE JUN WEI ………
Date : …..……30/8/2016……..…..

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 : ………………………………………………………..
Supervisor Name : ……DR. AHMAD ZAKI BIN HJ SHUKOR…..
Date : ……………...……30/8/2016…………………..…..

DEDICATION

To my beloved Mother and in my loving memory of Father

Thank you for your incessant support and encouragement. Your sacrifices and loves have helped me to achieve this accomplishment.

Dear Supervisor, co-Supervisor and Lecturers

Thank you for your continuous support, knowledge and guidance.

Dear Friends

Thank you for all the information, guidance, support and encouragement.

ABSTRACT

In future, robots and mechatronic system are required to support human, they should have a lot of abilities such as recognition of the real world based on the complicated human action to environment based on human sensation and so on. The word "Haptic" means sense of touch and haptic information is studied as the third type of multimedia information. Unlike audio and visual information which is transmitted to one direction (unilateral), haptic information is bidirectional information (bilateral), which applied "law of action and reaction" a tactile information in bilateral information. Thus, a bilateral control system with master and slave manipulator to transmit the information bilaterally has been researched. In this thesis, bilateral teleoperation control system is implemented in single link planar and two link planar manipulator which consisted of master and slave system. The modelling of bilateral teleoperation control system is designed with the integration of Disturbance Observer (DOB), Reaction Force/Torque Observer (RFOB)/(RTOB), position controller and force controller. Then further research on micro-macro bilateral teleoperation control system is done on multi degree-of-freedoms (MDOF) which is two link planar manipulator. The micro-macro bilateral control teleoperation system provides the human operator with a sense of feel to a micro or macro environment as if it is in the same scale environment. However, the micro-macro bilateral control system of this thesis consists of same size structure between master and slave manipulator. Thus a standardized modal space method is proposed to achieve for MDOF micro-macro bilateral control teleoperation system. This method able to scale the force and position information between master slave system. It is a novel method for transmission of force and motion in macro environment in order to realize the physical support for the macro activities. Nevertheless, this proposed method able to scale the haptic information between the master and slave system accordingly. To validate the performance of common mode and differential mode of the proposed method, 4 cases of free and contact motion experiments with different nominal mass ratio between master and slave system are conducted. Then the root-mean-square deviation of the nominal mass ratio and scaling α gain from 4 different cases is 1.12×10^{-5} and 2.55×10^{-5} for x-axis and y-axis, respectively. As conclusion, this proved that the standardized modal space method is able to scale different force information of MDOF micro-macro bilateral control teleoperation system.

ABSTRAK

Pada masa akan datang, robot dan sistem mekatronik diperlukan untuk menyokong manusia, mereka harus mempunyai banyak kebolehan seperti pengiktirafan dunia sebenar berdasarkan tindakan manusia yang rumit kepada alam sekitar berdasarkan sensasi manusia dan sebagainya. Perkataan "Haptic" ertinya rasa sentuhan dan maklumat haptic dikaji sebagai jenis ketiga maklumat multimedia. Tidak seperti maklumat audio dan visual yang dihantar ke satu arah (unilateral), maklumat haptic adalah maklumat dwiarah (dua hala), yang menggunakan "undang-undang tindakan dan reaksi" maklumat sentuhan di dalam maklumat dua hala. Oleh itu, satu sistem kawalan dua hala dengan induk dan hamba pengolah untuk menghantar maklumat secara dua hala telah dikaji. Dalam tesis ini, sistem kawalan teleoperasi dua hala dilaksanakan dalam satu satah penghubung dan dua satah penghubung pengolah yang terdiri daripada sistem induk dan hamba. Pemodelan sistem kawalan teleoperasi dua hala direka dengan integrasi Pemerhati Gangguan (DOB), Permerhati Reaksi Daya / Permerhati Reaksi Kilas (RFOB) / (RTOB), pengawal posisi dan pengawal daya. Kemudian penyelidikan lanjut mengenai kawalan sistem teleoperasi dua hala mikro-makro dilakukan pada pelbagai darjah kebebasan (MDOF) yang merupakan dua satah penghubung pengolah. Sistem kawalan teleoperasi dua hala mikro-makro memberi pengendali manusia untuk merasa persekitaran mikro atau makro seolah-olah ia adalah dalam persekitaran yang sama saiz. Walaubagaimanapun, sistem kawalan dua hala mikro-makro tesis ini terdiri daripada struktur saiz sama antara induk dan hamba pengolah. Oleh itu kaedah ruang model yang seragam adalah dicadangkan untuk mencapai sistem teleoperasi kawalan dua hala mikro-makro MDOF. Kaedah ini dapat mengubah skala maklumat daya dan maklumat posisi antara sistem induk hamba. Ia adalah satu kaedah baru untuk penghantaran daya dan gerakan dalam persekitaran makro bagi merealisasikan sokongan fizikal untuk aktiviti-aktiviti makro. Bagaimanapun, kaedah yang dicadangkan ini mampu mempertingkatkan maklumat haptik antara sistem induk dan hamba sewajarnya. Untuk mengesahkan prestasi mod lazim dan mod berbeza daripada kaedah yang dicadangkan, 4 kes eksperimen gerakan bebas dan sentuhan dengan nisbah jisim nominal yang berbeza di antara sistem induk dan hamba dijalankan. Kemudian punca purata kuasa dua sisihan bagi nisbah jisim nominal dan berskala α dari 4 kes yang berbeza adalah 1.12×10^{-5} and 2.55×10^{-5} *bagi paksi-x dan paksi-y. Sebagai kesimpulan, ini membuktikan bahawa kaedah ruang model yang seragam mampu untuk mengubah skala maklumat daya yang berbeza bagi sistem teleoperasi kawalan dua hala mikro-makro MDOF.*

