

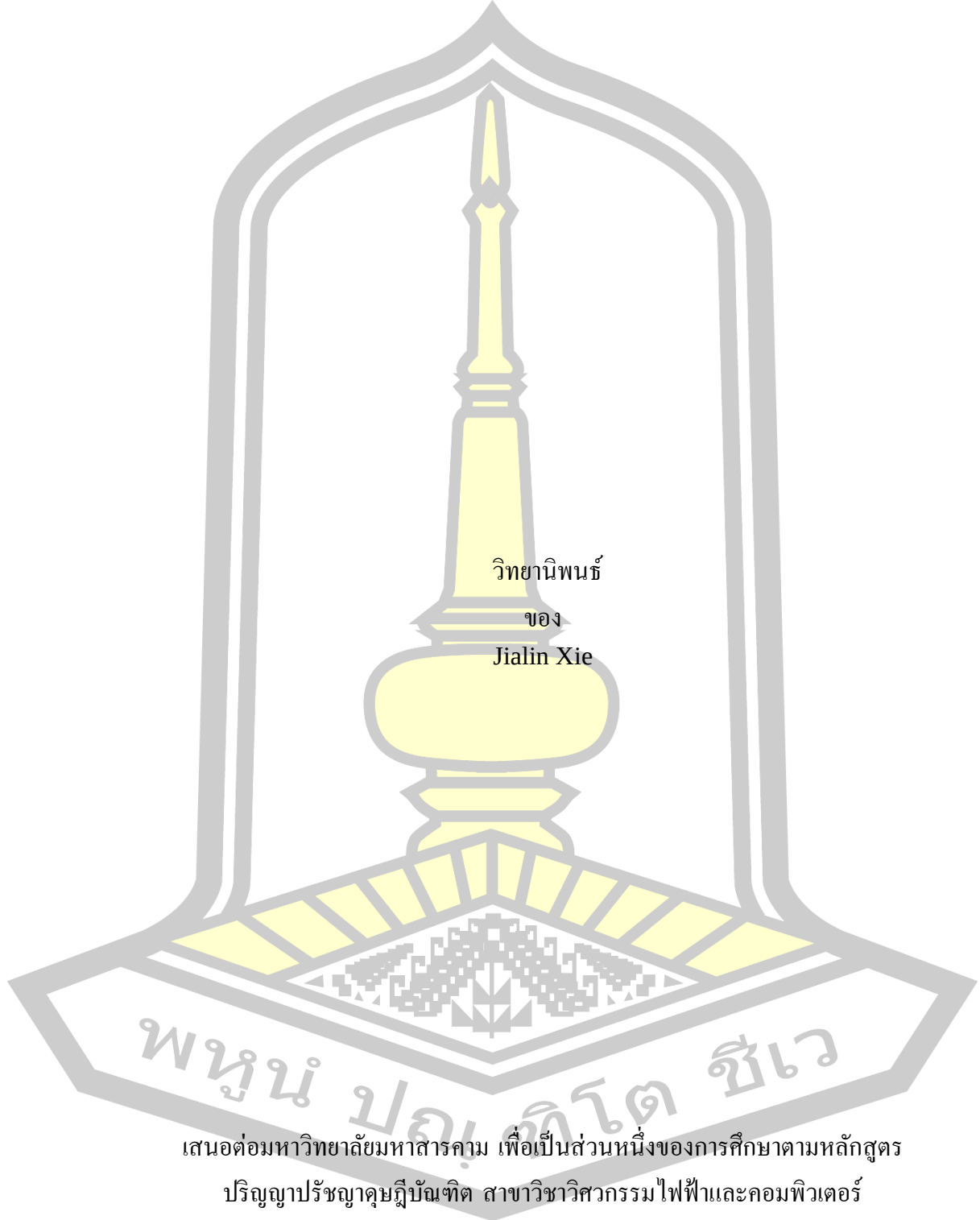
Robust Impedance Control of Series Elastic Actuator for Human- Robot
Teleoperation

Jialin Xie

A Thesis Submitted in Partial Fulfillment of Requirements for
degree of Doctor of Philosophy in Electrical and Computer Engineering
March 2026

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Teleoperation



วิทยานิพนธ์

ของ

Jialin Xie

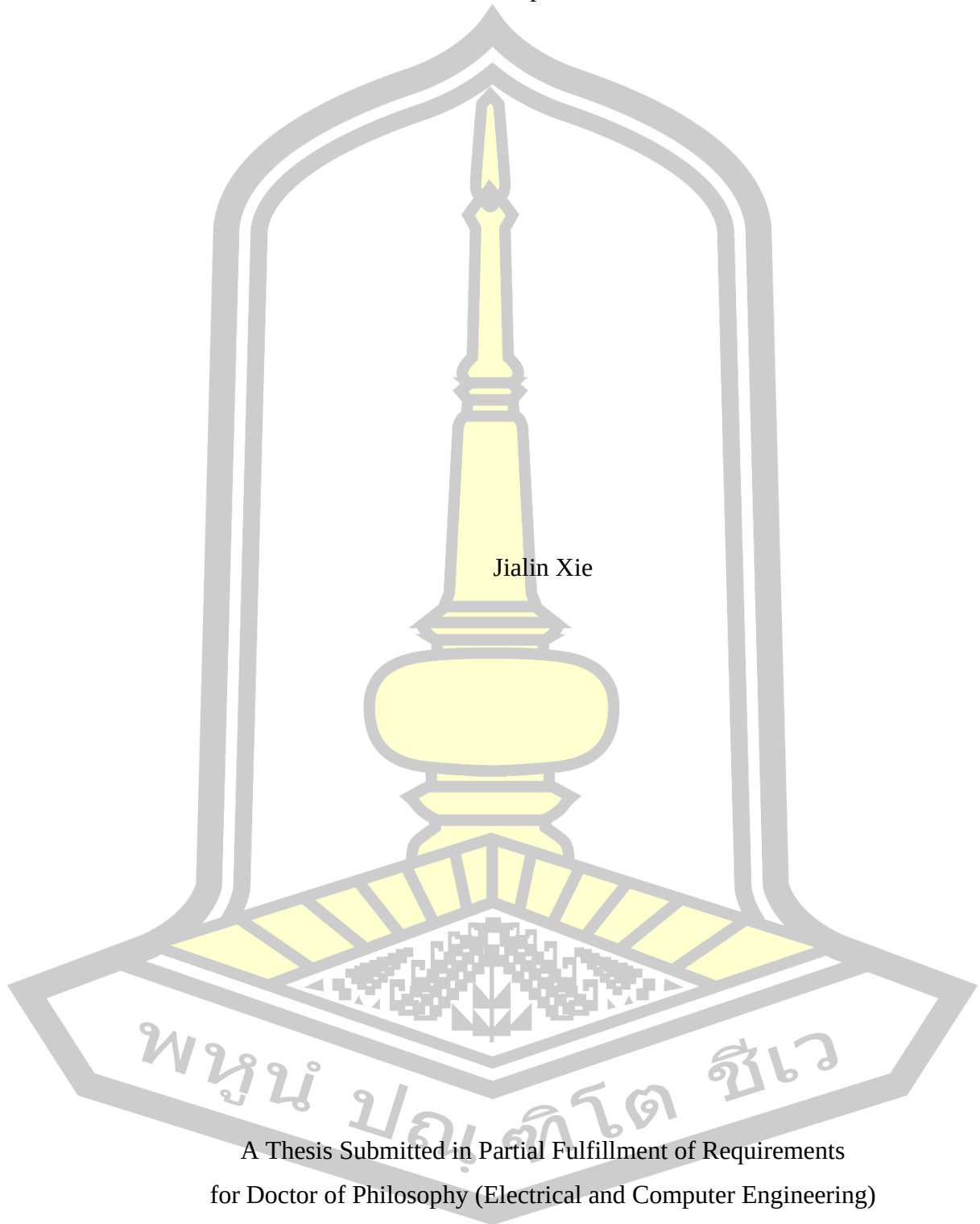
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Teleoperation

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A Thesis Submitted in Partial Fulfillment of Requirements
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March 2026

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ABSTRACT

Series elastic actuator(SEA) has promising application in human-robot teleoperation area,which supplying inherent safety under unknown disturbance from inner or outer environment,compared with the limitation of rigid actuator in the past. In this paper,a kind of series elastic actuator feedback system model for teleoperation with robust impedance control was proposed. The control themes including traditional PI controller and (H_∞) norm robust controller based on linear matrix inequality (LMI) was designed. Through experiment setting of step signal,impulse signal,and sinusoidal exciting,the results were obtained,simulated by Matlab/SIMULINK. Compared with un-controller system and PI control,the experiments had shown the effectiveness of the H_∞ norm robust control scheme. Finally,the improvements of the performance including the response time,rising time,and over shoot were illustrated.

Keyword : ADD elastic actuator(SEA), Feedback system, Impedance control, (H_∞) control, LMI



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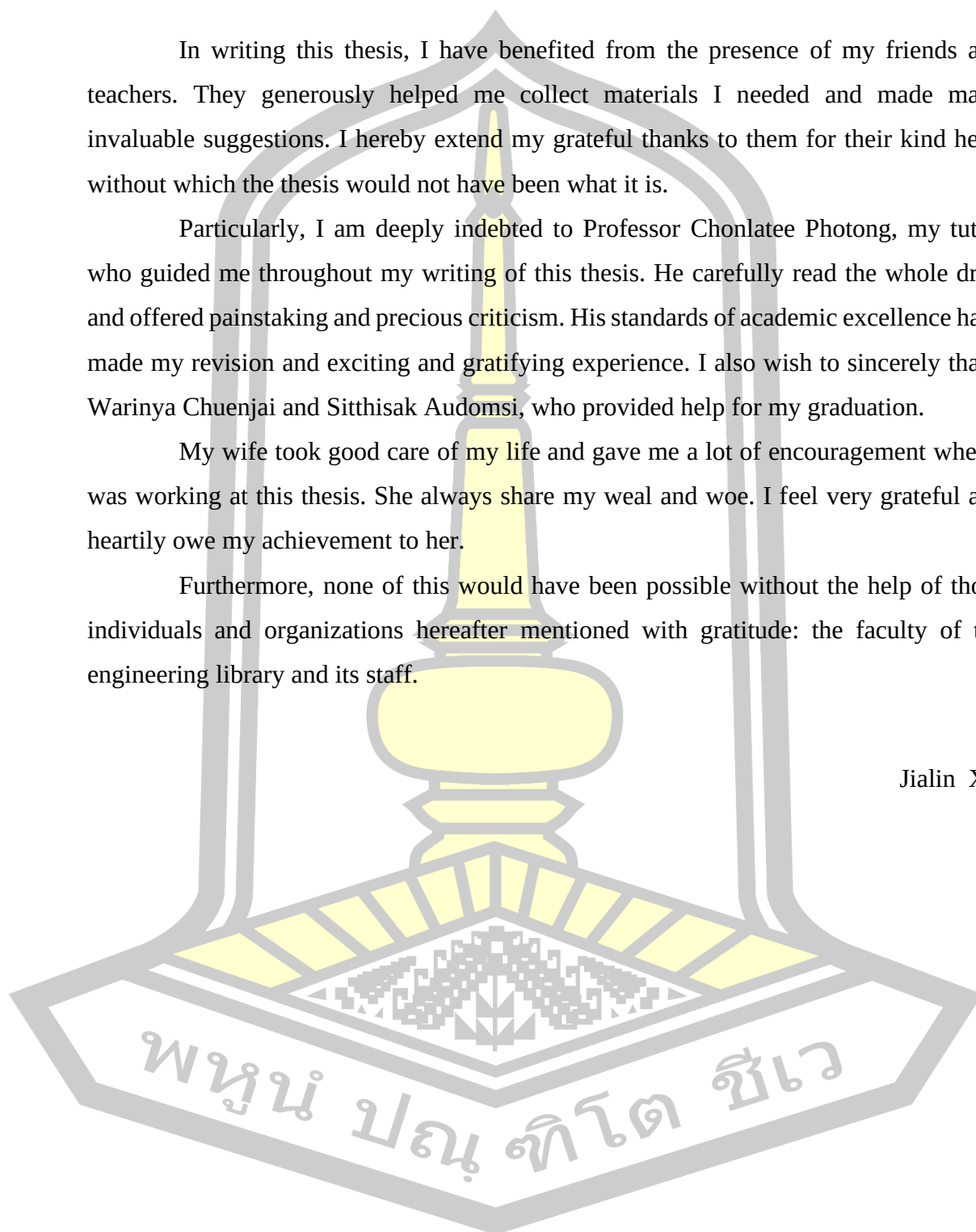


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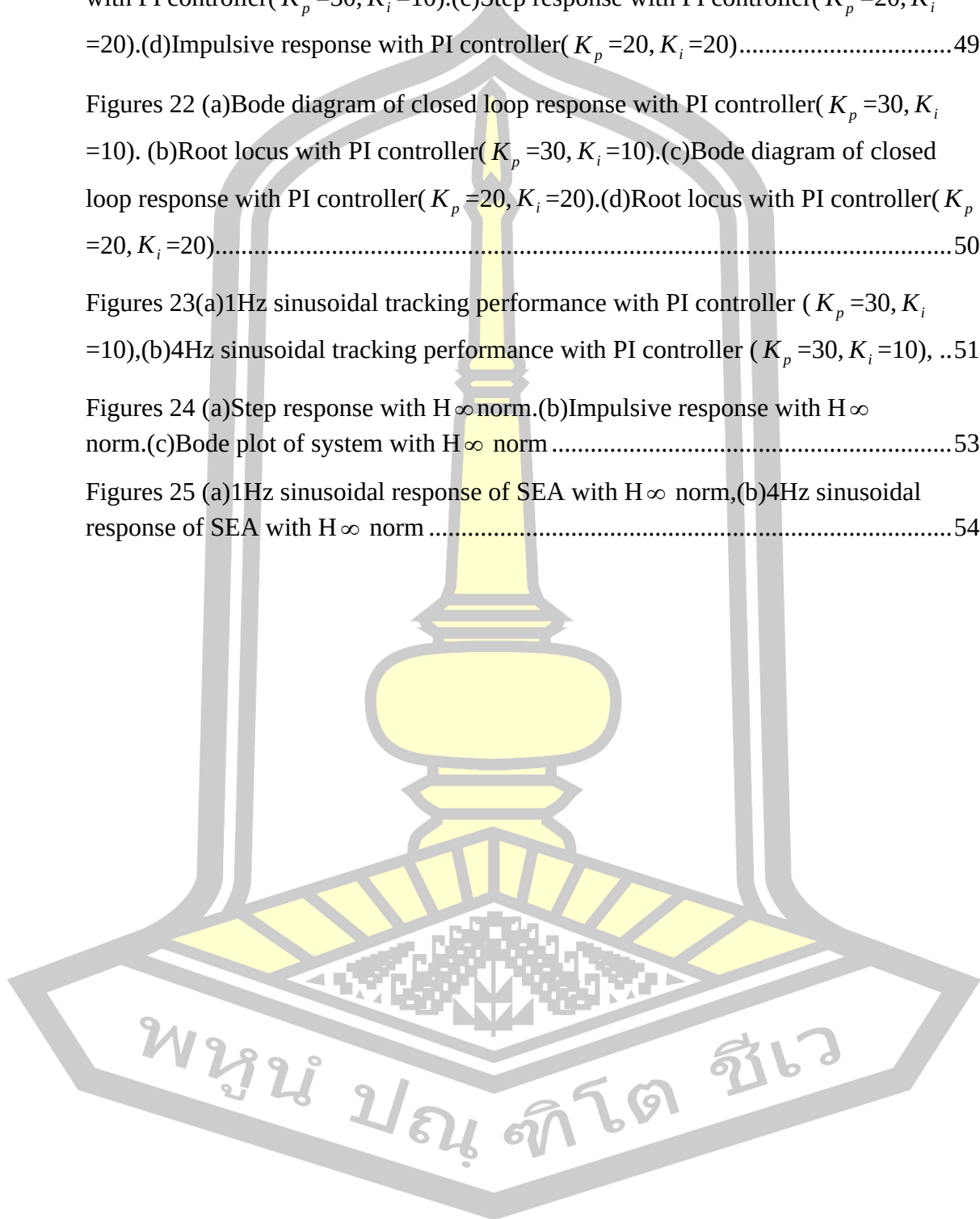
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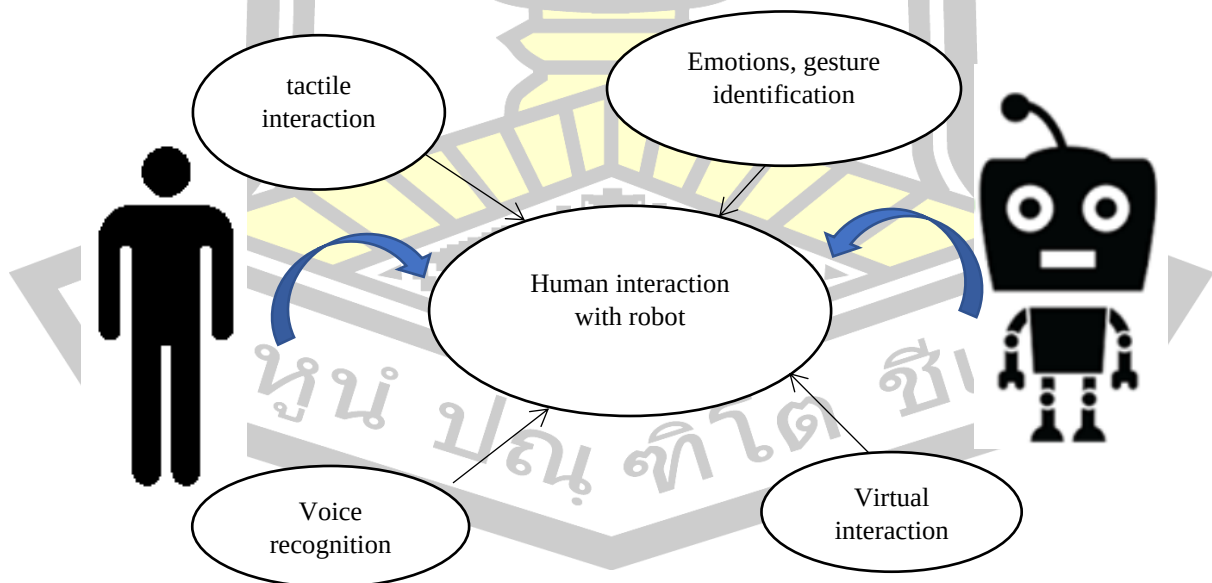
CHAPTER 1

INTRODUCTION

1.1 Research Background

Robots have played many important roles in the industry since 1900s and nowadays become closer to humans' daily lives. Therefore, there are many research works carrying on several development projects on human aiding robots. However, one of the most challenges for these robot types is to develop robots that are easy to communicate with the system called Human-Robot Interaction (HRI) system. When considering the whole robot system, not only to the user interface, but HRI was also the field of study dedicated to understanding, designing, and evaluating robotic systems for use by or with humans [1]. It is a fast-growing research field in robotics which has been gathering interest over recent years and seems to be most promising for robotics' future and its effective production into more and more areas of everyday life.

