Co-operative Control of Multi-robot System with Force Reflecting via Internet

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Abstract

With the considerably improvement of information technology, Internet has evolved from a simple data-sharing media to an amazing information world where people can enjoy different kinds of service. Recently, the use of the Internet has been expanded to the field of automation, i.e. using the Internet as a command tool to control equipment located at remote sites.

Using Internet as a command transmission media, we can gain the benefits of low cost, widespread and high speed. However, there is a drawback of time delay. This drawback is the critical issue on teleoperation over the Internet as the time delay is not a constant or upper bounded, but time varying. The random time delay over Internet communication will result in the problems of instability and unreliability, and also make the design of the controller difficult. To overcome these difficulties, an event-based controller which takes an event s instead of time t as the reference was adopted. As a result, the system will be a function of event and independent from the random time delay problem.

In this project, a cooperative multi-robot teleopertion system with force reflecting is developed. The system consisting of a robot hand and a mobile robot carrying a stereo vision can be controlled remotely by several operators at different sites via the internet. As the camera is mounted on the mobile robot instead of fixing in one configuration, operator is able to explore a large workspace. In addition, with force feedback, operators can feel the interactions between the robots and the working environment. The robots therefore can be controlled in a safer and more effective way. Moreover, the feasibility and the effectiveness of the developed approach has been verified successfully with experimental results obtained in teleoperation experiments conducted among Hong Kong, the Mainland China, and USA.

摘要

隨著資訊科技的快速發展，互聯網已由一個簡單的數據共享工具演變成一個多姿多采的資訊世界，在那裏人們可以享受不同種類的服務。最近，互聯網的應用已伸延到自動化的領域，亦即是利用互聯網作爲指令工具來控制設在遠方的機器人。

利用互聯網作爲媒介來指令傳遞，我們可以得到廉價、廣泛傳播和高速的好處，但卻有一個時間延遲的缺點。這個缺點是利用互聯作遙控工具的一個關鍵因素，因爲互聯網上的時間延遲並不是一個常數或有上限的變數，而是不斷在改變的。網路溝通上的隨意延遲會導致系統不穩定和不可靠等問題，而且更令控制器的設計變得困難。爲了解決這些問題，一個以事件爲基準的控制器被採用於本系統內。因爲時間不再用作基準函數，所以本系統便能獨立於時間延遲的問題。

在這項研究中發了一個有回饋力的多機器人合作遙控系統。這個系統由一個機器手和一個裝有立體視覺的移動機器人所組成，它可以由數個位於不同地方的操作員透過互聯網來遙距操作。因爲攝像頭是安裝在移動機器人上而不是固定在一個設定，所以操作員能探索更大的工作環境。再加上有力的反饋，操作員能夠感受到機器人與外圍環境之間相互作用。因此，機器人能以一個更安全和更有效的方法來操控。而這套系統和方法的可行性和效用已被香港、中國和美國所做的遙控實驗和所取得的數據驗證成功。

Acknowledgement

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Tables of Content

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Internet-based Tele-cooperation

Internet-based tele-cooperation, combining the strength of Internet-based teleoperation and robot cooperative control, is easy to be implemented and flexible in remote control aspect. Internet is widely spread and accessible all over the world. Moreover, it has a high transmission rate while the cost is relatively low. Using this world wide network as a communication tool, the operator is able to control the robot everywhere. It is convenient for several operators at different location to collaborate concurrently in real time.

1.1.1 Cooperative Control of Multiple Robots

Nowadays, robotic system has been widely applied to many different fields, not only in industry, to achieve a higher productivity with fewer man powers, or to prevent the human labours from exposing to a hazard area. With the every changing necessity, many processes become too complicated to be finished by only one single robot, and so a group of robots is needed. Different robots work on different processes and cooperate with human operator to complete the task. In such situation, cooperative control among the robots and the operator is important and necessary for the operation to be carried out in an efficient and systematic way. Concerning cooperation in robotics, it can be divided two types: multi-robot cooperation and human-robot cooperation.

Multi-robot cooperation occurs when a task is necessary to be completed by two or more robots. Pagello et al. [1] proposed a method of using task constrains to plan the action of a multirobot system for implicit coordination. Rekleitis, Dudek, and Milios [2] used a pair of robots in exploration to reduce the odometry errors and hence improve the accuracy of the obtained map. Burgard et al. [3] presented an approach of exploring an unknown environment with a team of robots. Each robot explores different regions simultaneously. And at last, all the individual maps are integrated into a global map. Botelho and Alami [4] developed a general architecture for multi robots task achievement called "M+ Cooperative task achievement". Borkowski, Gnatowski, and Malec [5] introduced a model of cooperation among a team of robot in which each robot possessed different resources.

Human-robot cooperation is an approach to combine the physical strength of the robot and the human's skill in the operation. Fernandez at el. [6] introduced an intention recognition capability which allows the robot generates its own motion plans to collaborate with the master human worker. Takubo, Arai, and Tanie [7] proposed to assign a virtual nonholonomic constraint to the robot hand, and so the operator can handling a long object to a desired position and posture in 3-D space like using a wheelbarrow. Hirata at el. [8] developed a decentralized control algorithm with which multi mobile robots can transport a single object according to the force and the moment applied by human. Based on impedance control, Kosuge, Kakuya, and Hirata [9] presented a motion control algorithm for the mobile robot with dual arm for handling an object with human-robot cooperation. To achieve a smooth cooperation, Maeda, Hara, and Arai [10] used the minimum jerk model to estimate the human motion in cooperative manipulation.