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ω_n

LIST OF ABBREVIATIONS

l_1 - Link 1

l_2 - Link 2

J - Real inertia

J_n - Nominal inertia

M - Real mass

M_n - Nominal mass

J_L - Load inertia

$N_1 : N_2$ - Gear ratio

K_{tn} - Nominal torque constant

α - Arbitrary scaling factor of position

β - Arbitrary scaling factor of force

K_p - Position gain

K_d - Velocity gain

K_a Acceleration gain

K_f - Force gain

C_p - Position controller

C_f - Force controller

ω_n - Natural angular frequency

δ - Damping coefficient

g_{dob} - Cut-off frequency of disturbance observer

g_{rtob} - Cut-off frequency of reaction torque observer

J_{aco} - Jacobian

${J_{aco}}^T$ - Jacobian transpose

τ - Torque

F - Force

θ - Angle

$\dot{\theta}$ - Angular velocity

$\ddot{\theta}$ - Angular acceleration

x - Displacement

$\dot{x}$ - Velocity

$\ddot{x}$ - Acceleration

$(superscript)^{ref}$ - Reference value

$(superscript)^{res}$ - Response value

$(superscript)^{dis}$ - d value

$(superscript)^{ext}$ - External value

$(subscript)_M$ - Master system

$(subscript)_S$ - Slave system

$(subscript)_C$ - Common mode

$(subscript)_D$ - Differential mode

$(subscript)_x$ - x-position

$(subscript)_y$ - y-position

$\widehat{\ }$ - Estimated value

LIST OF PUBLICATIONS

The following publication have been achieved by this research work.

Journals:

1) L. J. Wei, A. Z. H. Shukor, and M. H. Jamaluddin, "Workspace Control of Two Link Planar Robot Using Micro-Box 2000," *J. Teknol.*, vol. 77, no. 20, pp. 9–18, 2015. **(SCOPUS)**
2) L. J. Wei, A. Z. H. Shukor, and M. H. Jamaluddin, "Investigation on the Effects of Outer-Loop Gains , Inner-Loop Gains and Variation of Parameters on Bilateral Teleoperation Control System Using Geared DC-Motor," *Int. J. Mech. Mechatronics Eng. IJMME-IJENS*, vol. 16, no. 01, pp. 54–69, 2016. **(SCOPUS)**
3) L. J. Wei, A. Z. H. Shukor, and M. H. Jamaluddin, "Investigation on MDOF Bilateral Teleoperation Control System Using Geared DC-Motor," *Modern Applied Science*, vol. 10, no. 11, pp. 54–66, 2016. **(SCOPUS)**
4) L. J. Wei, A. Z. H. Shukor, and M. H. Jamaluddin, "Investigation on Standardization of Modal Space by Ratio for MDOF Micro-Macro Bilateral Teleoperation Control System," *Modern Applied Science*, vol. 10, no. 11, pp. 98-109, 2016. **(SCOPUS)**

CHAPTER 1

INTRODUCTION

1.0 Background/Motivation

Imagine a world that human being is strong, able to be present in deep underwater, or outer space to explorer and feel the environment which normal human being cannot exist and able carry big and heavy objects. Unfortunately, human being does not. Human being is incapable and do not possess such abilities, but robot can. Human can control with a controller from a recliner at home while robot does the bidding in the world.