The interaction contain tactile interaction (force contact), visual recognition (such as human faces emotions and body gesture), voice recognition (human language identification), and virtual interaction (virtual reality). There is a general framework of human robot interaction shown in Figure 1

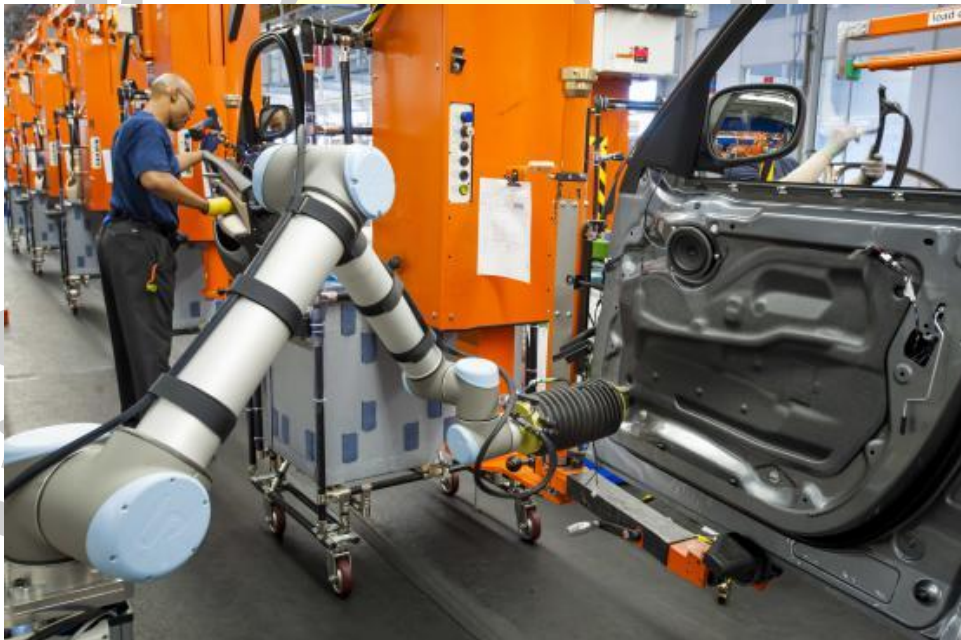


Figures 1 General framework of human robot interaction

1.1.1 The application of HRI

HRI is used in many fields covering industrial, medical and rehabilitation, agriculture, service, educational environments, etc. The applications of industrial contain part's assembly, picking and placing of production line, co-manipulating tasks, welding processing, and painting [2-6]. In the industry, the primary purpose and application of HRI is to perform useful tasks for human, which means that robot can understand human behavior including emotional express, voice, gesture and force contact and collaborate with humans in a seamless and natural way.

There are some examples of the practical application as presented in Figure 2 to Figure 5. In Figure 2, the robots cooperate with workers to perform the task of door assembly in BMW factory located in South Carolina. The foil with adhesive bead is placed and pressed slightly in the door by line-workers with the robots help of fixing the door. The labor-intensive fixing process, in the past carried out by humans, is handled by robot arms, leading to high efficiency of production. Also, the robot system obeys the top priority of human safety. The robots are stopped immediately avoiding potential damage while the sensors detect obstacle in way[7].



Figures 2 The corporation between human and robot in BWM assembly line [7]

In practice, the aircraft manufacture process is very complex. It is difficult to achieve fully automation in present technological condition; especially, for small batch production that would lead to high production cost. It is impossible to eliminate human elements during process in general because complex tasks need to be done by skilled workers. Suffering the danger and narrow situation is unavoidable for workers. In this case, the concept of HRI can be introduced into the area. Some aircraft manufacturers, such as Boeing, have successfully integrated corporate robot systems into the process. In Figure 3, it shows that 3 KUKA robots have been taken part in Boeing aircraft manufacture process to achieve fastener installation. One robot located on the outside of the fuselage is drilling holes while the other two inside the fuselage are installing components. The external and internal are aligned to have greater accuracy during working and the platform is moveable to cover the total surface of the fuselage [8]. At the same time, the workers are responsible for the other tasks in the same place as robots. For human safety, when workers get close to robots, it will slow down or even stop to protect people.



Figures 3 The robots and human work together in Boeing aircraft manufacture [8]

In the past sub-assembly process of tramway window and door frames was a dangerous and heavy task for operators. It need to apply silicone and insert the rivets into the drilled hole with special tools manually again and again, leading to injuries after a prolonged utilization of the riveting tools. In Figure 4, a collaborative robot provide by ALSTOM company located in Europe is applied in the riveting task of

tramway door and window sub-assembly processes. While the operator is responsible for preparing the piece for riveting and checking quality [9].



Figures 4 Human and robot corporate in tramway sub-assembly processes [9]

In factory, lifting and putting down work pieces is unavoidable in manufacturing process. Tying manually to lift heavy items can cause injury to workers, and even death in the case of work pieces that fall during accident. In this scenario, a robot controlled by a human can take place the job. In Figure 5, the manipulator used a robot to carry heavy loads with haptic device in a European market. With the help of robots, humans can be taken out of the danger zones, away from heavy work pieces. Also, the physical interaction between human and robot means that the workers just pay minimum strain on handing operations, reducing tiredness and danger [10].

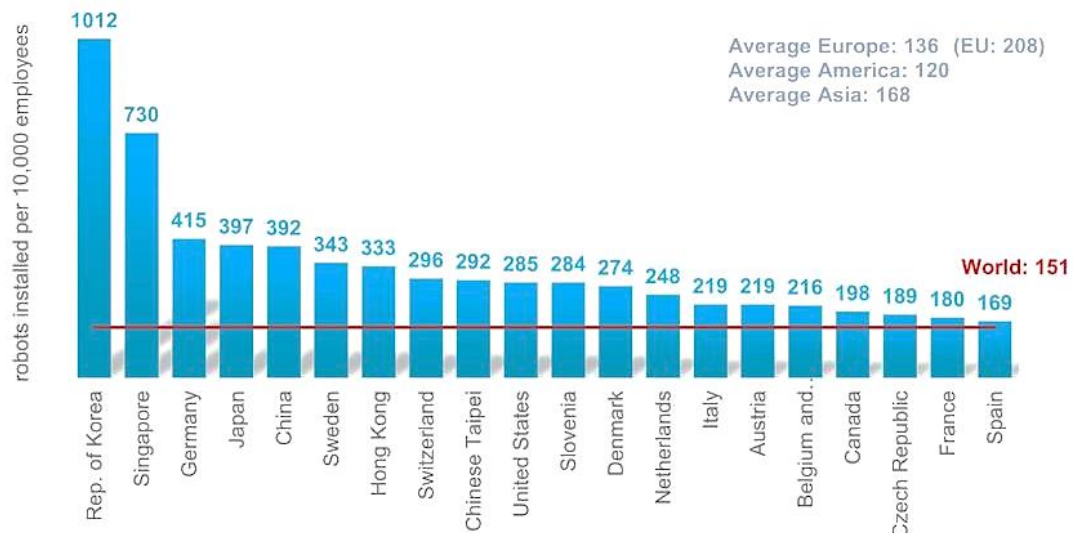




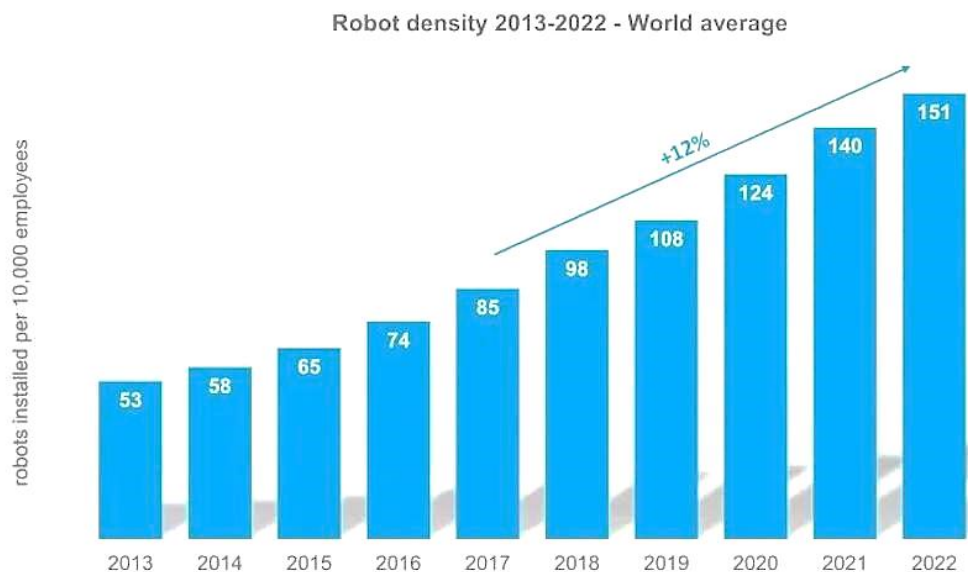
Figures 5 The worker operated the robot to carry heavy load with haptic device in the industry workplace [10]

As mentioned above, the applications of HRI in industry have the advantages of increasing productivity, increasing flexibility, and ensuring human safety. Currently, as the time of Industry 4.0 coming with the character of smart manufacturing, some countries such as USA, UK, China, Japan, Korea, Singapore, and Germany have paid more attention to improve the production lines, including key manufacturing machine and the other equipment through investing and applying collaborative robot in industry. HRI technique for increasing production efficiency while decreasing the need for human labor, has been more and more applied in practical factories. There is some data that can reflect the trend from one side. The data is according to the World Robotics 2022 report by International Federation of Robotics (IFR) regarding the density of robots in manufacturing industry from different countries around the world as shown in Figure 6 [11]. It could be seen that Korea and Singapore have the highest density of robots compared to other countries with 1,012 and 730 robots installed per 10,000 employees while the average world robot density is 151.

Robot density in the manufacturing industry 2022

**Figures 6** The data of Robot density in the manufacturing industry 2022 [11]

According to the statistical data shown in Figure 6, the world hits a new record of 3.9 million operational robots in 2022. By regions, Korea (1,012 robots per 10,000 employees) and Singapore (730 units) have the most automated production. The others fall behind with a large gap compared with the two countries. It is noted that the value from Asia (168 units) is the highest compared to Europe (136 units) and America (120 units) on average. Also, the development of robot density in China continues dynamically: In 2022, the robot density in the manufacturing industry ranked 5th worldwide, nearly equaled to Japan. In Figure 7, the data of robot density for the world average from 2013 to 2022 is presented. The data showed that the curve of density was increasing during these years; especially, nearly 5 years the growth rate continues to keep above 12%, which was higher than past time. These characters mean that more and more collaborative robots have been utilized in practical manufacture.



Figures 7 The data of Robot density of world average in 2013-2022 [11]

1.1.2 The Challenges of HRI

Even though there are a number of benefits provided by HRI, but there would have some several challenges which would need more research on the development of high-performance HRI as follows:

1. HRI for the complex situations

A robot assisted but human guided assembly has various significant advantages compared to full automation (compared with fully automated assembly robotic systems). Typically, an automated assembly robotic system provides a couple of advantages such as operation without breaks and fatigue and high productivity for simple assembly tasks. However, the flexibility of automated systems such as robots normally is restricted due to high programming effort and limited abilities for handling complex or limp parts. In fully automated assembly robotic systems, a sophisticated controller is responsible for accurate and fast positioning of the robot. For assistance of the worker, however, the robot needs additional capabilities, which significantly exceed the demands for accurate positioning only. Especially the abilities of interacting with human workers and providing power assistance in complex human-guided assembly appear to be very complex [2]. On the other hand, a human provides incomparable abilities for complex handling tasks, can quickly adapt to new process sequences but is

restricted in force and precision. On the contrary, HRI towards smart operations, which means that humans are not replaced by Artificial Intelligence, robotics, and automation, rather their capabilities are to be enhanced by smartly designing special solutions [12]. These characteristics stand for the trend of Industry 4.0. The cooperation of human and robot applied in dealing with complex situation in working compared with fully automated assembly robotic systems combines the advantages of a human and an automated system.

2. HRI for high-performance working conditions

The robot's cooperation with the human in the industry could enhance the effectiveness of both the human and the robotic system. Collaborative robots are used for humans' assistance, and this leads to an increase in their capabilities in three issues: precision, speed, and force. Furthermore, robots can reduce the human operator's stress or tiredness and therefore improve working conditions. For example, HRI can also be used for the assembly of heavy or bulky parts. The workers manipulate heavy payloads ergonomically with minimum strain during handling operations [13].

3. HRI for high capacity for human safety

The application of HRI can keep safe distance in handling workpieces or in extreme environment. This kind of human robot interaction (HRI) means that human and robot are separated respectively and don't have direct contact during the process of interaction. For example, the nuclear industry has some of the most extreme situations with high radiation levels, restraining human access to many facilities [14]. HRI with intelligent handling remote operation can decommission sites above acceptable limitation facilitatively, achieving higher level of safety.

As a results, the development of HRI could be carried on for these issues, which would lead to the interest of this research work.

1.2 Objectives

1.2.1 to study and design high-performance HRI to achieve higher levels of stability compared to the conventional HRI during the complex working conditions.

1.2.2 to evaluate the performance of the designed HRI compared to the conventional HRI using the MATLAB-Simulink and related computer programs.

1.3 The Benefits of the Research

1.3.1 to obtain the new type of HRI with high-performance of stability for complex working conditions.

1.3.2 to achieve the evaluation of performance and capacity of the developed HRI compared to the conventional HRIs.

1.3.3 to provide an alternative way of enhancing performance of HRI for the industry.

1.4 Conclusion

In this chapter, the concept of HRI is demonstrated. The advantages of HRI are shown though giving some examples of practical applications. And the development trend of worldwide is described briefly, which is based on the IFR data. However, some challenges cannot be ignored and remain to be solved. However, on the other hand, the problems are worth doing research fields for the development of human robot interaction. The collaborative robot system contains many parts, such as controller, actuating mechanism, sensors, interface, and so on. In this context, the research focuses on the interface between human and robot. For this usage, the common user interface is a touch display. The other possibility is using haptic device to operate and guide a robot for programming purposes. In this thesis, the physical force contact of haptic device is the emphasis.

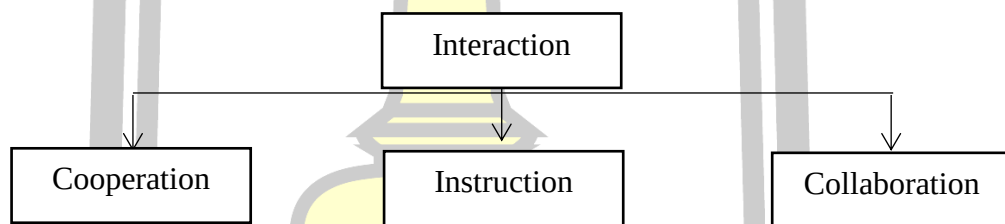
CHAPTER 2

LITERATURE REVIEWS

In this chapter the theories, principles and some research related to HRI will be presented. The details on the classification of HRI types and their levels in the industry are first presented. Then, the principles of HRI control are introduced; following by the literature reviews on the control methodologies utilized for HRI. The summary of the details of the chapter is finally presented by the end of the chapter.

2.1 Classification of HRI in Industry

There is a view that HRI be characterized as either cooperation, instruction, or collaboration for a common goal, enlisted in Figure 8.



Figures 8 The classification of interaction between humans and robots[15]

2.1.1 Cooperation of HRI

Cooperation is defined as a series of actions in HRI to achieve shared goals. It is noted that each partner, nevertheless human and robot, works independently for separated sub-tasks during the process. Each partner's work is independent each other without communication between the human and robot after the task divided into different parts.

As the definition of human-robot cooperation, the research area is related to deal with the human motion prediction, avoiding colliding with human in dynamic environment. This type of robot is called co-manipulator robot. The main challenge of designing controller is that how to preserve safety while maintaining robot efficiency. One approach is to use robust optimal control method that safeguard against every possible future human state to maximally preserve safety. It is robust to cope with mis-

specified situation but often too conservative robot plans. The other is called “intent-driven predictor”, which means that the robot makes decisions relying on building data-driven models of human actions. But it can make poor predictions when the intent-driven model is mis-specified. This in turn will likely cause unsafe robot behavior.

2.1.2 Instruction of HRI

Instruction is defined as a series of actions which is governed by human’s decision making. The human operates the robot to do the tasks while exchanging information each other during the process. This type of robot has character of interface such as touch screen and haptic device for human interacting with robot.

Robust contact stability theory initially developed for controlling robot/environment interaction, has been expanded to control and synthesis of haptic interfaces interacting with a virtual or real environment. The primary concern in haptic systems is to achieve stable interaction under any operating conditions and for all simulated virtual environments, even dynamic conditions.

J. Kru ger et al [10]. proposed a framework developed for a robustly stable control design for interactive robots serving as intelligent assist systems for flexible and highly adaptable assembly.

The experimental evaluation of the developed robust control framework was performed on a 2-DOF hand-driven handling manipulator with 100kg payload capacity. Hand control forces were measured by force sensors. The experimental test site was in a European market. The control design of the system was focused on reduction of apparent inertia and damping in free space. The goal aiming at manipulating heavy payloads ergonomically with minimum strain for the worker during handling operations was reached.

2.1.3 Collaboration of HRI

Collaboration is defined as a series of interdependent actions in HRI setting towards common goals. The human and robot have mutual influences, such as mutual learning, mutual trust, and mutual adaption during the process. This type of robot has the character that human and robot take part in the same tasks commonly.

In the industrial context, it is traditionally that robot is responsible for performing a repetitive task in production line. In the future industry, it is desired that both the person and the robot can share this environment or even interact continuously to accomplish a task. However, the main challenge is how to deal with the tradeoff between the classical qualities including accuracy and force of the robot and the compliant behavior needed for the safety of the person during interactions in uncertain condition.

To combine the qualities of the robot to perform a task by itself, while allowing the person to naturally interact and collaborate with the robot in any condition. Martín Mujica[16] et al presented a novel approach for a collaborative industrial task, where the person and the robot not only can have their own independent behaviors but also collaborate together easily at any moment. The novelty is to directly enhance the robot's adaptation to cooperate with the person by using Robust Control to manage the unknown payload.

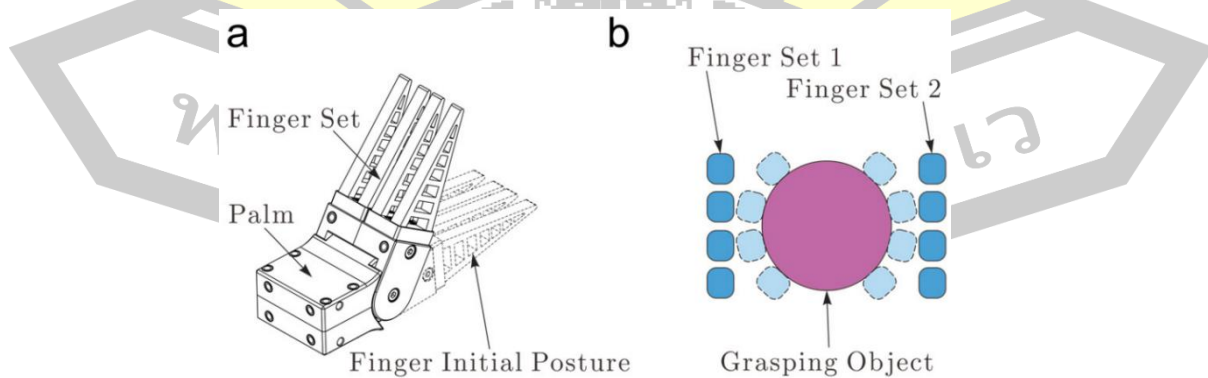
The experiments were carried out with the robot Kuka LBR iiwa 14 R820 with a box rigidly attached to the end-effector. Then, a six-axis force/torque sensor RFT76-HA01 from Robotous3 was also attached to the other side of the box. The robot was controlled using the Fast Robot Interface (FRI) system. Person can interact with the robot by manipulating the hold of the sensor.