1.1.2 Internet-based Teleoperation

With the rapid development of information technology, Internet has been growing considerably in the past few years. At the very beginning, it was just a simple data sharing media, but now it becomes an amazing electronic world where you are able to enjoy many different kinds of service and entertainment. And, the potential of this global computer network is still expanding. Recently, the use of the Internet has been extended to the field of automation by using it as a command transmission media for controlling the machine remotely. In order to reduce the healthcare cost, Meng et al. [11] developed an E-service robot for health care use to look after the elderly and the disable at home. To reduce the danger of human force worked in hazardous environment, Hamel and Murray [12] proposed the use of teleoperated system in risky place. Schulz et al. [13] presented two web-controlled tour guide robots which can lead both remote and local visitors around the museum. In CMU, Simmons et al. [14] built an autonomous mobile robot system which accepts commands from the web to travel to different offices and carry out some simple tasks. In the PumaPaint Project, Stein [15] designed a website allowing users draw a picture with a PUMA 760 robot. In the website of Mercury Project [16], visitors can control the robot arm, equipped with camera and air nozzle, to unearth the buried objects in the sand box

1.1.3 Time Delay of Internet Communication

Due to the unpredictable network congestion and varying data transmission routine, the time delay of the Internet is therefore unpredictable and varying. Although the random time delay may not affect the data transmission, it may result in instability and greatly affect the reliability and performance of the system. Many researchers have proposed different ways to solve this critical issue. Brady and Tarn [17], by using state space framework, developed a supervisory architecture which considers the time varying nature of the communication medium as part of the design. Sano et al. [18] based on the framework of the H_∞ gain-scheduling to design a time-varying controller. The controller they developed can achieve the stability for all the time delays less than 1second. Niemeyer and Slotine [19] used wave-variable filters to preserve the stability. Besides, Luo et al. [20] proposed a behavior-based control scheme to overcome the time delay problem. Taylor and Dalton [21] adopt a supervisory control to eliminate the instability problem. Furthermore, Lloyd et al. [22] developed a model-based telerobotics system in which an operator does not interact with the remote site directly, but the model of the remote site. And, Calkin et al. [23] built a robot manipulator which is commanded through a virtual robot arm and environment model. Moreover, using an event-based controller can also make the teleorobotics system independence from the time delay problem [24] [25].

1.2 Related Work

Collaborative teleoperation is an interesting area in engineering. Today, many works have been reported in the cooperative control of telerobot over internet.

Goldberg et al [26] set up a collaborative teleoperated system. Through the developed client's Internet browser, several users can play the well known Ouija board game together.

Elhajj et al [27] developed a multi-site Internet-based teleoperation system which allows operators from Hong Kong and Japan control the mobile manipulator located at USA cooperatively in real time.

Chong et al. [28] built a tele-manipulation test bed in which one local operator and one remote operator control the robot with a local on-line graphics simulator to tackle the time delay.

Kheddar et al [29] developed a long distance multi-robot teleoperation system between Japan and France using an intermediate functional representation of the real remote world by the means of virtual reality.

Suzuki et al [30] [31] designed a human interface system to control multi-robot using the World Wide Web. Each robot in the system has its own ID number, and the operator is able to operate all of them by using the developed interface system. And, the system is extended to the use of cooperative inspection.

1.3 Motivation and Contribution

1.3.1 Motivation

Nowadays, many operations and maintenances require the technical operators travel around to perform their on-site work. It is time consuming and increasing the cost.

Substituting these on-site jobs with remote teleoperation via Internet can spend the resources in a more effective way. In addition, there is a growing need to perform work remotely. Now, people pay more attention on the safety issue of the working environment. However, it is still unavoidable to expose the human to some hazard environments such as nuclear power plan, underwater environment, and underground mine. With the technique of teleoperation, worker is able to control the machine from a long distance and therefore no need to put themselves in such dangerous area.

1.3.2 Contribution

In this project, a multi robots teleoperation system consisting of one mobile robot and one multi-fingered robot hand is developed. The system can be operated remotely and collaboratively by multi operators at different location in real time via Internet. And, the problem of random time delay is overcome by using an event-based controller.

The developed system is different from other system in several aspects:

1. The cooperation between a fixed robot arm and a mobile robot is being concerned.
2. The mobile robot is carrying stereo vision which enables the operator to explore a large workspace.
3. A tracking system is introduced to determine the interaction between two robots

by the means of visual tracking.

1.4 Thesis Outline

The rest of the thesis will be organized as follows. The developed system will be introduced, and discussed in details in term of the hardware and the software in Chapter 2. In Chapter 3, the modeling and the control of the system and the methods of generating force feedback will be presented. The experimental setup and the obtained results will be discussed in Chapter 4. At last, the conclusion will be offered in Chapter 5.

Chapter 2

The Internet Robotic System

2.1 System Architecture

A real-time force reflecting cooperative telerobotics system is developed. The system can be divided into four main subsystems which are client system, mobile robot system, multi-fingered robot hand system, and visual tracking system. Each subsystem has different function. The command input part is done by the client system, and the mobile robot system is responsible for exploring the working environment. The grasping task is carried out by the multi-fingered robot hand system, and the visual tracking system is used to find out the interaction between the mobile robot and the robot hand. All these subsystems are connected together through the Internet to form an Internet-based cooperative multi-robot system. The architecture of the system and the variable used are shown in Figure 1 and Table 1 respectively.

The local site and the remote site are connected through Internet using TCP/IP socket which is one of the standardized communication protocols. TCP/IP protocol allows a number of computers to share resources through a computer network using the client/server model of communication. TCP/IP communication is primarily point-to-point, meaning each communication is from one point in the network to another point or host computer.