It is similar as a teleoperation system. Teleoperated robots are used where human is not physically present in the environment. The common applications of teleoperation are handling inaccessible or hazardous environment such as nuclear plant, deep underwater and outer space. As the technology of teleoperation become more advanced, teleoperation is also applied in medical surgeries. During surgery, the human operator operates the surgical tools located at another room which is in a different location with patient to provide comfort for the patient during the surgery. The human operator depends on the projected image of the patient on a monitor and controls the position of the surgical tools. However, in order to achieve minimally invasive surgery (MIS), the ability of human operator to sense the motion in the teleoperation system is vital.

In the future, for robots and mechatronic system are required to support humans, they should have a lot of abilities such as recognition of the real world based on human action, and transmission of sense of touch of the environment based on human sensation. Thus, with the ability to sense touch and manoeuvrability in teleoperation system, the human operator can manipulate the environment as if the human operator is present in the environment. In this case, during surgery, the human operator manipulates a surgical tool to cut a tissue of a patient, the human operator is able to perform the task and at the same time sense the stiffness of the tissue to avoid damage to the tissue and surrounding organs.

In fact, sensation from the environment is always a way to feel and recognize everything that is touched. With auditory and visual information utilised together with the haptic information, human can feel total immersion in augmented reality using Avatar robots going to distance or unreachable places instead. In other words, unmanned aerial vehicles (UAV) used for deep underwater exploration can implement haptic system to obtain haptic information other than audio and visual information from the deep underwater environment.

In that case, the system must have interactivity for human operator to get information from environment through bilateral control system. This means that the haptic information from the real environment is only received when making contact with the real environment. Thus, a bilateral control system with master and slave manipulator is needed to transmit the information bilaterally. Each manipulator is equipped with actuators and sensors having one or more degrees of motion freedom.

Further application of bilateral control system is micro-macro bilateral control systems. The micro-macro bilateral control system consists of different size of master and slave system. This system allows to transmit haptic information between different scaled objects. Nevertheless, this system must able to scale the haptic information between the master and slave system accordingly. Thus this allow operator to feel sensation as if they are touching different scale of environment. It is also effective for application where operator cannot manipulate directly.

Real-world haptic is the current attention not only as the principle of attaining real-world haptic information in teleoperation but also the key technology for future human support. There are haptic fields that will expected to have great demand in our society. In the next decade, haptic technology will become part of human's compliant device for any age of people and any occupations or professions. This includes human-support technologies, medical/rehabilitation, exploration and industry. It will bring new technical issues in haptic system.

1.1 Problem Statement

In particular, geared motor has been implemented vastly in industrial field such as factory automation, robotics, industrial machine and medical sciences and laboratory technology. Geared motor also brings cutting-edge technology application such as outer-space and underwater exploration, advanced robotics, and machinery. The advantages of geared motor are able to produce high torque. To produce a high torque out from a motor itself without gear for power transmission, the size of the motor has to be big. This in fact not just costly, but also impractical in size. Thus, it is important to realise that the higher the torque required, the larger the size of the motor. With many different types of gears and ratios, the engineer can decide the torque output required for an application.

However, in the past approaches, researches on bilateral teleoperation control system utilised linear motor. The output force is powerful but the cost is high. Moreover, it controls in linear position. Nevertheless, some researches approached bilateral teleoperation control system using motor. But the output power is very low. For instance, the implementation of geared motor in bilateral teleoperation control system is a new step in research. The outcome of the teleoperation using geared motor able to realize a low cost teleoperation system. Unfortunately, geared motor produces large joint friction in teleoperation and affects the force/torque sensorless control.

Furthermore, industrial robots that seen in automation and car manufacturing industry, the operation of the robots are programed based on trajectory position. Those usually are for pick and place or assembly task. Yet, the operation area is fenced around to avoid human access the operation zone. This is because the industrial robots are rigid and sensor-less to external environment, thus it will harm and injured when it contacts with human during operation. Consequently, these industrial robots are not safe during operation and not human friendly. In order to be safer, accessible and human friendly, the system must have external force feedback from the environment other than operation task. By all means if the system able is to track external force, the industrial robots will halt the operation immediately when it makes contact to undesired force from the environment.

Scaled teleoperation has been developed since decades ago. This which means the physical and parameters of master and slave device are totally different. Even though teleoperation systems used for human to operate larger scale slave manipulator such as excavator, underwater UAV for exploration or maintenance purposes, these applications have no haptic feedback information from the environment. In teleoperation between different scale world, it is vital to consider the scaling effect in micro-macro bilateral control system that able to provide the human operator with force feedback. In other words, it is important to develop an effective method which can easily manipulate a different size manipulator with scaling effect. Then the motion and force scaling are required for this bilateral control system to realize physical support and manipulate in different scale of environment. Thus, the micro-macro bilateral control system provides not just easy to manipulate different size of master and slave device, also able to provide human operator with a sense of haptic to a micro or macro environment as if it is in the same scale environment.