The experiment showed that the Robust Motion control used was validated to handle different levels of uncertainty in the payload. Also, it proved that the method allows to handle collaborations while preserving the robot's own task, enhancing the capabilities of modern compliant robots for the industry.

As mentioned above, Robust Control can be used in some applications of HRI, such as human motion prediction, contact force analysis in haptic interfaces and uncertain loaded force analysis during human-robot co-manipulation. The human motion prediction is related to probability distribution, Hamilton-Jacobi (HJ) reachability analysis and Hamilton-Jacobi-Bellman equation. The contact force model can be simplified as 1 DOF mass-spring-damping-model. The uncertain loaded force matrix analysis is related to Lyapunov function stability analysis.

The research of robust control in HRI mainly focuses on the contact force between robot and human in this paper. The simple force model based on impedance control is regarded as one degree of freedom(1-dof) robotic system, such as mass-spring-damping-model. For example, Sehun Kim and Jeha Ryu [17] proposed robust stability control (RSC) method to ensure robust contact stability in an interaction between an impedance controlled robot designed based on a nominal environment and uncertain environments having a wide range of impedance. Comparing to traditional robust control method, the RSC is based on the inherent contact stability limit of the robot system and so its stability condition is irrespective of environment parameters.

As above mentioned, the human robot interaction(HRI) can be classified in three categories : cooperation, instruction, and collaboration. In this paper, the type of robot operated by haptic device that belonged to instruction of HRI is interested. The research focuses on stable analysis of the physical haptic interface between human and robot. The overall structure of robot concludes two haptic interfaces, two robot grippers, and a controller. The two grippers inspired by a human two-finger cooperative handing strategy that through two fingers cooperative, human could grasp objects by adjusting the fingers force and position to achieve stable grasping state. The modular of each haptic interface is based on 1-dof with the function of catching objectives and releasing objectives. The interface component exchanging information with human, manipulated by human of robot is the research point, converting human input force to robot output motion. The overall robotic modular hand with two fingers has been shown control in Figure 9 [18].

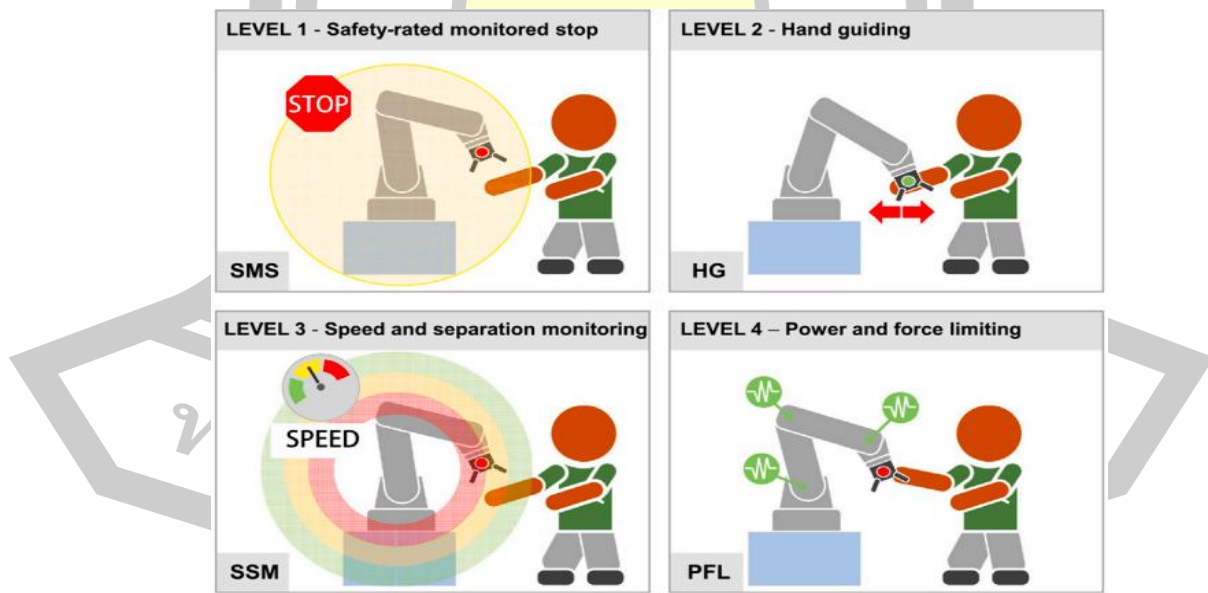


Figures 9 Mechanical structures of the modular hand.(a)Major component of the hand,(b)The object grasped by two fingers

In previous studies[19][20][21],the research of robot hand focused on the ability improvement, such as grasping a wider range objects in different sizes and shapes, picking up objectives at high speed while being tolerant to collision, and accomplishing tasks with high-precision. The common character of the design is complex wiring. Generally, a robot's degree of freedom determines its functionality. While having more degree means a robot is capable of a wider range of motion. However, the drawback of the design is that the robot has many degrees that complexity of robot system were increased and the stability was reduced under some extreme conditions. Therefore, the simplified module design is chosen in the condition of satisfying the application of grasping and releasing objects.

2.2 The classification of levels

There are 4 levels of interdependence and shared representations in HRI defined by the International Federation of Robotics (IFR) [22], which are Safety-rated Monitored Stop (SMS), Hand Guiding (HG), Speed and Separation Monitoring (SSM), and Power and Force limiting (PFL) as shown in Figure 10 Details are as follows:



Figures 10 Levels of HRI defined by International Federation of Robotics [9]

Level 1: Safety-rated Monitored Stop (SMS)

The Safety-rated Monitored Stop (SMS) HRI is used in applications where the robot system and human need to work side-by-side in the workspace. This mode is based on the robot system which has a “protective stop” (Stop category 2 - a controlled stop with power left to the machine actuators) before any operator enters the collaborative area. In that mode the robot must remain stop until the operator leaves the area. Then it may resume automatically after detecting operator leaving by safety cameras or a light curtain. Some collaborative robots are featured with motion limitation and force sensors which function to achieve a protective stop. And during working, the safety devices monitor the workspace for any man entrance.

Level 2: Hand Guiding (HG)

Hand Guiding is used when its paths or positions are reprogrammed by the operator. The motion commands are transmitted to the robot system through a hand-operated device. This mode requires that the robot must have SMS to ensure the safety of the operator entering the collaborative area and safety-rated speed monitoring to ensure the robot moving at a controlled speed without introduced additional hazards.

Level 3: Speed and Separation Monitoring (SSM)

Speed and Separation Monitoring (SSM) is used when both operator and robot may need to move simultaneously in the collaborative area. The goal of SSM is to anticipate collision between moving resources, robotic systems, and humans by controlling and maintaining a safe distance. During robot motion, the robot system keeps protective distance to the operator to avoid danger. It is noticeable that the distance changes dynamically and in real time. It is determined by the robot's speed, robot's reaction time and stop time as well as the human's speed and the safety-rated monitoring system's response time and uncertainties measured by monitoring sensors or robot measurements system. If the separation distance decreases below the protective separation distance, the robot control system may take actions to reduce the speed followed by a transition to safety-rated monitored stop or execute an alternative path which can maintain the protective the protective separation distance, continuing with active speed and separation monitoring. In this safety mode the robot needs to be

equipped with safety-rated speed monitoring functions, safety-rated stop monitoring functions, and safety-rated soft-axis, as well as space limiting functions.

Level 4: Power and Force Limiting (PFL)

Power and Force Limiting (PFL) is used when the robot and the operator can have physical contact intentionally or unintentionally. It requires the robot systems to have not only a passive and inherently safe design such as smooth surfaces but also an active safety-related control system such as sensitive force monitoring functions that can dissipate collision forces and that do not violate determined force limits.

2.3 The principles of HRI control

For all these different applications and levels, highly efficient HRI must be achieved, and this must be considered into 3 main factors [23]: safety, stability, and compliance, which have details as follows:

1. Safety

Safety is very crucial and necessary during the collaboration between the robot and human in the same area or workspace. This is because the human's closeness to the robot could make possible injuries. Thus, a system depending on collision avoidance or detection must be developed and embedded into robot control.

2. Stability

The most important task for the control of interaction among human, robot and environment is to ensure the stability of the system despite uncertainties and inaccuracies since an unstable control of the robot interaction can cause damages of the workpiece or – even worse – injury of the operator. Hence the principles for stable and robust control design of the contact interaction between robot and its environment are conservative, which means safety oriented.

3. Compliance

Many robotics applications and varieties of tasks lead to the necessity for developing variable parameter controllers for accomplishing the robotic task. The controllers should be adjusted depending on the human collaborator's intention as well as the changes of environment (e.g., the payload of the robot). Therefore, friendly robots with humans are performed.

Therefore, advanced controllers are the core of the research in HRI to satisfy these, which lead to the tasks executed efficiently, easily and robustly. Robotic manipulation control of objects should include several aspects: studies of the end-effector (gripper or multi-fingered hand), studies of the sensing type (force, position) and of the measurement approach (force sensor, model-based measurement, vision-based measurement), and studies of the control.

Robotic control of HRI for object manipulation involves many issues such as object non-linearity and lack of object behavior knowledge. Unlike manipulation of rigid object which can be considered as a continuity of the robot end-effector, robotic manipulation of dynamic object can be seen as an under-actuated system because the object deformation introduces additional degrees of freedom and variable parameters. The parameters of HRI controllers should be adjusted depending on human behavior or intention as well as the change of the environment. Several control strategies have been previously explored with different types of feedback for accomplishing robotic tasks. In this context, the research object of HRI concentrates on force control of the robot interacting with humans. The object is seen to nonlinear system and its parameters are variable relying on the human operator's input. For that, as the theory of robust control, a controller based on matrix analysis will be applied for achieving performance of uncertain disturbance.

2.4 The research of control method in HRI

The robot's interaction with human in industry could enhance effectiveness of working tasks. The study of HRI should contain several aspects: studies of the robotic languages communication with human, studies of robotic vision identifying human emotion and gesture, and studies of contact force with human. In this context, the contact force is the core of the research.

To achieve desired performance, impedance control is a unique control scheme that is employed to achieve desirable dynamic interaction between human and robots [24]. There have been significant interests and efforts in the field of impedance control on robotic manipulation over last decades. The impedance is usually relative to the relationship between the motion variables of human and the contact force. The challenge in this field is the variation caused by uncertainty and non-linearity of humans. Several control strategies have been previously explored with impedance control. The major advanced control strategies include force-tracking impedance control, hybrid impedance control, robust impedance control, adaptive impedance control and learning impedance control. To achieve desired performance, in some cases, several techniques are integrated together in a controller.

The impedance control has three special features compared with other regular robotic control strategies, just like position control, force control, and hybrid position/force control. One is that the core idea of impedance control is to control the dynamic interaction between motion and contact force instead of controlling these variables independently. The another one is that impedance control can be utilized in all human manipulation phases consisting of free motion, constrained motion, and the transient process between them, without the need of switch different modes. The last one is that impedance control has the performance of controlling motions and contact forces simultaneously by designing a proper interaction between human and robot.

2.4.1 Research of Hybrid Compliance Control (Impedance/Admittance)

Compliance control (impedance or admittance) is essential for tasks involving dynamic interaction of the robot with the environment with contact forces. Pure compliance control has no sufficient performance during the interaction since small variable input and disturbance may generate large contact force, which may impair the

environment and the manipulators. In addition, the compliance control has very low impedance in the force-controlled subspace; however, has extremely high impedance in the position-controlled subspace.

To deal with the problem, designing flexible and comprehensive controller in different subspace become an effective scheme to improve the adaptability of the pure compliance control. In early time, Anderson and Spong [25] proposed hybrid impedance control which combined impedance control and hybrid position/force control into one control scheme to satisfy different environment. As the technology development, more kinds of hybrid controllers are proposed to cope with more general and sophisticated robot application.

There are two primary compliance control: a passive mechanical compliance in which mechanical structure such as spring is attached to the manipulator, an active compliance implemented in the control servo loop that position and generated force of the manipulator are controlled according to the reaction force detected by the force sensor[26].The former is simple and powerful, but it is impossible to change the mechanical impedance arbitrary. The latter is possible that the desired impedance is selected arbitrary in the controller on the contrary.

(1) Compliance control with hybrid position and force

Considering the limitation of the passive control which is only suitable for pre-specified tasks, Teja et al. developed active compliance control algorithm module with hybrid position and force to take the tasks to achieve compliance motion including Position Path and Force Profile [26]. The active compliance algorithm had been programmed and tested by using a PUMA560® dynamic model in MATLAB®. The results showed the algorithm achieved accuracy and stability performance of position and force.

(2) Impedance control with velocity and force

Vincent Duchaine and Clement M. Gosselin proposed a novel online variable impedance control and a low-level velocity controller for human-robot cooperation

[27]. The time derivative of the applied force was used in virtual admittance control for inferring the human's intentions.

Lecours et al. developed a virtual admittance control in which both virtual damping and virtual inertia. Their controller was implemented for a four degree of freedom assistant device, considering the operator's force and measured velocity [28].

2.4.2 Research of force-tracking impedance control

As mentioned above, fundamental impedance control can realize desired performance, which means that the interaction force can be regulated well through selecting appropriate parameters of virtual trajectory and impedance parameters in the clear condition of stiffness and location of robot. But in uncertain practical environment, the trajectory is hard to determine previously. Thus, the inability to track a reference contact force in some conditions could damage to the control performance. Therefore, there are some approaches to strengthen the force-tracking ability of impedance control.

H. Seraji and R. Colbaugh proposed two simple force feedback schemes (Direct Adaptive Control Scheme and Indirect Adaptive Control Scheme) for automatically generating the reference position trajectory in order to provide force tracking capability under impedance control [29].

Seul et al. developed new simple stable force tracking impedance control scheme with the ability of tracking a specified desired force and compensating for uncertainties in environment location and stiffness robustly [30]. The robust force control law estimated a velocity profile of the environment during tracking unknown environment positions. In other words, it is very simple to minimize the force error directly.

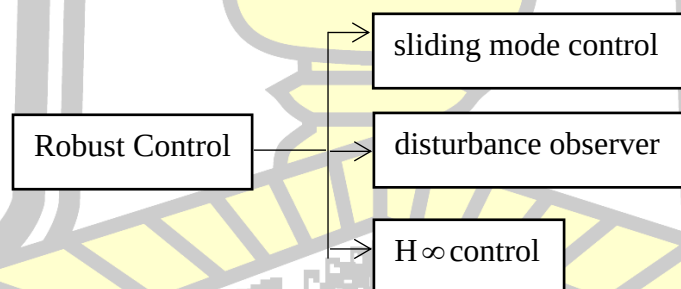
Based on force-tracking control laws, L. Roveda et al. implemented and tested the deformation tracking control of a soft unknown environment in a full rigid body assembly real task [31]. It is noted that the tasks presented involve full body spatial interactions with a time-varying environment stiffness.

Impedance controller has the limitation that not allow introducing the situation of not controlled force overshooting during the interaction, especially at the contact

transients. Therefore, L. Roveda et al. selected set-point deformation method with a two-layer (the internal control layer and the external layer) structure to overcome this by comparing with variable impedance adaptation method [32]. The internal control layer contains a pure impedance control with constant parameters. The external control layer contains an admittance controller providing the estimation of the interacting environment parameters calculated as solution of the Linear Quadratic Regulator (LQR) problem.

2.4.3 The research of robust impedance control

In real control situation, the uncertain elements such as parametric uncertainty, unknown environments, external disturbances, and so on damage the stability and performance of impedance control. The problem can be solved by combining robust control theory with fundamental impedance control. Robust control techniques provide an effective way to handle system parameter variations and unmodeled dynamics, common issues in power electronic systems. The types of robust control mainly including sliding mode control, disturbance observer, and H^∞ control as presented in Figure 11, have been applied into impedance control due to their superior performance and robustness properties.



Figures 11 The types of robust control

(1) Impedance control combining with sliding mode control

The sliding mode control, as a crucial nonlinear robust control method, is well known its robustness properties and used to deal with mode uncertainties and disturbances from internal or external environment. When the impedance system is in the sliding mode defined in the state space of the system, the region of the state space must be defined by equation. And the state trajectory is kept in or near the sliding

surface in the state space continually [33]. When the system reaches the arbitrary small region in the vicinity of the sliding surface, the impedance error will close to zero in the condition of uncertainties ultimately [34]. Then, the appropriate control law is switched or designed to make the system always toward onto the sliding surface, resulting in a reduced-order system insensitive to matched uncertainties and disturbances. Therefore, the original impedance control problem is converted into sliding mode control problem with robustness.

A. Ibeas and M.de la Sen proposed an impedance-type sliding mode controller for task space trajectory tracking. The sliding manifold defined by the tracking errors of the system contains an integral term which ensures the asymptotic converge of all the tracking errors to zero of the task space position, velocity and acceleration tracking errors [35]. Moreover, to reduce the amplitude of the high frequency oscillations of the systems output due to the uncertainty of system, a higher order supervision algorithm was present.

Calanca, A. et al. proposed a force control approach based on sliding-mode control (SMC), which ensures the stability and robustness of the coupled human-robot system and regards the human dynamics as interference element to reject. A chattering free solution that employs simple task models to obtain high performance, comparable to second order solutions, was developed. Theoretical stability was proven within the sliding mode framework, and predictability was reached by avoiding the reaching phase by design. In addition, safety was introduced through appropriate design of the sliding surface [36].

(2) Impedance control combining with disturbance observer

The disturbance observer estimates the total sum of disturbance torque imposed on the human manipulator. The disturbance torque is canceled out in joint space and the realization of the robust motion controller is expected. On the other hand, the estimated disturbance torque is utilized for reaction torque estimation and is resolved into two components. One is internal disturbance effect which is described by the motion equations of the manipulator. The other is external disturbance effect which corresponds to the reaction torque in force task. Therefore the external disturbance

torque is obtained by subtracting the calculated internal disturbance effect from the estimated disturbance.

Toshiyuki et al. proposed the force sensorless control to realize the compliance motion. The disturbance observer was utilized for the disturbance suppression and the reaction torque estimation imposed on the manipulator[37]. The compliance control was realized that the total disturbance torque had been estimated by the feedback of the estimated reaction force.

Yichen Zhong et al. [38] proposed a novel composite bilateral tele-operation controller combining adaptive impedance control with nonlinear disturbance observer-based sliding mode controller. The adaptive impedance controller is constructed to achieve high-precision tracking of desired contact forces and ensure the safety of grasping various flexible targets. The designed controller was to accurately estimate the composite disturbance signals as well as to ensure the stability and the high accuracy of the trajectory tracking and proved by the Lyapunov function.

(3) Impedance control combining with H_∞ control

H_∞ (H-infinity) control is a robust control method used to design controllers to achieve robust performance and stability. The main goal of the H-infinity control method is to minimize the maximum gain of the transfer function of the system from the disturbance input to the output error, from infinity to negative infinity, hence the name H-infinity. This makes the system less sensitive to uncertainties and improves performance over a wide frequency range by solving a set of nonlinear matrix inequalities.