Variable	Meaning
V_d	Desired velocity of the mobile robot sent by the operator
L_d	Desired offset of the end effector of the robot arm sent by the operator
F_m	The force feedback reflected by the robot server based on the distance between the obstacle and the mobile robot
F_a	The force feedback sent by the arm server based on the shortest distance between the workspace boundaries and the effector of the robot hand
F_{vm}	The feedback force sent to the mobile robot operator obtained by the visual tracking system
F_{va}	The feedback force sent to the robot arm operator obtained by the visual tacking system
G	The grasping signal for controlling the grasping motion of the fingers
Image	The image captured by the camera mounted on the pan tilt head of the mobile robot

Table 1. The explanation of the various variables

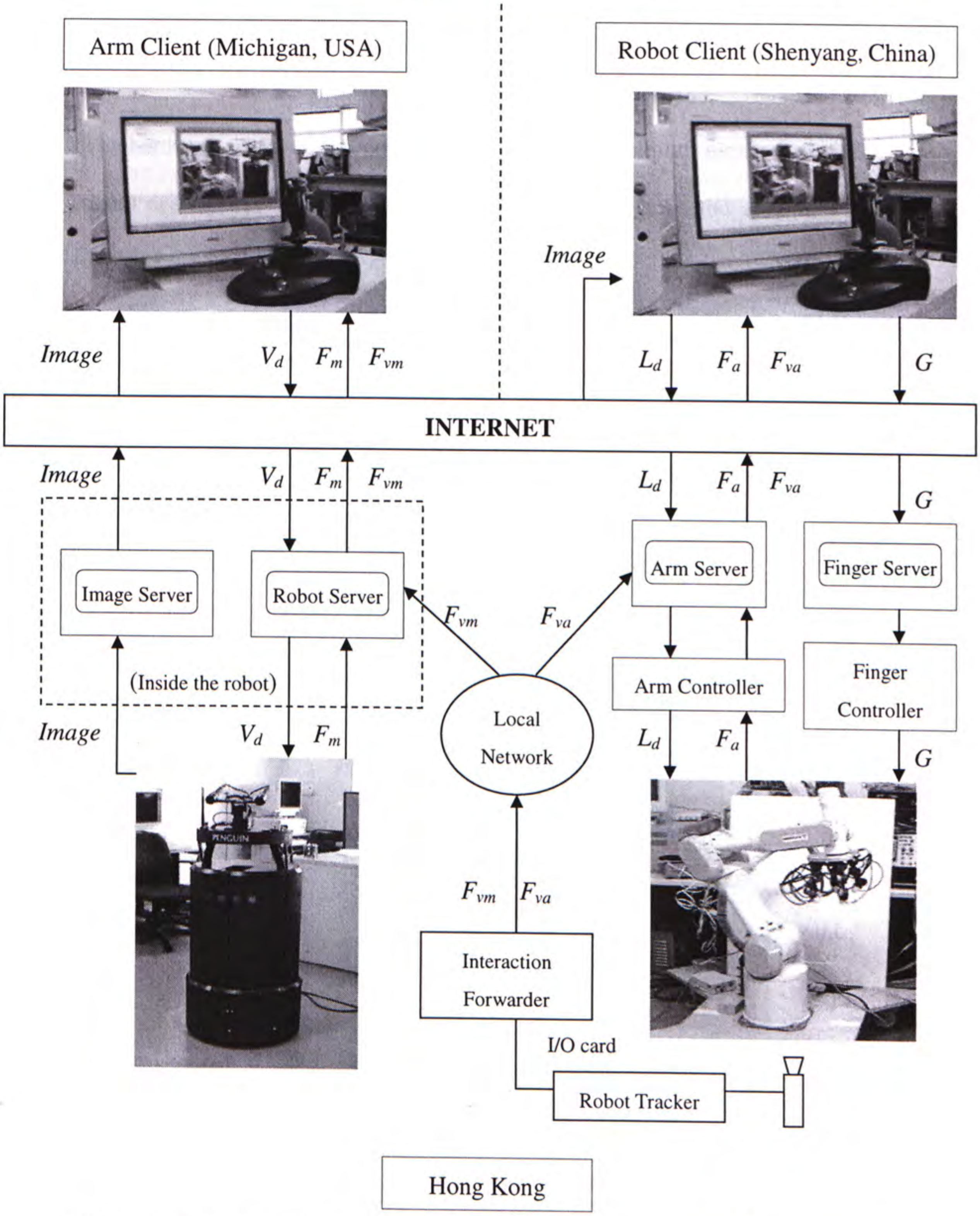

Figure 1. The architecture of the internet based cooperative telerobotics system

2.2 The Hardware

The hardware of the developed system can be classified into four systems. They are client system, mobile robot system, multi-fingered robot hand system, and visual tracking system.

2.2.1 Client System

Figure 2. SideWinder Force Feedback Pro.

The input device, as shown in Figure 2, is a force feedback joystick which can provides a simple way of command input and force feedback generation. Thus, the operator can have a better control on the robot.

The joystick used is the programmable Microsoft SideWinder Force Feedback Pro. which has 3 degrees of freedom (the conventional x and y movement and the rotation about z-axis). In addition, with the two installed motor, it can generate the forces in x and y directions, and simulate different feelings of vibration.

2.2.2 Mobile Robot System

The mobile robot, as shown in Figure 3, is the b21 indoor mobile robot manufactured by Real World interface. The mobile robot is 52.5cm in diameter and 106cm in height. It is driven by a four wheel synchronous mechanism which allows the robot moving freely in translation and rotation. On the top of the robot, a pan tilt head with two colour CCD cameras are installed. To keep the robot online, a wireless Ethernet bridge is incorporated to connect the robot to the Internet.