Mourad Benoussaad and Micky Rakotondrabe proposed a feed-forward controller which is based on H_∞ technique to compensate the nonlinearity of module of 1-dof interaction between human and robot. It added robustness against uncertainty and satisfied desired performance [39].

D. Larby and F. Forni developed a approach which connecting impedance control to robust control, with the goal of shaping the robot performances via feedback [40]. The approach was based on linear matrix inequalities with sparsity constraints to derive

impedance controllers that satisfy a H_∞ performance criterion. The controller guaranteed passivity of the controlled robot and local performances near key poses.

J. C. Pérez-Ibarra et al.[41] designed and evaluated an H_∞ -based force controller that guarantees robust stability in the inner loop of the impedance control strategy to be applied on an SEA (series elastic actuator)-based ankle rehabilitation platform. In order to analyze the effect of the validate of the human impedance in the actuator dynamics, a model of the system that includes a second-order description of the human joint dynamics (including inertia, damping and stiffness) was formulated.

In the research,a force controller considering the human robot interaction as a source of disturbances and uncertain ties had been designed.If disturbances are limited, the controller performance is not affected. On the other hand, considering the human's activity as a source of uncertainties help to understand the changes in controller performance and system stability.

Dragoljub Surdilovic et al [42]. applied the robust control approach for the design of the haptic impedance control which was intended for the interaction of industrial robots with a passive or active environment. They utilized H_∞ norm to analyze the stability of impedance control system discretized by Tustin transform(bilinear transform).

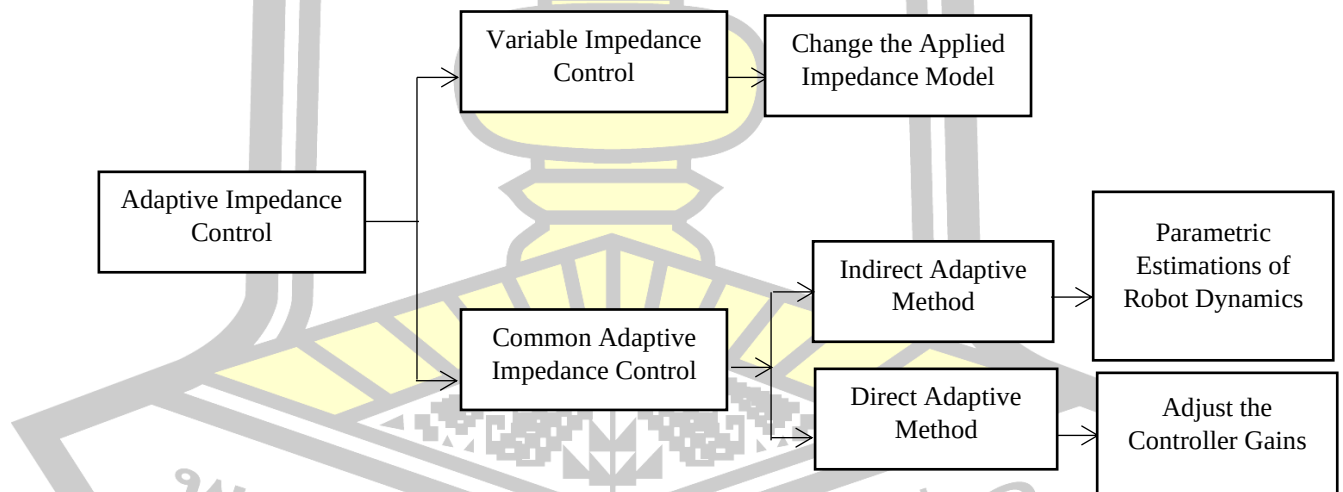
The experimental system consisted of a single linear axis with a direct-drive actuator consisting of a linear hybrid (variable reluctance) stepper motor with air bearings. The position and impedance control was implemented in SIMULINK and realized using Real Time Workshop (RTW) and real-time dSPACE rapid control prototyping system. During experiments, the operator pushed the actuator by hand in the virtual wall direction until the contact is achieved, pressing on the wall and pulling back. The hand force and simulated wall force were measured. The result showed that robust control design approach can ensure the human-robot interaction stability even when the environment varied.

Also, in fully automated assembly process the abilities of interacting with human workers and providing power assistance are very complex for robot controller, which is responsible for accurate and fast positioning of the robot.

(4) Impedance control combining with Adaptive control

To reduce the negative effect of model uncertainties and unknown environment on the control performance, adaptive control techniques have also been applied to the impedance controller. The main character compared with robust control is that utilizes online modulations to adapt to a controlled system with parameters which vary, or are initially uncertain.

The adaption of adaptive control is classified into different levels, namely the high level and the low level. On the high level, the parameters are adjusted online in different condition to satisfy special operators' requirement. It is named as variable impedance control. On the low level, the control law is also divided into two methods. One is called indirect adaptive method which is used to estimate dynamic parameters of robot. The other is called direct adaptive method which is to update the control gains. The classification of adaptive impedance control is shown in Figure 12.



Figures 12 The classification of adaptive impedance control

Variable Impedance Control: The variable impedance control is mainly applied in the field of human–robot cooperation. It is known that humans can change their body impedance easily to perform elaborate manipulation. This kind of ability is also required for the robot cooperating with humans. Therefore, different methods to vary the impedance of robot properly in different situations were proposed.

Rongrong Tang et al[43].proposed a variable impedance control algorithm with human-like characteristics for the application of rehabilitation robot. Compared with impedance control algorithm with constant parameters (IC) and another vIC algorithm, which is only modified tracking error (vIC-e), the character of the algorithm is that the damping value of the proposed method is varied with the target position as well as through the tracking error. The control algorithm shows the validation to improve the tracking accuracy and trajectory smoothness.

Common adaptive impedance control: The variable impedance control deals with how to adjust impedance in different situations. Differently, the common adaptive impedance control handles how to keep the chosen impedance or the controlled value stable in the presence of model uncertainties or unknown environments, including the indirect methods and the direct methods. Many adaptive control techniques used in position control are introduced into the impedance control frameworks.

Indirect methods: In the indirect methods, the estimations of uncertain parameters of robot dynamics are executed online. Then these estimated values are adopted in the design of adaptive laws or control laws. This method aims to reduce the parameter errors between the actual values and the estimated values to zero rather than control the response error directly, thus it is called “Indirect”. However, the parametric estimation needs a pre-known structure or form of the robot dynamic model. If there exist some un-modeled dynamic properties, the performance of this approach cannot be guaranteed.

Direct methods: To overcome this limitation, the direct method was proposed. Its adaptive law utilizes the tracking error directly to adjust the control gains. The primary target of this method is to make the tracking error vector converge to zero.

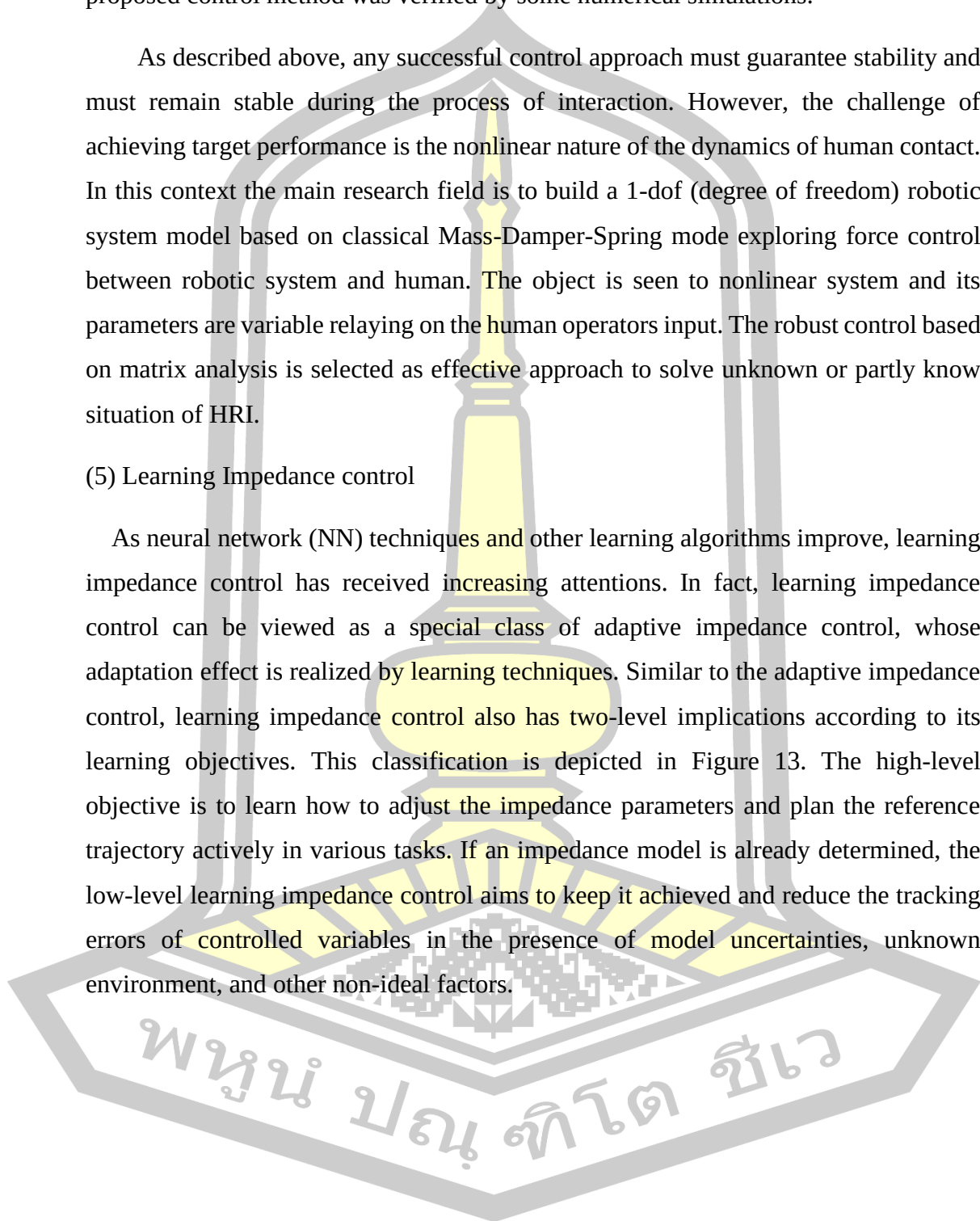
Liang X et al. proposed a time-varying impedance controller that didn't need to use acceleration-based feedback or measurement of the external loads, and the adaptive controller can tolerate considerable structure parameter errors[44]. By employing a Lyapunov-like stability analysis approach, the globally uniform stability of the time-varying closed-loop system was analyzed, and a simple controller parameters selection

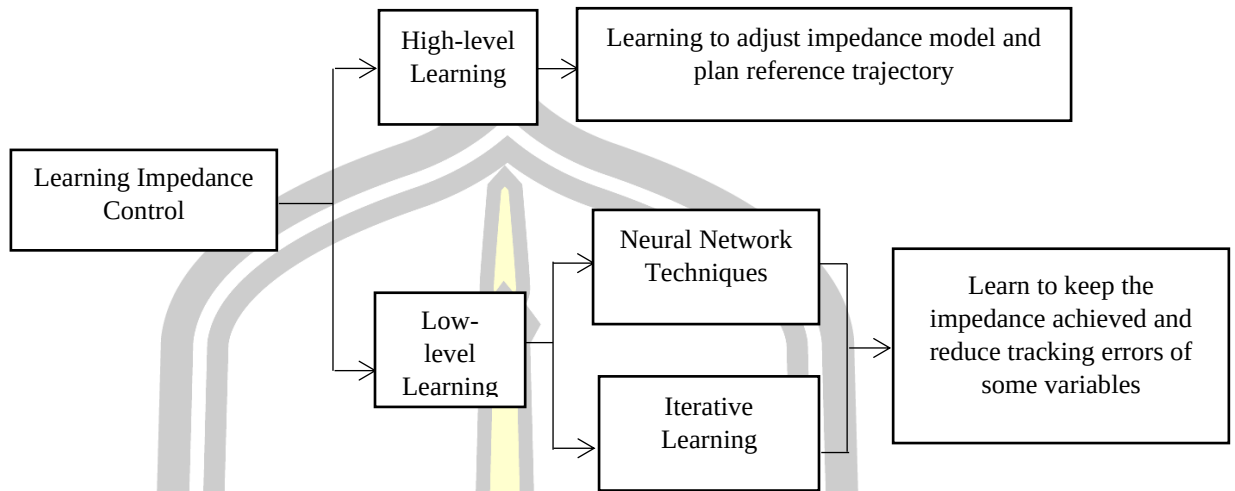
approach was presented. Through a planar 2R manipulator, the feasibility of the proposed control method was verified by some numerical simulations.

As described above, any successful control approach must guarantee stability and must remain stable during the process of interaction. However, the challenge of achieving target performance is the nonlinear nature of the dynamics of human contact. In this context the main research field is to build a 1-dof (degree of freedom) robotic system model based on classical Mass-Damper-Spring mode exploring force control between robotic system and human. The object is seen to nonlinear system and its parameters are variable relaying on the human operators input. The robust control based on matrix analysis is selected as effective approach to solve unknown or partly know situation of HRI.

(5) Learning Impedance control

As neural network (NN) techniques and other learning algorithms improve, learning impedance control has received increasing attentions. In fact, learning impedance control can be viewed as a special class of adaptive impedance control, whose adaptation effect is realized by learning techniques. Similar to the adaptive impedance control, learning impedance control also has two-level implications according to its learning objectives. This classification is depicted in Figure 13. The high-level objective is to learn how to adjust the impedance parameters and plan the reference trajectory actively in various tasks. If an impedance model is already determined, the low-level learning impedance control aims to keep it achieved and reduce the tracking errors of controlled variables in the presence of model uncertainties, unknown environment, and other non-ideal factors.





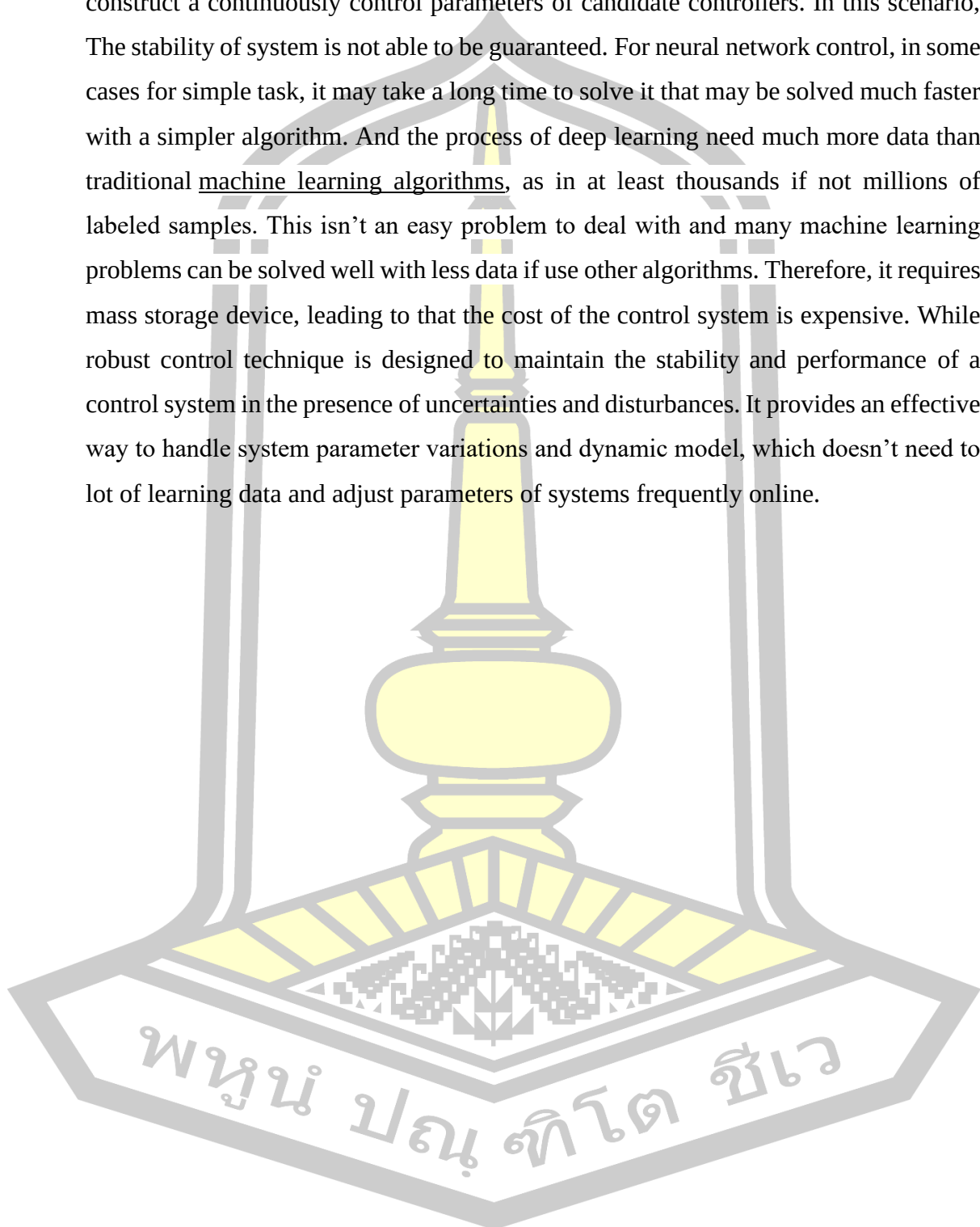
Figures 13 The classification of learning impedance control

2.5 Conclusions

In this chapter, the types of HRI in industry mainly include human motion prediction, haptic control, and Human–robot co-manipulation. There are 4 cooperative levels based on interactive strength between human and robot as FRI defined. Also, The principles of HRI have been demonstrated. The robot’s interaction with human contains several aspects. In this paper, the research aspect is physical contact force including the analysis of human input force or motion and robot response force to human. That is belonged to Level4(Power and Force Limiting) and used for haptic device. The impedance control is an effective control method for force contact which means that the human input force or motion to robot system to control the robot to output physical force to do tasks(handing or lifting components).Some control strategies for getting optimal results have been illustrated briefly.

In this paper, the technique of impedance control combined with robust control is employed in the research, by comparing with adaptive control, force-tracking impedance control, and neural network control. The force-tracking impedance control is an effective method to forecast the change of force in the next step though adding reference force from feedback loop. However, the controlled model and disturbance must be known for achieving desirable result. Adaptive control can be applied for solving uncertain conditions, adjusting control parameters online with the change of environment. But the scheme deeply rely on adjustment online. If the disturbance

cannot be predicted appropriately or the regular cannot be found, it is very difficult to construct a continuously control parameters of candidate controllers. In this scenario, The stability of system is not able to be guaranteed. For neural network control, in some cases for simple task, it may take a long time to solve it that may be solved much faster with a simpler algorithm. And the process of deep learning need much more data than traditional machine learning algorithms, as in at least thousands if not millions of labeled samples. This isn't an easy problem to deal with and many machine learning problems can be solved well with less data if use other algorithms. Therefore, it requires mass storage device, leading to that the cost of the control system is expensive. While robust control technique is designed to maintain the stability and performance of a control system in the presence of uncertainties and disturbances. It provides an effective way to handle system parameter variations and dynamic model, which doesn't need to lot of learning data and adjust parameters of systems frequently online.