In addition, inside the robot, there are two computers. One of computers is the robot server operated in the Linux environment. The robot server is responsible for the communication and the motion control of the mobile robot. Another computer, used for the image transmission, is the image server of the robot which is using Window98 as the operating system.

Figure 3. The b21mobile robot

And, for navigation, the robot has equipped three kinds of sensor, sonar sensor, tactile sensor and infrared sensor, around its body to get information from the outside environment. The arrangement of the sensors is shown in Figure 4.

Sonar sensors: There are 24 sonar sensors running around the perimeter of the robot's upper enclosure at about 74cm above the floor level. The sensors are numbered for the purpose of identification. The reading of sonar sensors is taken about three times per second. For each reading, an estimated distance to the object that bounced back the echo is calculated by the total time between the generation of the ping and the receipt of the echo, coupled with the speed of sound in the robot's working environment. And, the effective range is about 6.7m. Because of the long effective range, the obstacle detection and avoidance is mainly reply on the sonar sensors.

Tactile Sensor: The robot is equipped with an array of tactile sensors. Each door has 4 sensors located more or less behind the corners. Totally 56 tactile sensors are installed, 24 on the enclosure and 32 on the base. As the sensory data can be obtained only when there is an object dumping on the door, the tactile sensors fail to be used for the long range obstacle detection. However, these bump switches can be think as the last guard of the machine which prevents the robot from either blindly bumbling the working environment or damaging itself.

Infrared Sensor: The robot incorporates several rows of infrared sensors. There are 56 in all, 24 along the lower section of the upper enclosure and 32 around the lower part of the mobile base. Each sensor has its own number for the identification. The infrared sensors have a fairly short range, about 50cm. And, the returned sensory reading is the reflectance of the object instead of the distance to the obstacle. In addition, the reflectance value is heavily dependent on the colour of the object detected, and the reading is easily confused by the objects liked mirrors, glass walls or solidly black object. Therefore it is quite difficult to gain an accurate assessment of the proximity of an object. Because of these reasons, the infrared sensor will not be used for the navigation or obstacle avoidance in our case.

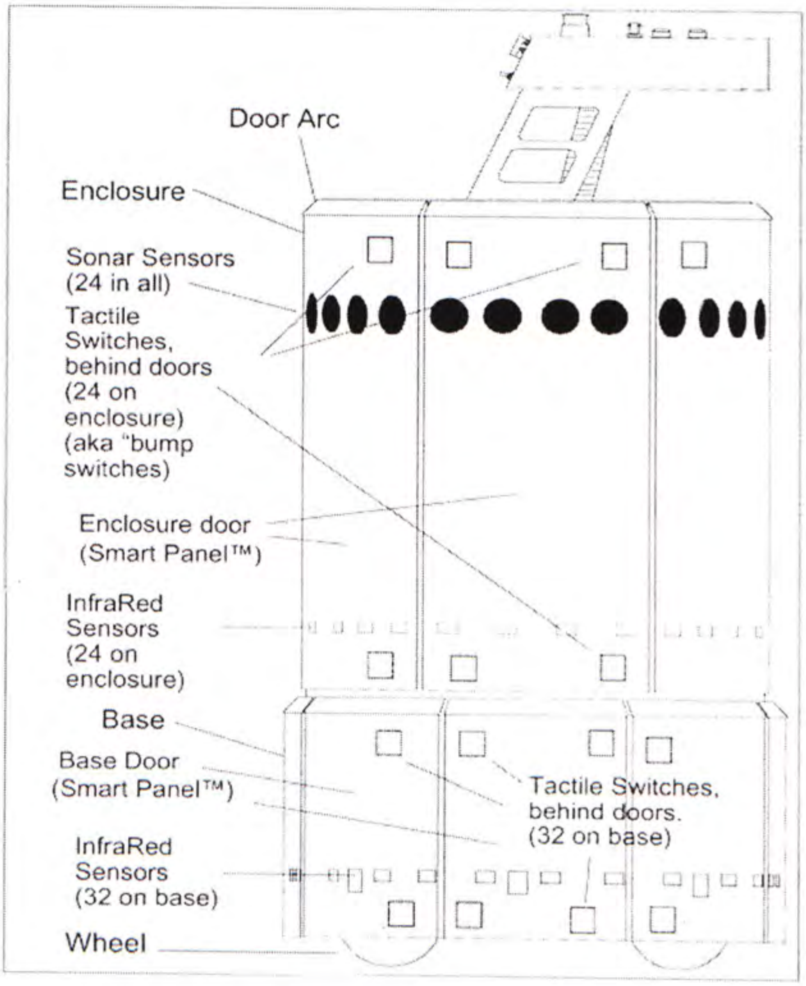

Figure 4. The sensors arrangement on the b21

2.2.3 Multi-fingered Robot Hand System

The multi-fingered robot hand system is composed of one robot arm and five robot fingers, as shown in Figure 5. The robot arm itself is the PA-10 portable general-purpose intelligent arm from Mitsubishi, which has 7 joints in all with symmetrical operation range and no offset from the centre. Total arm length is about 950mm. The workspace of the robot and the joint position are shown in Figure 6 and Figure 7 respectively. However, because of the safety reasons in our lab, the arm cannot move freely in its own workspace. A workspace in smaller size is defined for the arm during the teleoperation. For the end effector, liked a human hand, there are total 5 fingers installed. They are the product of Yaskawa Electric each of which has 3 degrees of freedom and is able to be controlled independently.

A SUN SparcStation 4 is used for the communication between the remote and local site. Two servers, the arm server and the finger server, are running in this workstation. The motion control of the robot hand is done by other machines. The control of the arm is done by the controller provided by the manufacturer, and the arm controller is linked to the workstation directly through the serial port. For the fingers, they are controlled by the controller developed in our lab. The connection between the finger controller and the finger server is through the local network.

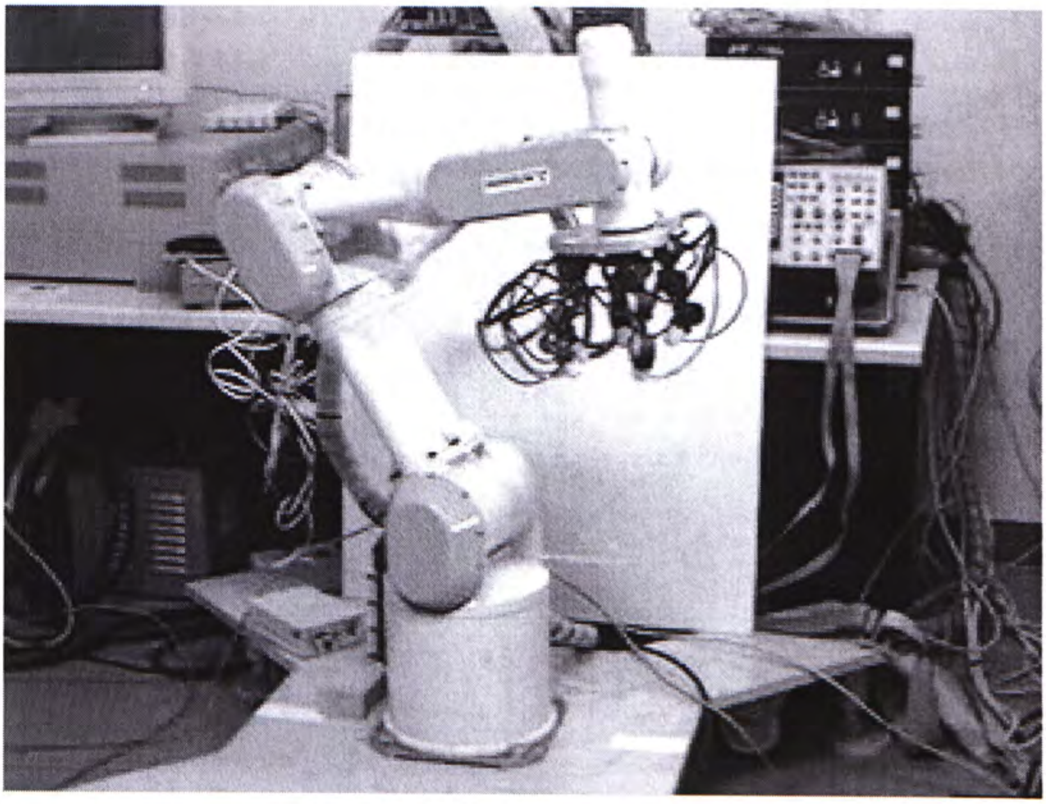

Figure 5. The multi-fingered robot hand

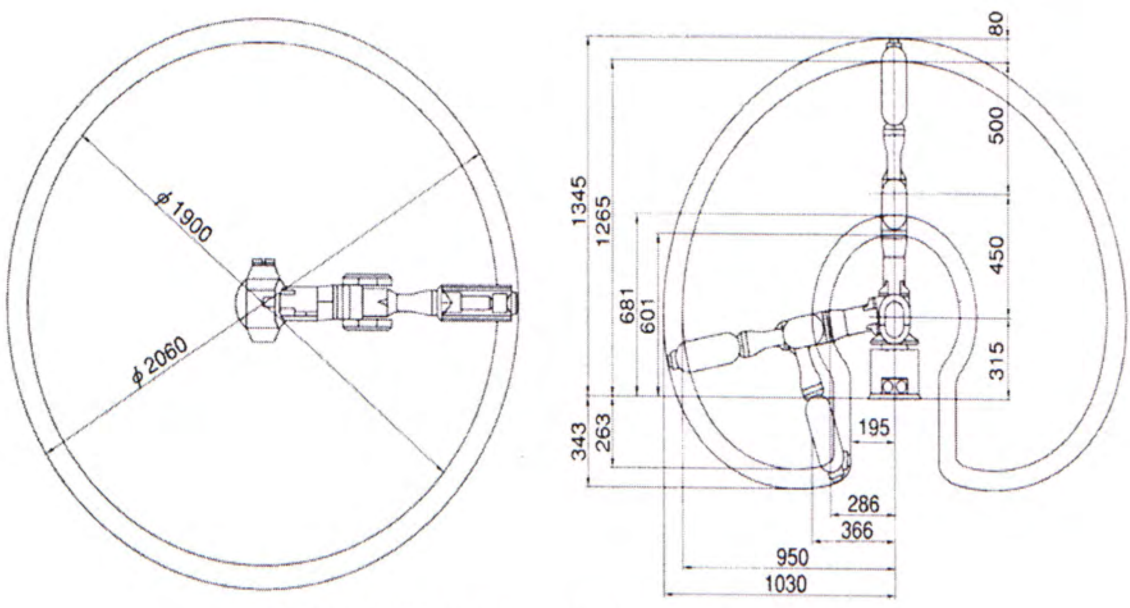

Figure 6. The workspace of the robot arm

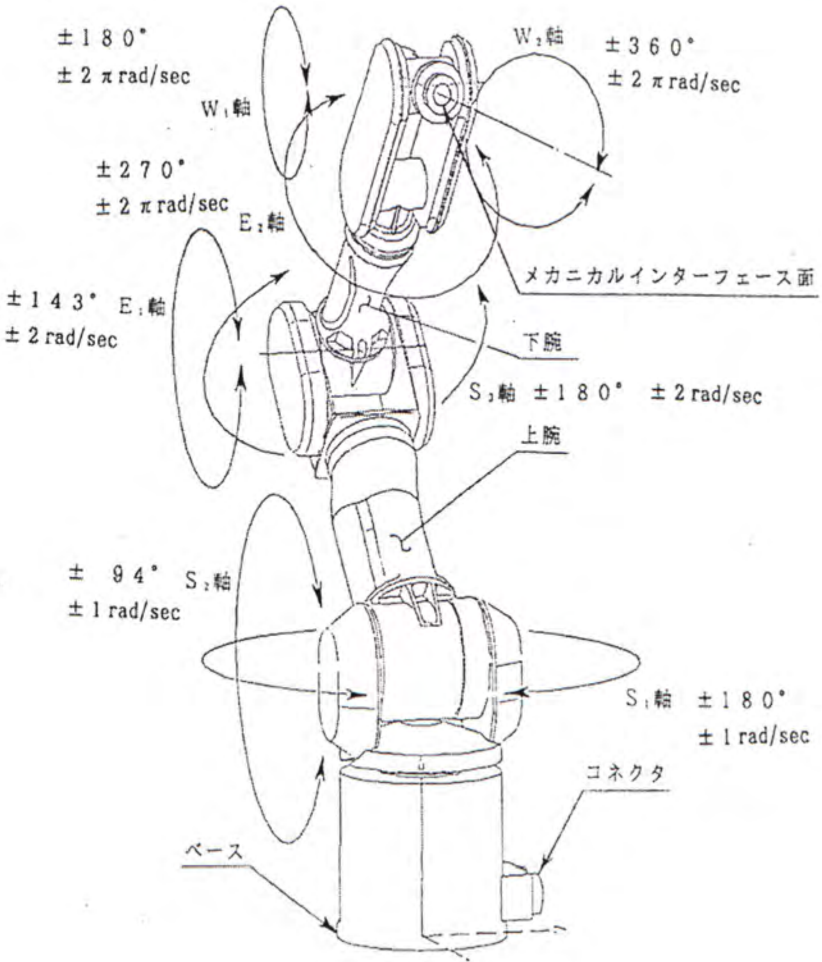

Figure 7. The joint position of the robot arm

2.2.4 Visual Tracking System

The visual tracking system is used to determine the interaction between the robot arm and the mobile robot by the means of visual tracking during the teleoperation. The set up of the visual tracking system is shown in Figure 8.

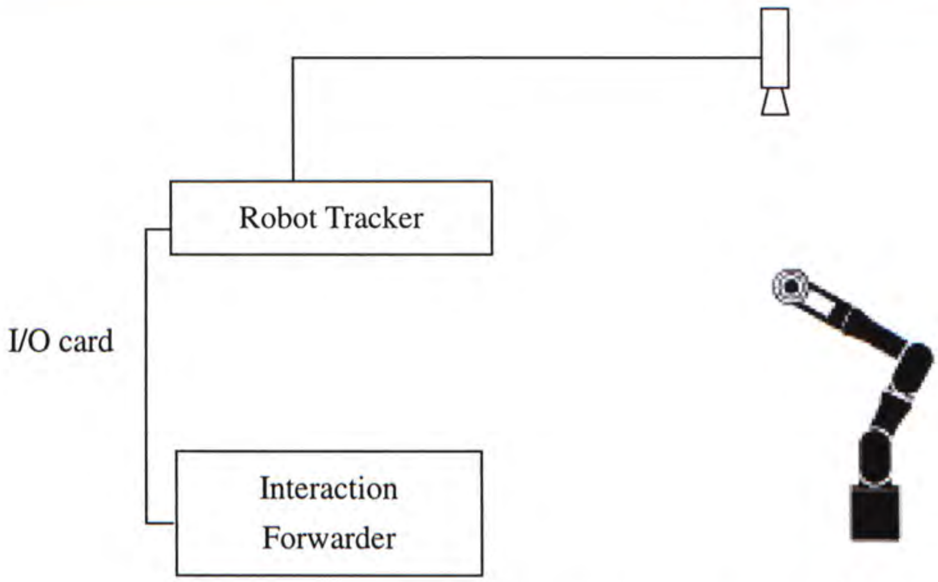

Figure 8. The set up of visual tracking system

The tracking process is carried out by a computer running Window95 as operating system with a Matrox pulsar frame grabber card installed. This machine is referred as robot tracker. The real time image is taken from the CCD camera which is hanged above the floor level about 2.5m and pointing to the arm's workspace from the top. The image of the workspace taken from the CCD camera is shown in Figure 9. Two makers in black colour are placed on the mobile robot and the robot hand respectively. The use of the marker is to make the robot easier to be recognized and reduce the noise from the background. And, both of the makers are symmetric because the orientation of symmetric pattern will not be changed easily when the robots are in motion.

Another computer running in Linux is the communication part of the visual tracking system and named as the interaction forwarder. The robot tracker and the interaction forwarder are connected together by using I/O card. And, the connection to the arm server and the robot server is via the local network.