CHAPTER 3

RESEARCH METHODOLOGY

In practically, the industrial environment is uncertain and variable. The passivity impedance control has some limitations. In this chapter, to overcome the disadvantages and limitations of a conservative passivity impedance interaction control, either the requirement of passivity must be relaxed or knowledge about the characteristics of the environment has to be considered in the design. In this research, the designed strategy based on simplified target impedance/environment interaction model is introduced.

3.1. Preliminaries

3.1.1. Robot-Object Interaction

As Newton's third law of motion, ignoring mechanical energy loss, the absolute value of output force which the robot exerts on the external object is equal to the reacting force while the force directions are opposite each other. In some situations that the robot fingers try to connect stiff object such as steel, the interaction forces are only determined by robot output force, which means that absolute value of output force and reaction force are equal. However, in other situation, the interaction forces are determined by the object reacting force when the robot fingers connect with soft or deformable object such as foam and sponge. The opposite force are not equal to the output force because of loss of energy. In this study, the reacting force is measured as the object character of stiffness constant and transferred as feedback to the system.

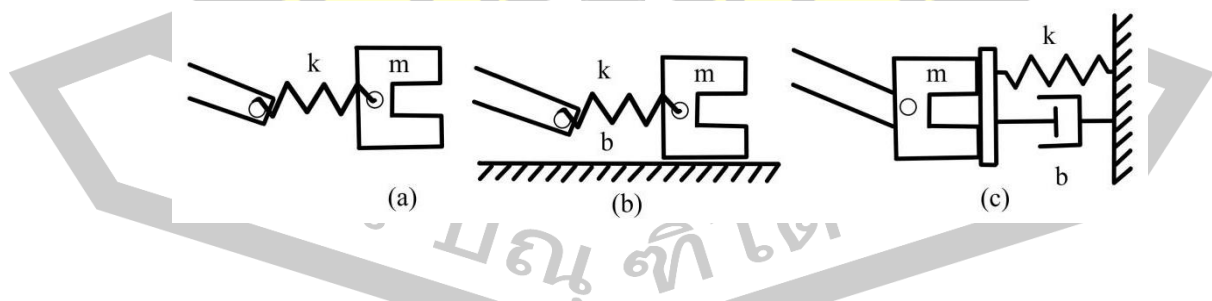
3.1.2. Human-Robot Interaction

The robot and human are in impedance causality during human-robot interaction of the system. As impedance control that velocity input converts force output, the human motion input such as push or pull the robot's end-effector can be transferred into robot force torque input. However, the react force from robot exerts on human motion with the effect of facilitation or restriction is defined as admittance control during the interaction. The character of human-robot interaction is feedback interconnection containing impedance and admittance control[45]. In this paper, the type of human-robot interaction is human-robot teleoperation, which means that human manipulates the robot to execute some actions via haptic device. The actions include touching,

catching, and releasing objects. For improving the control performance that the manipulator receives the feelings of the stiffness of object and adjusts input motion, these forces such as grasping force should be provided to human as feedback during teleoperation[46][47].

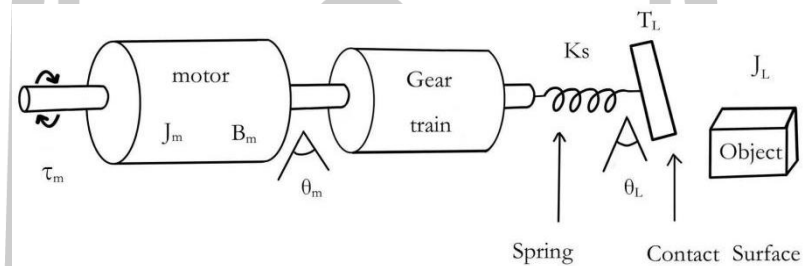
3.1.3.Simplified SEA model

In this paper, the robot-object interaction model is simplified as the parameters of dashpot b during interaction, spring k of the end of robot hand, and the mass m of object without considering characterization in practice. There are three types of environment[48],as shown in Figure 14. In Figure 14(a),it is a mass-spring system with the character of the end of a spring acting upon on an object. Its impedance Z_e is $mks/(ms + k)$ with the application of inertial system. In Figure 14(b),it is a mass-spring system that a compliant mass sliding across non-smooth surface. Considering the friction between mass and surface, its impedance Z_e is $b + mks/(ms + k)$ with the application of resistive system. In Figure 14(c), it is a mass-spring-damper system, consisting of a complaint surface with damper element, a spring, and a capacity with altering energy during connection. Its impedance Z_e is $ms + b + k/s$ with the application of capacitive system. In this paper, the approximate robot-object interaction is modulated as the inertial model to produce force vertically to object surface by detecting motor angle movement and the damper caused of surface friction is eliminated.



Figures 14 Types of interaction component:
(a)Inertial;(b)Resistive;(c)Capacitive

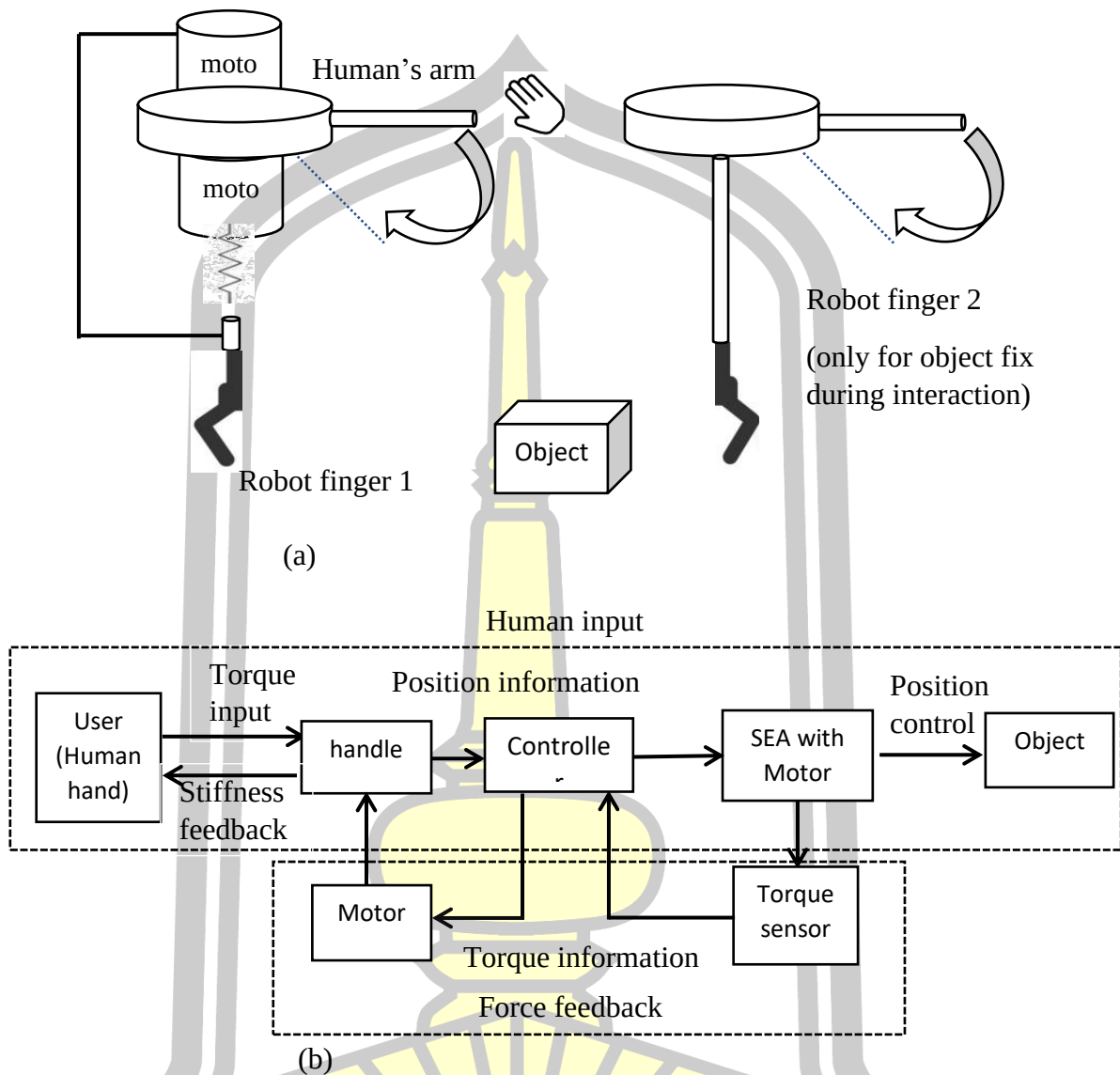
The SEA, acting as critical joint in human-robot interaction, consists of a electric motor, a gear train, and a spring attached to object load[49]. Spring, in generally, was regarded as a sophisticated component with non-linear, time variation during interaction because of its helical structure. However, the component can be simplified as linear time invariant(LTI) model for low-frequency dynamic interaction such as only just take simple motion to the end effect of robot. To reflect the character of the LTI model, classical mass-spring-damper system will be utilized with the parameters of linear spring k , damper b_f , and mass m . The approximation mode of SEA is quantified as passive system that does not produce energy by itself while dissipating energy to external object[50].



Figures 15 Schematic of SEA

3.2. System Modeling

A control theme is shown in Fig 16, if the robot handle is pushed or pulled by human arm in horizontal plane, it will just like the spring system in interaction. However, if the human rotates the handles with his arms to catch object, the human simple motion will be converted into minimal contact torque. The torque exerted on the external object through mechanical hands. The system contains two 1-dof(one degree of freedom) hands to work for grasping or pushing behavior.



Figures 16 Control system of teleoperated.
 (a)Schematic of system,(b)The block of control system

3.2.1. The cable-driven series elastic actuator(SEA) scheme

The SEA system is depicted in Figure 16. The spring is connected with gear train and the contact surface, creating softness and low impedance torque output. The motor is linked to the gear train, generating angular velocity to the gear. The gear is utilized to magnify or reduce the velocity generated by an electric motor. Then the adjusted velocity is transmitted into the spring through gear, causing the torsion spring generating torque and applying on the finger. With the torque driving, one of the contact surface,

acted as finger1,can rotate and touch the object. While the other contact surface, acted as finger 15 ,only is response for fixing the object during interaction. More over,the reflect torque acting on external object affects on the angle deflection of spring. In this structure, spring has the abilities of absorbing torque shock cause by various reflecting torque of object.

3.2.2.The mode of SEA

In this paper, the robot-object interaction torque can be calculated by spring deformation as feedback in close loop system, the motor is regarded as a velocity source[51], the equation associated with motor can be written as:

$$\theta_s = \frac{\omega_m}{s} - \theta_L \quad (1)$$

Considering the object has initial properties J_L in practical. The interaction position of the object and robotic finger θ_L is affected by J_L and output torque acting on object T_L ,written as[51]:

$$\theta_L = T_L \frac{1}{J_L s^2} \quad (2)$$

The reflect torque from external object T_L is proportion to spring displacement by Hook's Law.

$$T_L = K_s \theta_s \quad (3)$$

The transfer function from motor velocity source to SEA output torque by combining above three transfer functions is derived as below:

$$\frac{T_L}{\omega_m} = \frac{K_s s}{s^2 + \frac{K_s}{J_L}} \quad (4)$$

Where ω_m presents as angular velocity of motor, θ_s denote as spring displacement. K_s presents spring constant.

In Figure 15, the equation of motion for the motor is ruled as:

$$\tau_m = J_m \ddot{\theta}_m + B_m \dot{\theta}_m + K_s \theta_m \quad (5)$$

In the second order equation, where τ_m is represented as input torque applied to motor, θ_m is the output motor angle, J_m is represented as the motor inertia, B_m is represented the motor damp. Taking into the Laplace transform, the motor transfer function between input torque and output motor angle is:

$$\frac{\theta_m(s)}{\tau_m(s)} = \frac{1}{J_m s^2 + B_m s + K_s} \quad (6)$$

3.2 An Optimal Control based on Robust Control Method

As discussed in chapter1, it is well understood that uncertainties are unavoidable in a real impedance control system. Robustness is of crucial importance in control-system design. In general, the designed system is required to be stable. If it is not able to satisfy the performance of resisting disturbance signals, noise interference, unknown model, dynamic variations of parameters, the best design to realize that is to introduce feedback control mechanism, even if it could lead the issues of high cost (using more sensors) and system complexity.

Over last decades, robust control has been brought into limelight. In classical single-input and single-output (SISO) system, achieving the desirable performance depends on ensuring gain and phase margin. When multiple singles-input and multiple singles-output (MIMO) system control techniques had been developed in the 1960s, the emphasis was placed on achieving good performance, not robustness. The techniques based on linear quadratic performance criteria and Gaussian disturbances were successful to be applied in industry and aerospace exploring. The techniques have the advantages that accurate mathematical models can be obtained, and descriptions for external disturbances or noise based on white noise are considered appropriate. However, application of such methods, commonly referred to as the linear quadratic Gaussian (LQG) methods, in other industrial control problems. LQG controllers' exposure apparent poor robustness properties. It is essential to develop a theory that

explicitly address the robustness issue in feedback design. The pioneering work in the development of the forthcoming theory, now known as the H_∞ optimal control theory, was introduced by George Zames et.al[52]. The theory is not only suitable for linear system, but also for the extension into nonlinear system.

H_∞ (i.e. "**H-infinity**") approach is used in control theory to synthesize controllers to achieve stabilization with guaranteed performance. The approach is most suited to the problem of system model uncertainty, such as an additive perturbation or output disturbance, finding constrained mathematical optimization to solve problem. The advantage of H_∞ techniques compared with classical control techniques is that H_∞ are able to be applied to complex problems involving multivariate systems with cross-coupling between channels. The disadvantage of H_∞ is that the level of mathematical understanding is necessary to apply them successfully. It is noted that the control result is only optimal with prescribed cost function and doesn't mean that it represents the best solution for usual controller. Also, non-linear constraints such as saturation are generally not well-handled. In most cases, it would be sufficient to seek a feasible controller to achieve robust stability. The system can be described as elegant solution formulation, solve by algebraic Riccati equations.

The phrase H_∞ control comes from the name of the mathematical space over which the optimization takes place: H_∞ is the Hardy space of matrix-valued functions that are analytic and bounded in the open right-half of the complex plane defined by $\text{Re}(s) > 0$; the H_∞ norm is the supremum singular value of the matrix over that space. In the case of a scalar-valued function, the elements of the Hardy space that extend continuously to the boundary and are continuous at infinity is the disk algebra. For a matrix-valued function, the norm can be interpreted as a maximum gain in any direction and at any frequency; for SISO system, this is effectively the maximum magnitude of the frequency response.

H_∞ control technique can be used minimize the closed loop impact of a perturbation: depending on the problem formulation, the impact will either be measured in terms of stabilization or performance. However, simultaneously optimizing robust performance and robust stabilization is difficult. One method that comes close to achieving this is H_∞ loop-shaping, which allows the control designer to apply classical

loop-shaping concepts to the multivariable frequency response to realize ideal robust performance, and then optimizes the response near the system bandwidth to achieve ideal robust stabilization.

3.3 Research tools and equipment

At present, there are some Mathematics software for scientific research, such as *GeoGebra*, *Maxima*, *MathJax*, *Mathematica*, and *Matlab*. In this paper, *Matlab* software has been selected due to its mature tool module to solve robust control problem.

3.3.1 Using Matlab Software for Simulation

MATLAB is a programming and numeric computing platform used by millions of engineers and scientists to analyze data, develop algorithms, and create models. It combines a desktop environment tuned for iterative analysis and design processes with a programming language that expresses matrix and array mathematics directly. The software includes the Live Editor for creating scripts that combine code, output, and formatted text in an executable notebook, the optional toolbox that uses the MuPAD symbolic engine allowing access to symbolic computing abilities, and an additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamic and embedded systems.

Despite the mature theory and availability of the software packages, in this paper, Matlab software will be used in solving industrial HRI impedance control-systems design problems with H_∞ control technique and related methods. The Matlab software has the ability of translating industrial design with the complex mathematics of the advanced approaches and numerous presentations of formulas into relevant configurations.

In this context, elegant solution formulas of interaction between human and robot based on mass-spring-damper system have been developed, which are based on the solutions of certain algebraic Riccati equations and are readily available in software packages of Matlab. In the next work, the programming M-file with several basic commands from the Robust Control Toolbox can be used to compute the matrix about robust impedance control model and to save it in the Matlab.

3.3.2 Using Originlab Software for Analysis

Originlab is a proprietary computer program for interactive scientific graphing and data analysis. It is produced by OriginLab Corporation, and runs on Microsoft Windows. It has inspired several platform-independent open-source clones and alternatives like LabPlot and SciDAVis.

Data analysis in Originlab include statistics, signal processing, curve fitting and peak analysis. Origin's curve fitting is performed by a nonlinear least squares fitter which is based on the Levenberg-Marquardt algorithm.

Origin imports data files in various formats such as ASCII text, Excel, NI TDM, DIADem, NetCDF, SPC, etc. It also exports the graph to various image file formats such as JPEG, GIF, EPS, TIFF, etc. There is also a built-in query tool for accessing database data via ADO(ActiveX Data Objects).

In this context, the calculating parameters are adjusted and described as curves by using Originlab software. For deeper analysis, the results simulated from Matlab are converted into other formats, such as derived, integral, and linear operation.

3.4 Research Analysis

3.4.1. Disturbance Analysis

A mathematical model of any real system always just partly or almost comes close to the true of reality in practically. It is impossible that all the characters of real system is reflected by the constructing model completely. Uncertainties are unavoidable to exist in a real control system. In HRI control system, the uncertainty can be classified into two categories, one is disturbance signals, including input and output disturbance, sensor noise and actuator noise, etc. the other is dynamic perturbations, representing the discrepancy between the mathematical model and the actual dynamics of the system in interaction. Typical sources of the discrepancy contain unmodelled (usually related to high-frequency) dynamics, neglected non-linear in the modelling, effects of deliberate reduced-order models, and system-parameter variations due to environmental changes and system ageing factors. These modeling error may impair stability of a control system.

In this paper, the work is to explore uncertain elements and evaluate how the uncertainty effect to system performance in detail. Then searching appropriate approach to compensate the error is the important task in subsequent chapters.

3.4.2 Comparison with Different Control Strategies

(1) PID control

A proportional-integral-derivative controller (PID controller or three-term controller) is a control loop mechanism employing feedback that is widely used in industrial control systems and a variety of other applications requiring continuously modulated control. A PID controller continuously calculates an error value as the difference between a desired set-point (SP) and a measured process variable (PV) and applies a correction based on proportional, integral, and derivative terms (denoted PID respectively). The performance of error tracking and stabilization will be evaluated in the sequence work.

(2) H_∞ loop-shaping

The H_∞ loop shaping design procedure (LSDP) proposed by MaFarlane and Glover is one of many H_∞ optimization design methods. The H_∞ LSDP method could relax the restrictions on the number of right-half plane poles and produces no pole-zero cancellations between the nominal model and controller designed. This method does not require an iterative procedure to obtain an optimal solution and thus raises the computational efficiency. Furthermore, the H_∞ loop shaping design procedure inherits classical loop shaping design ideas so that maybe it is more convenience to use in practicing HRI control. In subsequent work, the H_∞ loop shaping design will be used in HRI for analysis stability, transient response to reference input, and transient response to disturbance input.

(3) μ -Analysis control

μ -analysis is now considered as a classical and close to mature robustness analysis technique, which has proved to be useful in many applications. It is a standard approach to robustness analysis, typically used to identify worst-case configurations and to compute guaranteed robustness margins. In this context, a robust performance design

specification for a control system with unstructured/structured perturbations will be transformed into a robust stabilization problem with regard to structured perturbation. Then these design specifications are related to some indications of this new setting, followed by introduction of μ -synthesis method.

3.5 Conclusion

In this chapter, the system mode based on mass-spring-damper is introduced for analysis of force contact between human and robot, converting matrix with unknown parameters. the H_∞ loop-shaping technique has been applied in impedance model for compensating uncertainty and nonlinear. To show the performance effectively, other techniques have been researched in the same condition as comparison. The comparison of the designed system with PID, H_∞ , H_∞ loop-shaping and μ -controllers may be related to the frequency responses of these controllers. These responses are produced by using the file `kf_mds.m` of Matlab software.

In the work, the model will be build and the discrete transfer function between human force and the actuating motion of robot will be deduced consequently. To test the performance, the analysis of force control response and impedance control are necessary. In force control, the frequency response of transfer functions with different situation such as human active : the contact part of robot is attached to human while the human is yielding force, and human passive : the contact part is attached to human while the human is completely not yielding force, will be simulated as the curves of bode. The bode curves contain magnitude-frequency curves and phase-frequency curves. Also, in time domain the analysis of temporal response of the system is to evaluate the performance of stability. To verify the robot system tracking performance, a step signal is planed be applied into the system for analysis of step response. The parameters conclude setting time, overshoot, and static error.

In impedance control, the frequency response of the impedance controller with different stiffness is implemented to be simulated for finding the performance verified caused by the parameter of robot system stiffness. And in the analysis of time domain, the effect of applied disturbance caused by human dynamics will be also considered.

CHAPTER 4

FINDINGS

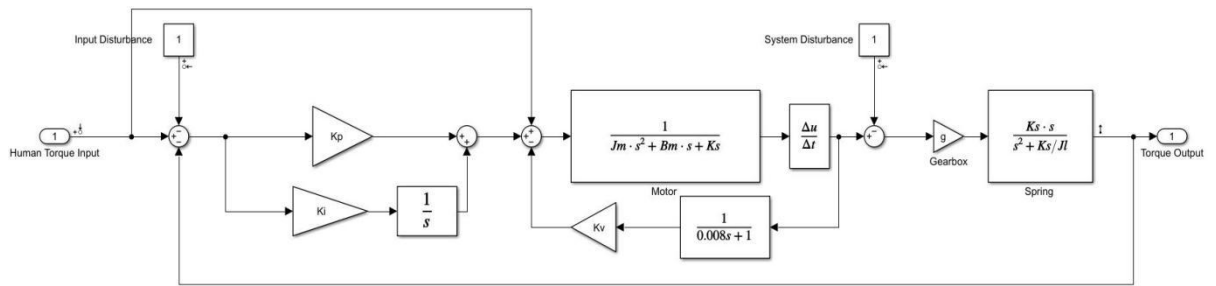
In practically, the industrial environment is uncertain and variable. The passivity impedance control has some limitations. In this chapter, to overcome the disadvantages and limitations of a conservative passivity impedance interaction control, either the requirement of passivity must be relaxed or knowledge about the characteristics of the environment has to be considered in the design. In this research, the designed strategy based on simplified target impedance/environment interaction model is introduced.

4.1 Introduction of the System Model

4.1.1 PI control strategy

As seen in Fig. 17, the system has two layers control loop: inner velocity control loop and outer torque feedback loop. The inner loop means that the motor has velocity feedback to deal with low frequency torque disturbance[51]. The velocity source contains motor model, derivation function converting motor output angle into velocity, and motor PI controller in feedback loop. The external loop can be seen as torque source and has torque feedback to PI controller for correcting errors caused by gear friction, external disturbance and dynamics. The PI controller is to make output torque follow desired torque input. The feedback torque is from the spring angle displacement. Also, the additional feedforward in this control is used to compensate action taken in response to measurement of a disturbance to regulate output torque equaling to desired torque. It is noted that the two layers control loop are not independent each other, which means that the output torque from motor is affected by human desired input torque and the system feedback force torque also affects the motor torque output. In the system, input disturbance d when human operates the handle, and sensor noise n are also considered.

In the system, input disturbance d when human operates the handle, and sensor noise n are also considered.



Figures 17 Block Diagram of Torque Control with PI controller

The close loop transfer function with PI controller is presented as below:

$$\frac{T_l(s)}{T_d(s)} = \left(1 + \frac{1}{G_{pi}(s)}\right) \frac{G_{pi}(s)G_1(s)G_2(s)}{1 + G_{pi}(s)G_1(s)G_2(s)} \quad (7)$$

Where:

$$G_1(s) = \frac{\omega_m(s)}{T_\Delta(s)} = \frac{0.008s + 1}{0.008J_ms^4 + (J_m + 0.008B_m)s^3 + (B_m + 0.008K_s)s^2 + K_s s + K_v}$$

$$G_2(s) = \frac{T_l(s)}{\omega_m(s)} = \frac{K_g K_s s}{s^2 + \frac{K_s}{J_L}}$$

$$G_{pi}(s) = K_p + \frac{K_i}{s}$$

4.2 H^∞ control strategy

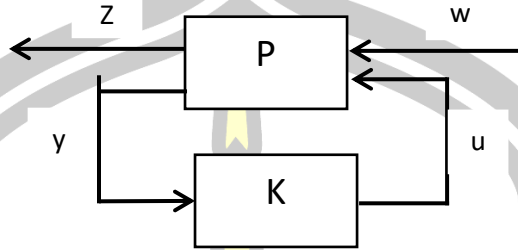
By known transfer function, the state space of system can be written as below:

$$\begin{cases} \dot{x} = Ax + B_1\omega + B_2u \\ z = C_1x + D_{11}\omega + D_{12}u \\ y = C_2x + D_{21}\omega + D_{22}u \end{cases} \quad (8)$$

Where $x(t)$ is the state, $u(t)$ is the control input, $y(t)$ is the measured output. $w(t)$ is the disturbance from inner system and external input.

H^∞ is to deal with uncertainty of system model. The block P presents controlled plant and the block K is represented as plant and controller respectively. In Fig.18, w and u denote external input, internal input respectively. z and y denote measured output

and regulated output respectively. By designing the feedback controller K to adjust the system characteristics, the system can meet the specified performance criteria.



Figures 18 The diagram of SEA H^∞ control system

The input-output relationship of the above augmented plant model can be expressed as:

$$\begin{bmatrix} z \\ y \end{bmatrix} = P \begin{bmatrix} w \\ u \end{bmatrix} \quad (9)$$

$$u = Ky \quad (10)$$

The matrix of plant P is decomposed into 4 blocks, corresponding to the dimensions of the input signals w, u .

$$P(s) = \begin{bmatrix} A & \vdots & B_1 & B_2 \\ \cdots & \cdots & \cdots & \cdots \\ C_1 & \vdots & D_{11} & D_{12} \\ C_2 & \vdots & D_{21} & D_{22} \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} z \\ y \end{bmatrix} = G(s) \begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix} \quad (12)$$

The relationship between w and z is presented as:

$$z = [P_{11} + P_{12}K(I - P_{22}K)^{-1}P_{21}]w \quad (13)$$

The transfer function from w to z is expressed as:

$$T_{zw}(s) = P_{11} + P_{12}K(I - P_{22}K)^{-1}P_{21} \quad (14)$$

The controller $K(s)$ must satisfied that the closed-loop system is internally stable, meaning that all eigenvalues of the closed-loop state matrix lie in the open left-half complex plane. Also, the goal of controller designing is to guarantee that the transfer function $\|T_{zw}(s)\|_{\infty}$ norm is bounded by a level of attenuation γ . In optimal control theory, the parameter γ that presents the system robustness should be minimal, closing to zero at best. However, it means that the gain of system will be large. In practical design, the constraint is often relax, and sub-optimal design is considered instead. In this paper, the linear matrix inequality(LMI) was used as a solution to solve H_{∞} problem for reduced order plant P by finding realization matrix K, which satisfying system inner stability and the H_{∞} norm of $\|T_{zw}(s)\|_{\infty}$ (from w to z) is less γ . Comparing with that Riccati equation solution rely on the system parameters tuning and the parameter γ can not be optimized, which leading to the conservative result and unguaranteed convergence, LMI can overcome these drawbacks.

The LMI approach has two characters, one is that via the bounded Real Lemma, H_{∞} -like constrains can be converted into algebraic Riccati inequalities (ARI)[53]. The other is that the solvability of the LMI just depends on the controlled plant P data and matrix variables R and S. The symmetric matrix R and S must satisfy the following condition:

$$\begin{pmatrix} N_1 & \vdots & 0 \\ \dots & \vdots & \dots \\ 0 & \vdots & I \end{pmatrix}^T \begin{pmatrix} AR + RA^T & RC_1^T & \vdots & B_1 \\ C_1 B & -\gamma I & \vdots & D_{11} \\ \dots & \dots & \ddots & \dots \\ B_1^T & D_{11}^T & \vdots & -\gamma I \end{pmatrix} \begin{pmatrix} N_1 & \vdots & 0 \\ \dots & \vdots & \dots \\ 0 & \vdots & I \end{pmatrix} < 0 \quad (15)$$

$$\begin{pmatrix} N_2 & \vdots & 0 \\ \dots & \vdots & \dots \\ 0 & \vdots & I \end{pmatrix}^T \begin{pmatrix} A^T S + SA & SB_1 & \vdots & C_1^T \\ B_1^T S & -\gamma I & \vdots & D_{11}^T \\ \dots & \dots & \ddots & \dots \\ C_1 & D_{11} & \vdots & -\gamma I \end{pmatrix} \begin{pmatrix} N_2 & \vdots & 0 \\ \dots & \vdots & \dots \\ 0 & \vdots & I \end{pmatrix} < 0 \quad (16)$$

$$\begin{pmatrix} R & I \\ I & S \end{pmatrix} \geq 0 \quad (17)$$

Where N_1 and N_2 represent bases of null space of (B_2^T, D_{12}^T) and (C_2, D_{21}) , respectively and are orthonormal[54]. It is noticeable that the subscription of 1 and 2 just means N_1 and N_2 are distinguish with the above LMI. In this paper, The K can be derived though augmented plant P and computed through hinflmi function in Matlab/SIMULINK.

4.3. Simulation and Discussion

In order to analyze the system performance of stability, response time and motion tracking accuracy, the simulations have been conducted by using Matlab toolbox. As Section 3 mentioned, the torque control performances of catching or releasing object depend on the spring constant of SEA[55]. Such as when the spring is fully compressed, the operation control just likes fully rigid control without SEA.

The appropriate spring torque within maximum compression is necessary to be considered. Also, in the experiment, the gear transmission mechanism is simplified that the gear ratio is just set 1 for simplifying module. Based on the module[56], the physical parameters of rotary series elastic actuator are set as : $J_m = 0.01 \text{ kgm}^2$, $B_m = 0.21 \text{ Nm}/(\text{rad}/\text{s})$, $K_s = 2.51 \text{ Nm}/\text{rad}$, $K_v = 1.2$, and $g = 1$. The object load inertial properties are assumed that from $J_L = 0.1 \text{ kg}/\text{m}^2$ to $1 \text{ kg}/\text{m}^2$.

4.3.1. Design of Experiment

Step response experiment

The output torque affected by step shaped torque input was used to assess how quickly and effectively the designed controller can reach torque reference in parameters including response time, setting time, ringing, and overshoot. To evaluate responsiveness of the SEA system in time domain, in this paper, the step signal is imitated as the simplified sudden change input torque during the teleoperation. The response time is defined as the rise time of output torque rising from 10% to 90% of the reference. The setting time is defined as the output reaches or remains the tolerance

band with the error 2%~5% around the final value. The overshoot is defined as the peak value during the response time.

Impulsive response experiment

Ideally, the system performance is only related to the structure design and controller design. However, there are various kinds of disturbance acting on the system to hinder the performance of accuracy position actually. The random impulsive input disturbance with the characters of sudden occurring, brief change at limit points, and high-magnitude but attenuating in geometric progression, are derived from external unexpected shocks, causing system structure vibration[57]. In this paper, the impulsive signal, deviation of the step single, is utilized for imitating the input disturbance which comes from environment to verify the system robustness.

Frequency response experiment

Frequency response is quantitative measure of output from sine input in frequency domain. In the experiment, the system frequency responses were depicted in bode diagram, visualizing the output change of the system's magnitude(gain) and phase shift with varying frequency. To analyze the characteristics of stability of the SEA system with different control themes, the close loop frequency response that from human torque input to output torque was tested. The parameters include peak magnitude, corresponded peak frequency, and bandwidth frequency where the system gain is -3dB, which means that the larger bandwidth frequency, the shorter rising time in time domain.

Human motion tracking experiment

In this paper, a sinusoidal signal was applied to emulate human motion trajectory sample during interaction, aiming at evaluating position tracking performance of series elastic actuator using different controllers. The dynamic performances of system, including trajectory tracking error and oscillation, are shown in the response. The lower trajectory tracking error indicates higher control accuracy. The more regular oscillation with the same frequency and same amplitude as the input sinusoidal signal means better following performance of the system. In the experiment,

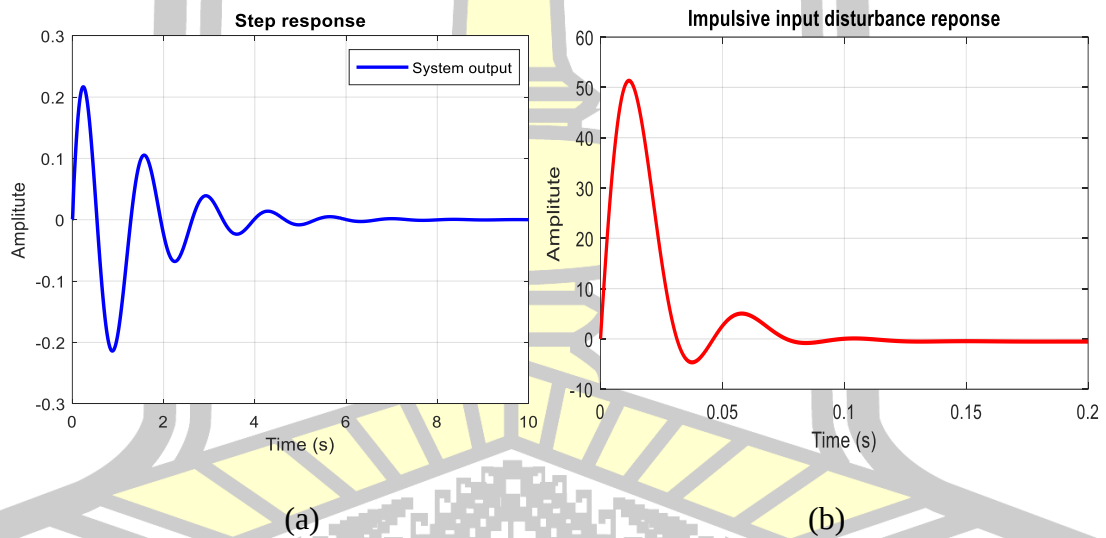
the system without controller, the system with PI control, and system with H_∞ controller based on LMI were excited by, a sinusoidal signal with amplitude 1, studying the result response by varying frequency from 1Hz to 4Hz.

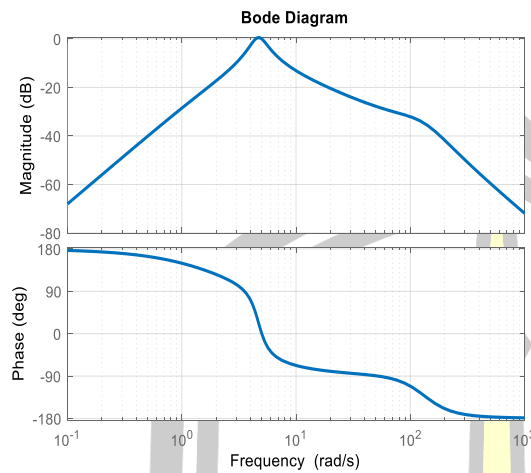
4.3.2. The experiment with System without torque controller

The obtained approximation of open-loop transfer function of SEA system is given by as the fifth orders polynomial:

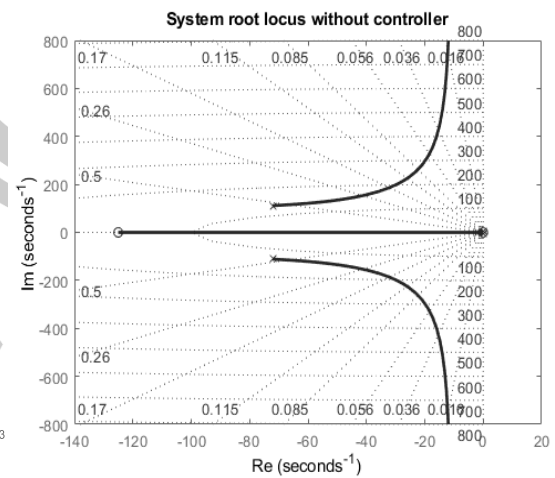
$$\frac{T_l(s)}{T_d(s)} = \frac{0.02008s^3 + 2.51s^2}{0.00008s^5 + 0.01168s^4 + 1.432s^3 + 2.803s^2 + 35.9s + 63} \quad (18)$$

The system control performance only rely on the inner motor velocity loop. The experiment results are depicted in Fig.19 and Fig.20



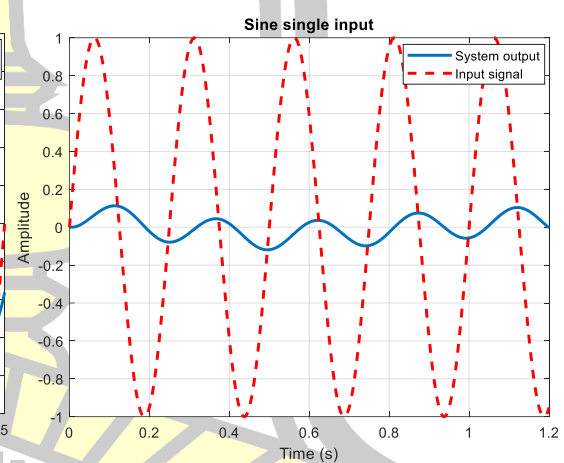
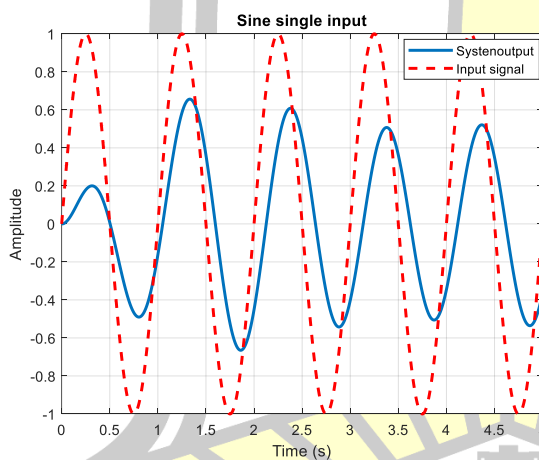


(c)



(d)

Figures 19 (a)Step response without torque controller.(b)Impulsive response without torque controller.(c)Bode diagram of closed loop response without torque controller.(d)Root locus without torque controller.