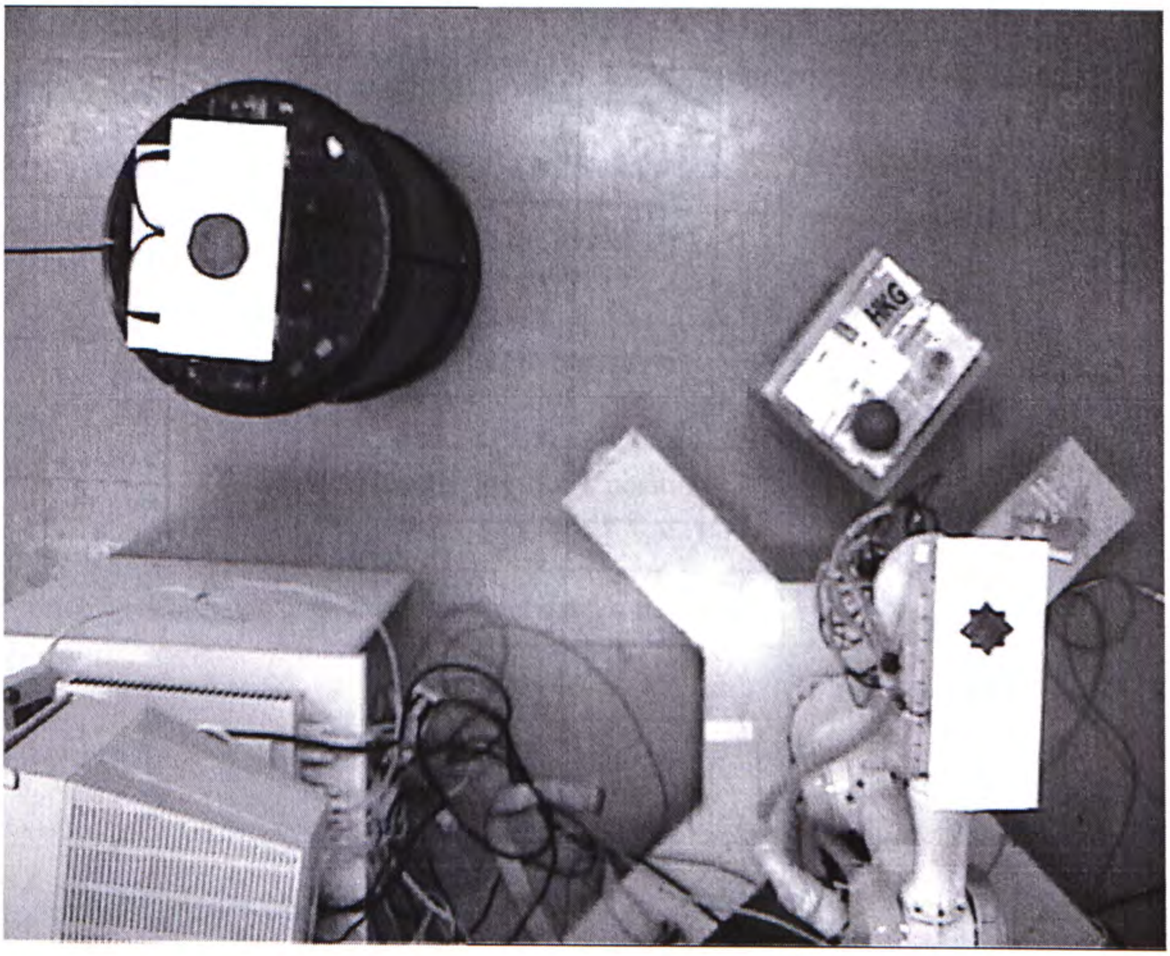

Figure 9.The image of the workspace taken from the CCD camera.

2.3 Software Design

For the software, it can be categorized into 9 parts: the robot client and the arm client at the remote site, the robot server and the image server executed inside the mobile robot, the arm server, the finger server, the arm controller and the finger controller of the multi-fingered robot system, and the robot tracker and interaction forwarder of the visual tracking system.

2.3.1 Robot Client and Arm Client

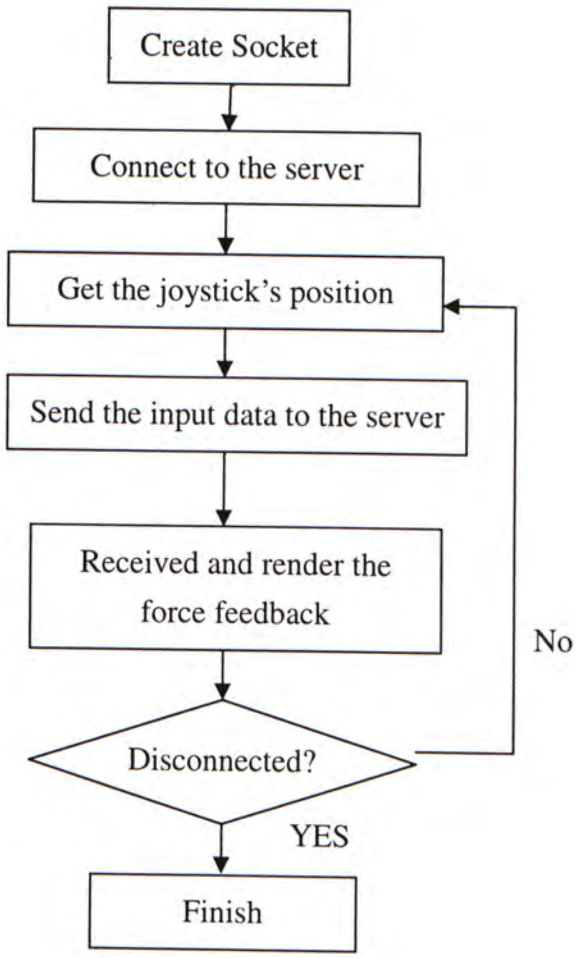

Figure 10. The control flow of the client program

The communication between the computer and the joystick is done by the client interface programmed in Visual C++ with the DirectX technology. As the input data are taken according to the joystick's position and the button pressed, the client program keeps checking the position of the joystick and its status. Besides sending the input data to the server, the program is also used for receiving the force feedback from the server and commanding the joystick to render the reflected forces. The control flow of the client program is shown in Figure 10.