Figures 20 (a)Sinusoidal tracking performance without PID controller(1 Hz) ;(b)Sinusoidal tracking performance without PID controller(4 Hz)

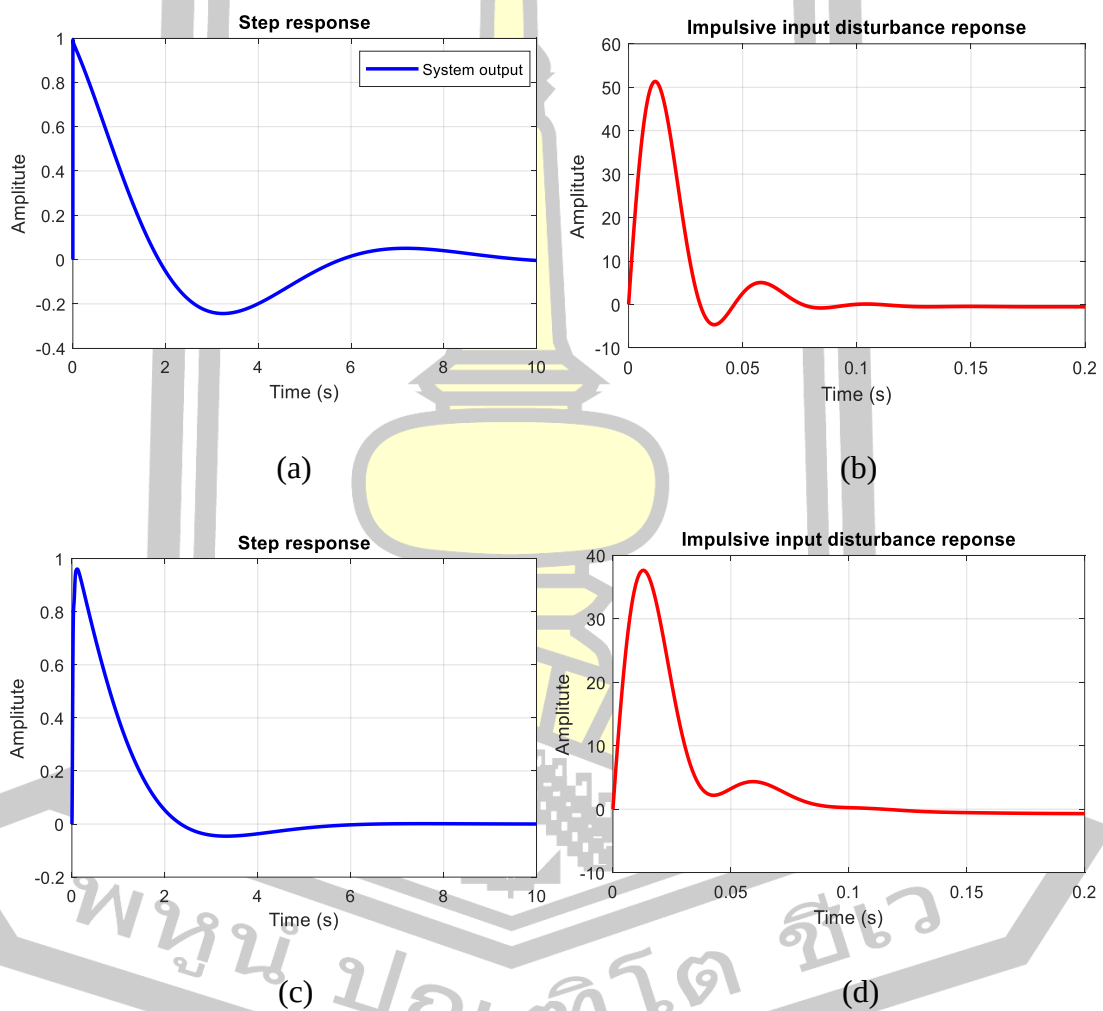
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4.3.3. The experiment with PI controller

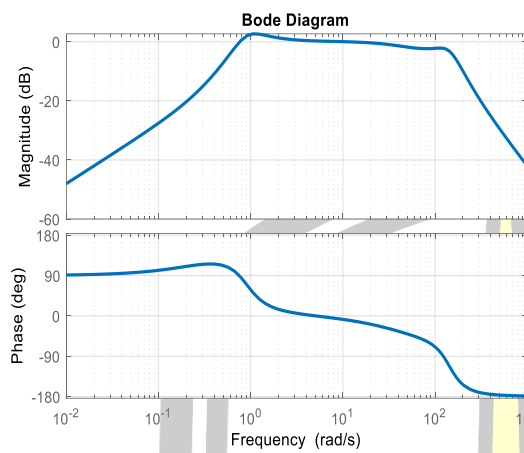
The close-loop transfer function with PID is obtained as below:

$$\frac{T_l(s)}{T_d(s)} = G_t(s) = \frac{0.02008s^3 + 2.51s^2}{0.00008s^5 + 0.01168s^4 + 1.452s^3 + 5.313s^2 + 35.9s + 63} \quad (19)$$

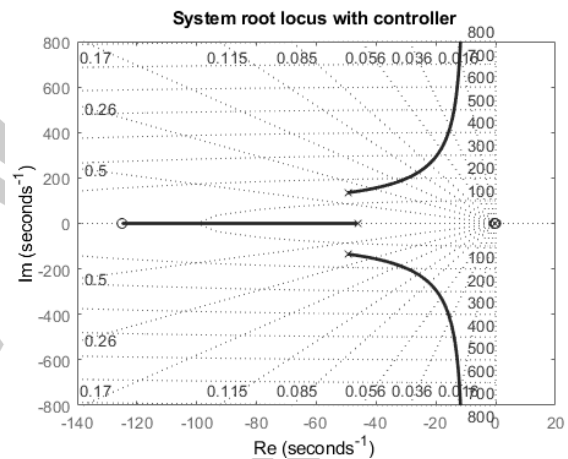
In the system with PI controller, the parameters of proportion and integration were selected, the experiment result are shown in Fig.21 and Fig.22



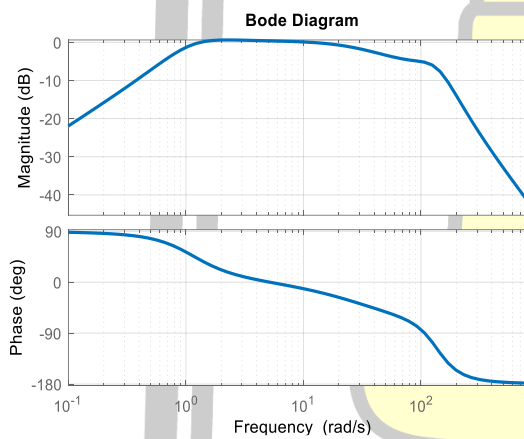
Figures 21 (a)Step response with PI controller($K_p=30$, $K_i=10$). (b)Impulsive response with PI controller($K_p=30$, $K_i=10$). (c)Step response with PI controller($K_p=20$, $K_i=20$). (d)Impulsive response with PI controller($K_p=20$, $K_i=20$)



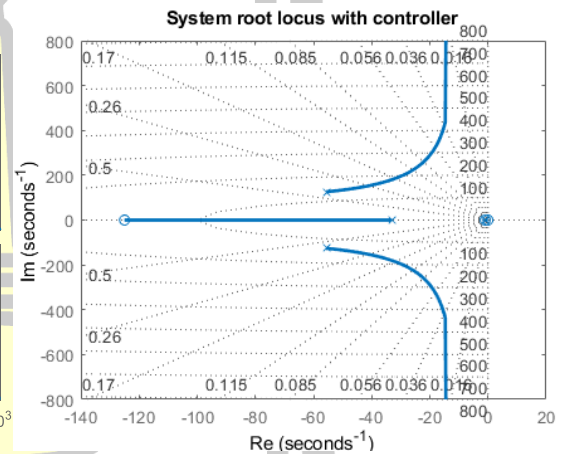
(a)



(b)



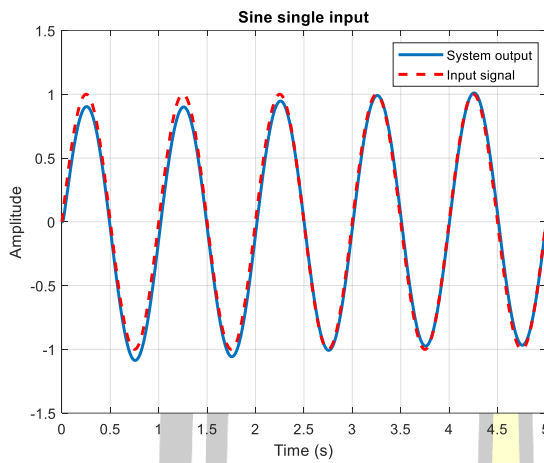
(c)



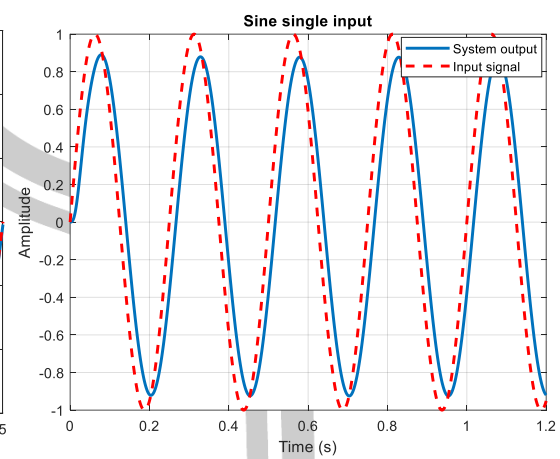
(d)

Figures 22 (a)Bode diagram of closed loop response with PI controller($K_p=30, K_i=10$). (b)Root locus with PI controller($K_p=30, K_i=10$). (c)Bode diagram of closed loop response with PI controller($K_p=20, K_i=20$). (d)Root locus with PI controller($K_p=20, K_i=20$).

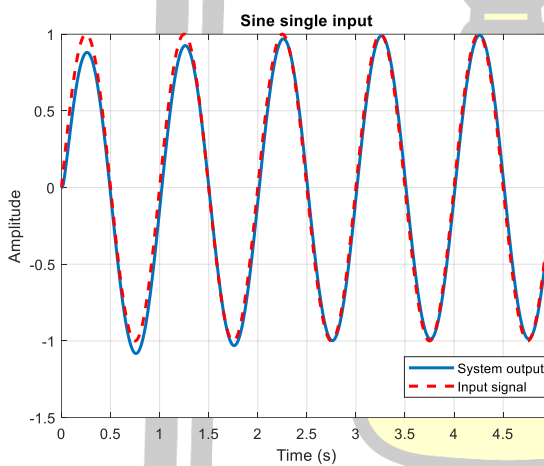
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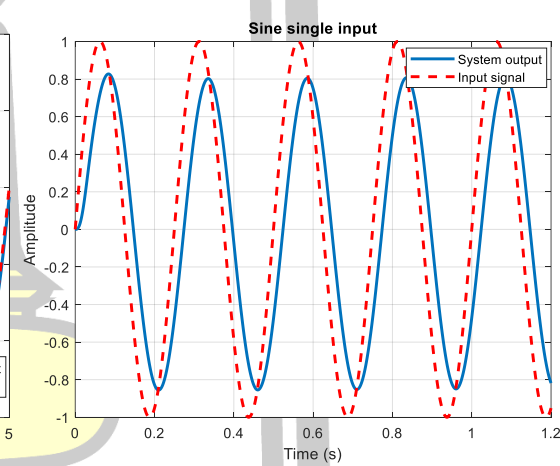
(a)



(b)



(c)



(d)

Figures 23(a) 1Hz sinusoidal tracking performance with PI controller ($K_p=30, K_i=10$), (b) 4Hz sinusoidal tracking performance with PI controller ($K_p=30, K_i=10$), (c) 1Hz sinusoidal tracking performance with PI controller ($K_p=20, K_i=20$), (d) 4Hz sinusoidal tracking performance with PI controller ($K_p=20, K_i=20$)

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4.3.4. The experiment with Robust controller based on H^∞ criterion

In the system, open-loop transfer function is obtained as:

$$\frac{T_l(s)}{T_d(s)} = \frac{0.02008s^3 + 2.51s^2}{0.00008s^5 + 0.01168s^4 + 1.432s^3 + 2.803s^2 + 35.9s + 63} \quad (20)$$

As the high order system model presented, reducing order modeling is necessary for reducing computational complexity of full-order model. Considering the constant of fifth orders variable was much less than the others, it was reasonable to make the polynomial down to fourth order for simplifying model analysis and control design while preserving the expected fidelity within a satisfactory error.

Though the open-loop transfer function of SEA system, the state space as shown in (8) was written as lower four dimensional state equation, where:

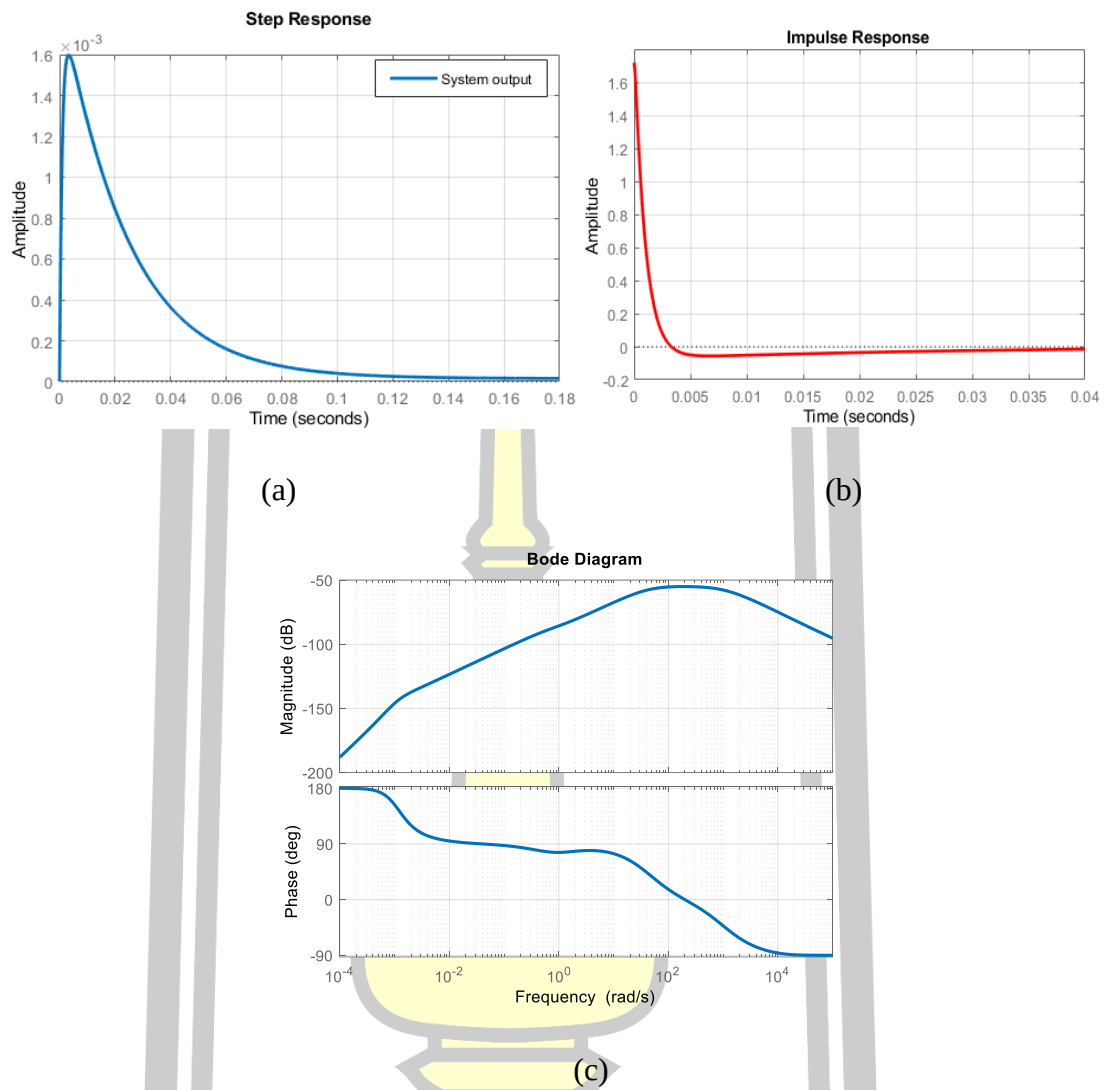
$$A = \begin{bmatrix} -122.6 & -240 & -3073.6 & -5393.8 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad B_1 = B_2 = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$C = [1.7192 \quad 214.8973 \quad 0 \quad 0], \quad D = 0 \quad (21)$$

The system with H^∞ norm based on LMI was formulated, using the previous mentioned diagram described in Fig.24 and satisfying the inequality condition(15),(16),(17). The transfer function of controller K is achieved:

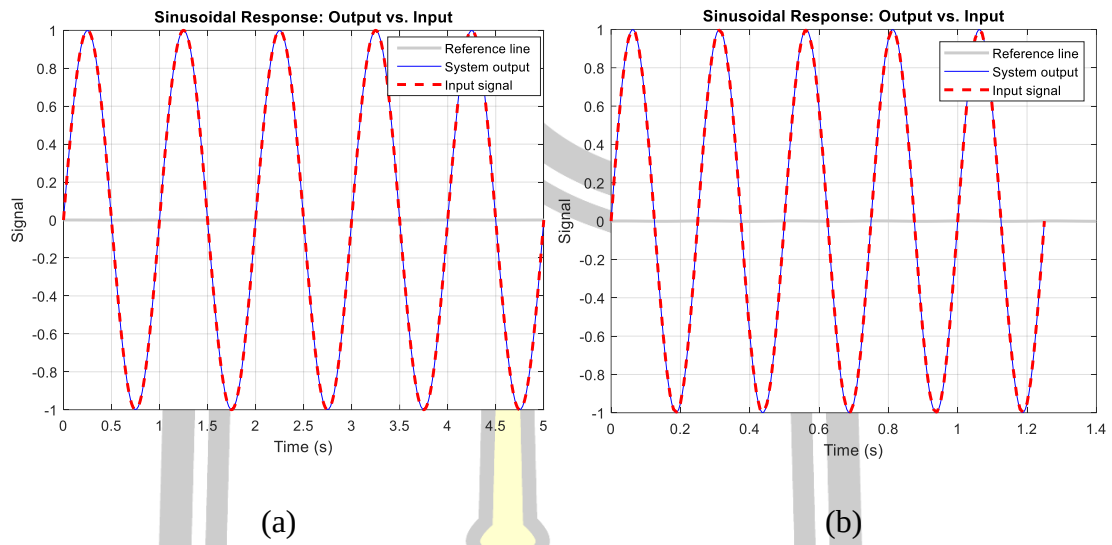
$$K(s) = \frac{-7.299 \times 10^6 s^3 - 1.178 \times 10^9 s^2 - 3.731 \times 10^{10} s - 2.501 \times 10^{10}}{s^4 + 1.283 \times 10^4 s^3 + 1.594 \times 10^6 s^2 + 1.682 \times 10^6 s + 1372} \quad (22)$$

The simulation also shown that $\|T_{zw}(s)\|_\infty < \gamma = 0.110395$, closing to desired optimal performance. The results of response are depicted in below:

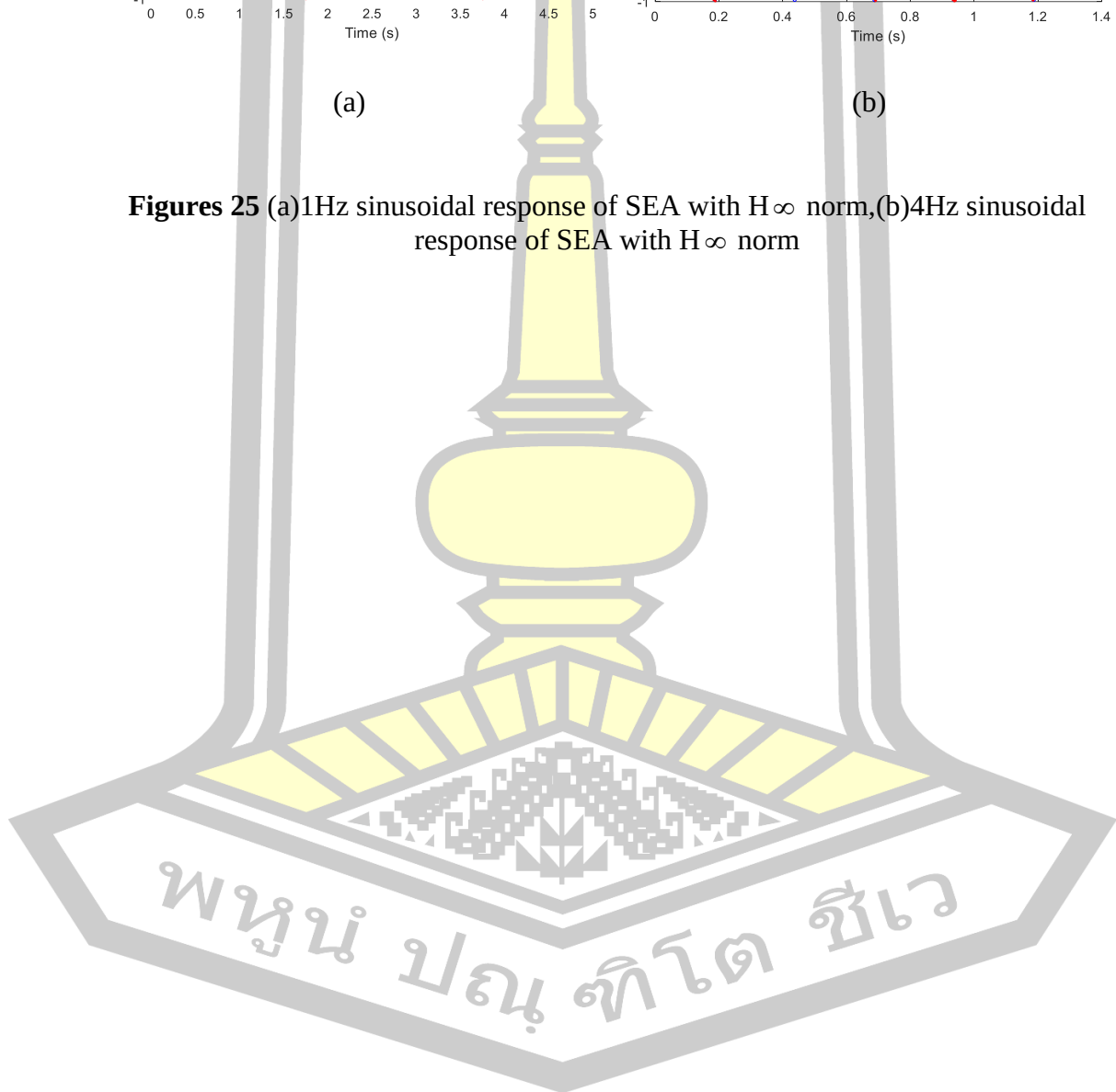


Figures 24 (a)Step response with H_∞ norm.(b)Impulsive response with H_∞ norm.(c)Bode plot of system with H_∞ norm

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Figures 25 (a) 1Hz sinusoidal response of SEA with H^∞ norm, (b) 4Hz sinusoidal response of SEA with H^∞ norm



CHAPTER 5

CONCLUSION

In practically, the industrial environment is uncertain and variable. The passivity impedance control has some limitations. In this chapter, to overcome the disadvantages and limitations of a conservative passivity impedance interaction control, either the requirement of passivity must be relaxed or knowledge about the characteristics of the environment has to be considered in the design. In this research, the designed strategy based on simplified target impedance/environment interaction model is introduced.

5.1 Key findings

The traditional controller designing has limitation to deal with the SEA system model with characteristic of nonlinear. As the controllers designed and experiments implemented in above presentation, the system without controller has poor stability. The fluctuation of the system without controller is obvious violent, comparing PI controller and Robust H^∞ controller in step response, which may lead to system unreliability. Although the system fluctuations with PI controller decay faster in step response than the system without controller, the overshoot is larger than that. The reason of the result is that the performance of system with PI controller rely on the parameters selection, which means that the process of selecting desired parameters contains randomness and experience. However, the H^∞ on LMI controller achieved satisfied performance that overshoot was minimal and fluctuations decay rapidly in step response.

In impulse response experiment, the system without controller and the system with PI controller, presented in Fig.19(b), Fig.21(b) and Fig.21(d), can not deal with impulsive signal, even through modifying parameters. On the contrary, the peak value of impulsive response is minimal in H^∞ controller, which means that the system has better robustness of against uncertain disturbance.

It is observed that the bandwidth frequency is higher than others in system with H^∞ controller is in bode plots, as shown in Fig.19(c), Fig.22(a), Fig.22(c), and

Fig.24(c), which means that the system has better quick response. In addition, the result of sinusoidal response are shown in Fig.20(a), Fig.20(b), Fig.4.23(a) to (d), Fig.25(a),

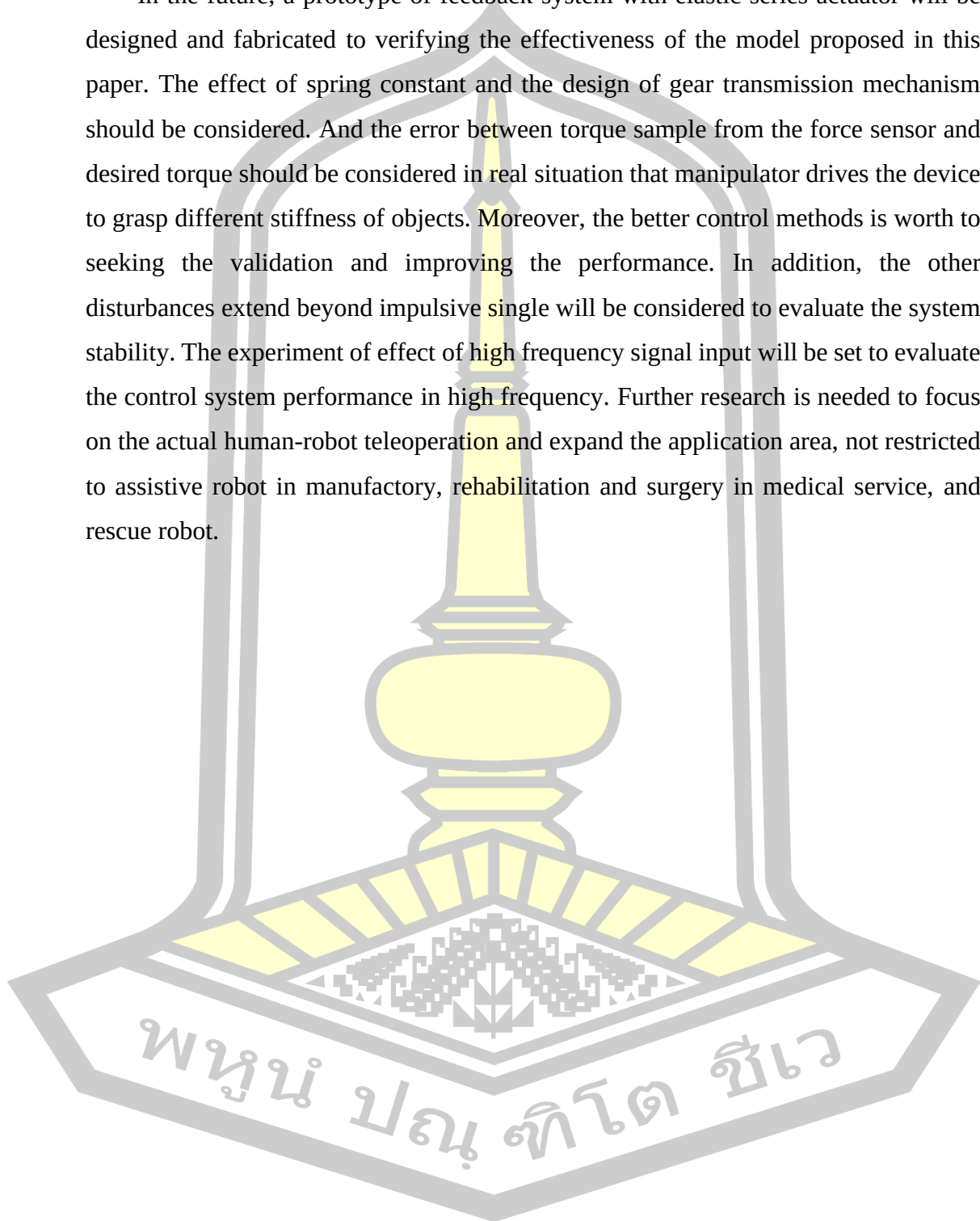
and Fig.22(b), the tracking errors are larger in system without controller than others, revealing that the system can not deal with dynamic environment. With the increase of input frequency, the tracking performance of system became deteriorated. The performance of tracking has been improved in PI controller as shown in Fig.22(a) to (d). However, with the increase of input frequency, the accuracy of the system decreases obviously. The system with H_∞ shows the accurate position performance when the input sinusoidal frequency vary from 1Hz to 4Hz. In this paper, the input signals are standard, not as made up complex signals in real life, which is for being convenient to extract system feature on an equal footing.

5.2 Contributions

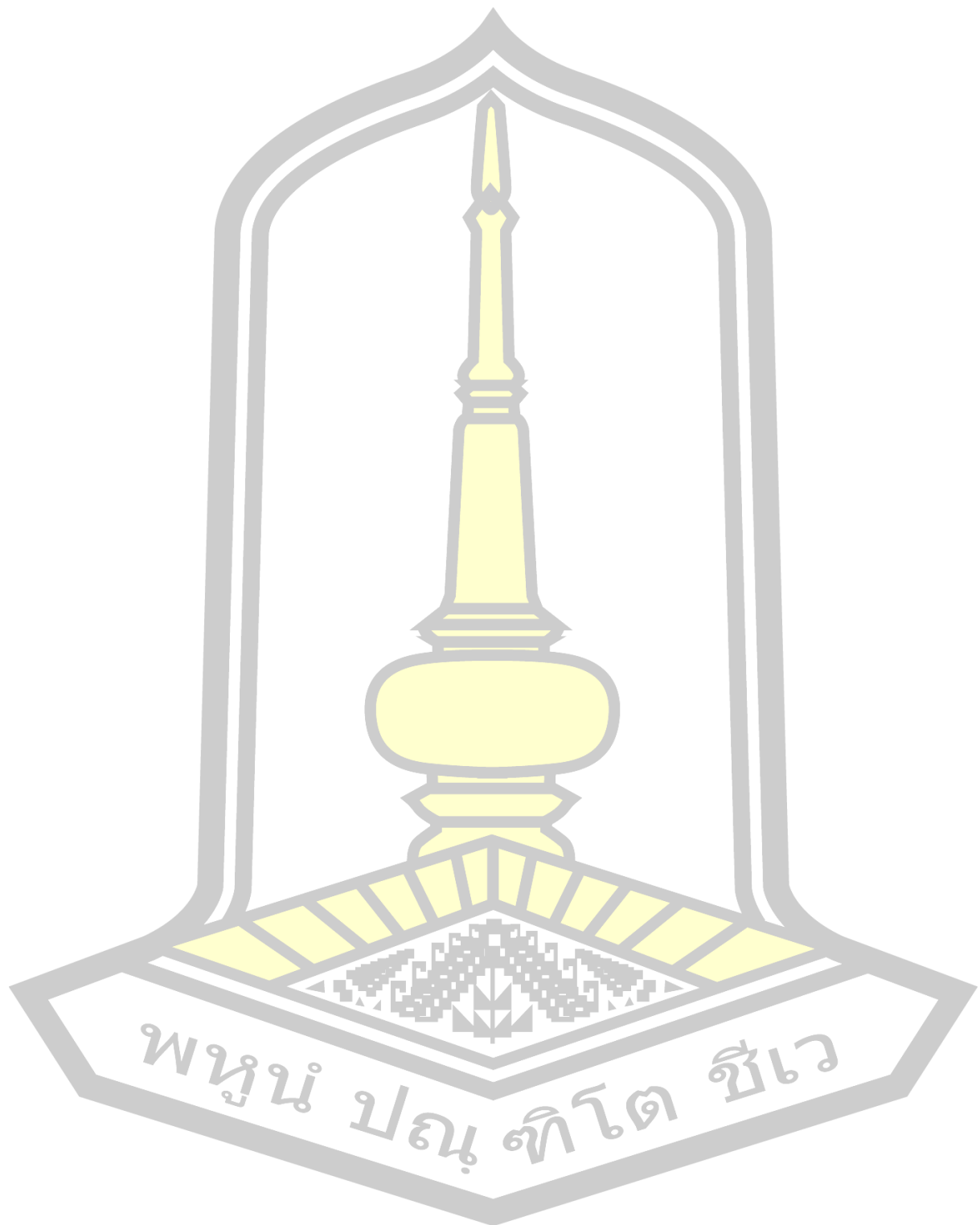
In this paper, a kind of force feedback system with SEA was proposed for teleoperation. Through mechanism simplified and impedance control theory, the system model regarding inner motor loop as speed control loop was formulated as transfer function. Then, PI control strategy and H_∞ control strategy based on LMI were discussed to improve the system performances of overshoot, response time, rising time, stability against impulsive disturbance, bandwidth and tracking error. For analyzing the control theme, several experiments were set, simulated by MATLAB /SIMULINK. The step response experiment was conducted to verify the performance of system turning. The impulse experiment was applied to evaluate the stability suffering sudden, uncertain disturbance. The sinusoidal experiment was using the sinusoidal signal acted as human motion to verify the performance of trajectory tracking error. At last, comparing with other controllers such as PI controller, the feedback system with H_∞ control strategy not only achieved rapid responsiveness under sudden signal input and accurate trajectory tracking performance, but also smaller overshoot in time domain. The proposed system has promising application in requiring frequent human-robot teleoperation.

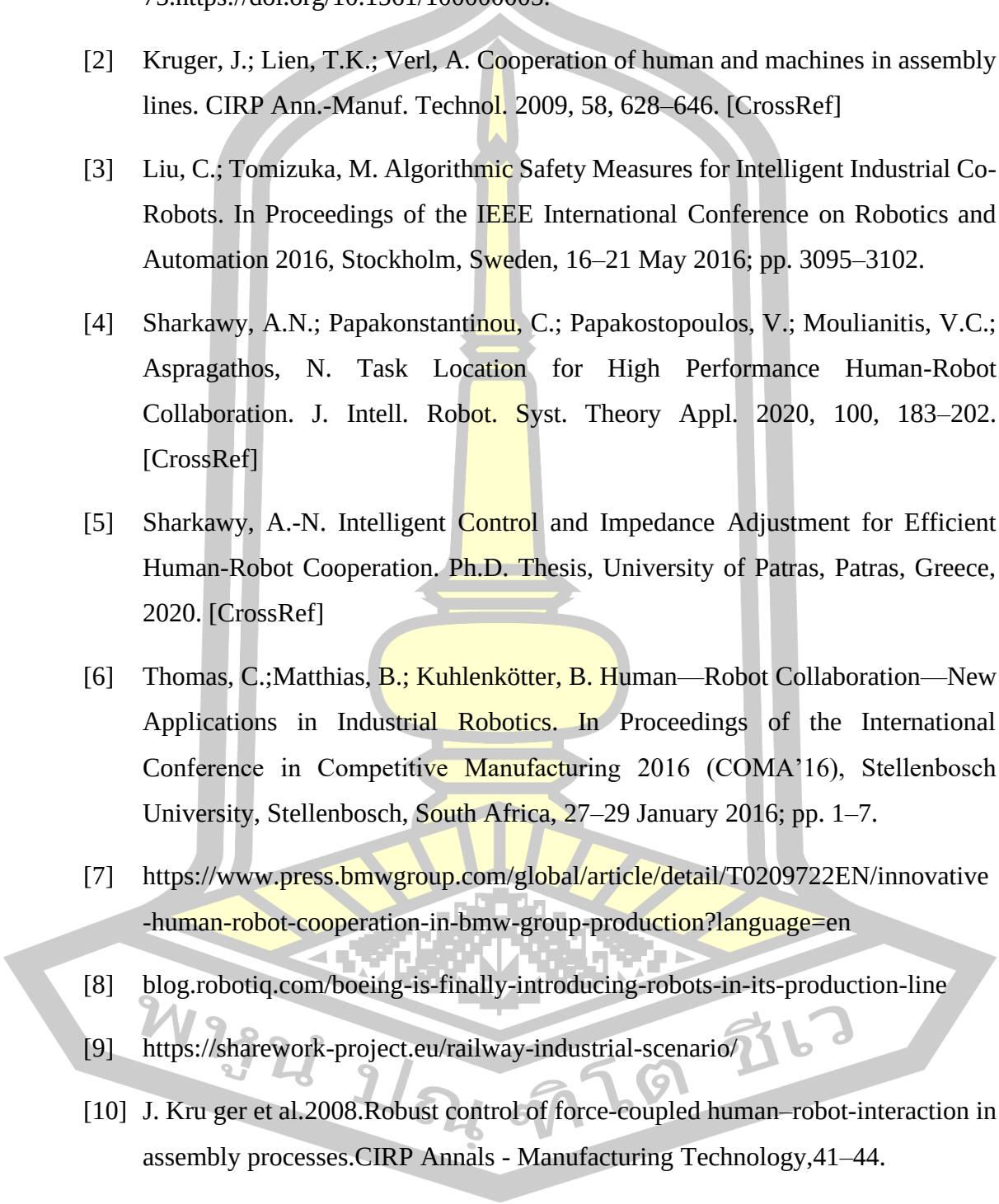
5.3 Future research

In the future, a prototype of feedback system with elastic series actuator will be designed and fabricated to verifying the effectiveness of the model proposed in this paper. The effect of spring constant and the design of gear transmission mechanism should be considered. And the error between torque sample from the force sensor and desired torque should be considered in real situation that manipulator drives the device to grasp different stiffness of objects. Moreover, the better control methods is worth to seeking the validation and improving the performance. In addition, the other disturbances extend beyond impulsive single will be considered to evaluate the system stability. The experiment of effect of high frequency signal input will be set to evaluate the control system performance in high frequency. Further research is needed to focus on the actual human-robot teleoperation and expand the application area, not restricted to assistive robot in manufactory, rehabilitation and surgery in medical service, and rescue robot.



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