2.3.2 Robot Server

The robot server written in C with the manufacturer provided BeeSoft software package is responsible for the motion control of the mobile robot, and the communication among the robot, the operator, and the visual tracking system. It receives the desired velocities from the operator and collects the workspace information through the installed sensors. The sensor reading is the distance between the robot and the detected obstacles measured in mm. If there is no obstacle near the robot, the server will command the robot to move according to the received desired velocity. Otherwise, the server will slow down or even stop the robot and obtain the force feedback. After combing the force feedback with the interactive force found by the visual tracking system, the total reflected force will be sent to alert the operator. Moreover, it also receives the desired position of the pan tilt head from the operator to control the pan tilt head's motion. The control flow of the robot server is shown in

Figure 11.

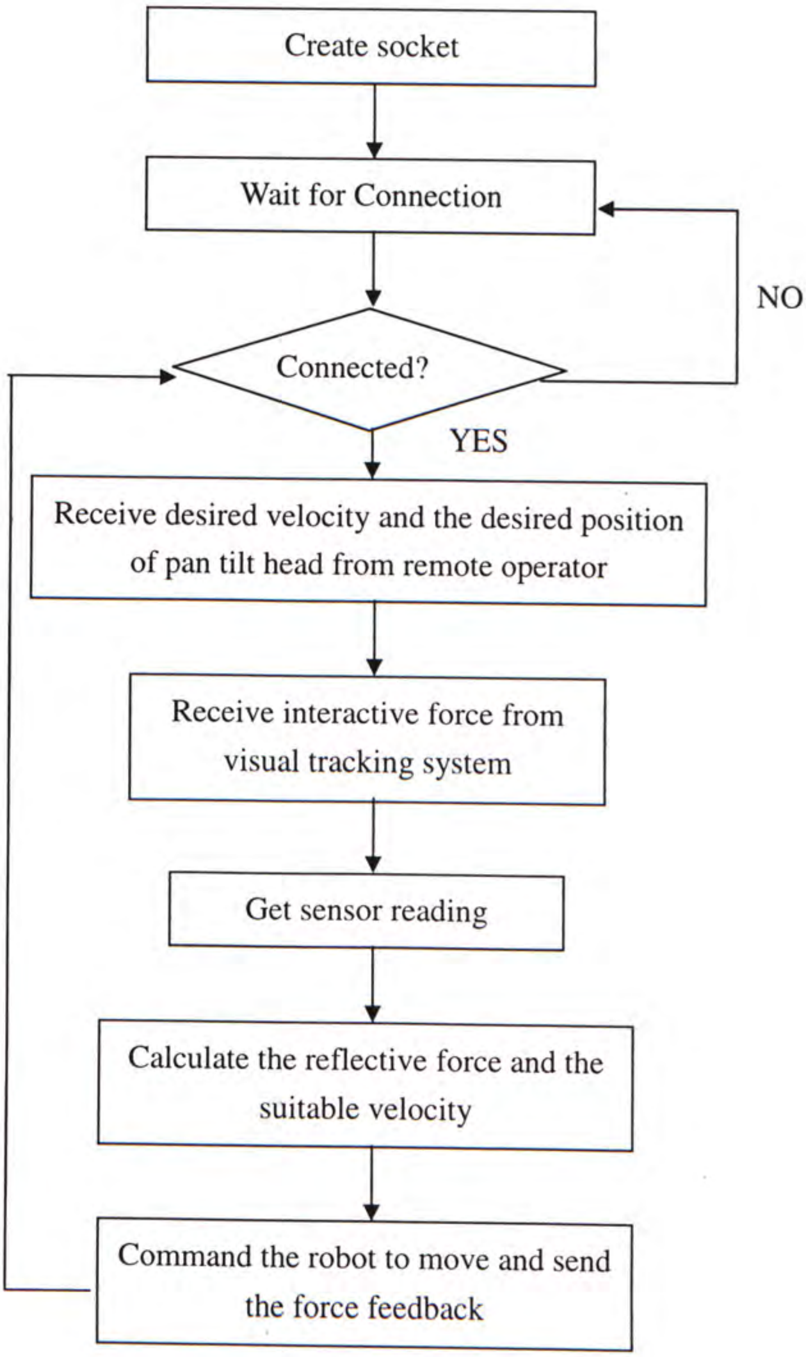

Figure 11. The control flow the robot server

2.3.3 Image Server

The image transmission is carried out by the image server. The server is built up by VIC which is a video conferencing application software package developed by the Network Research Group at the Lawrence Berkeley National Laboratory in collaboration with the University of California, Berkeley.

2.3.4 Arm Server

Arm server programmed in C is the interface linking the operator system and the arm controller together. The server accepts the desired offsets from the operator and the current position of the hand from the arm controller. The new position is then estimated from the received data, and checked with the dimensions of the pre-defined workspace of the hand stored in the server. The new workspace is in the shape of rectangular box to prevent the arm from reaching the singularity position. If the new position is within the workspace, the desired offset data will be forwarded to the arm controller to move the hand. However, if the new position is outside the boundaries, the server will command the controller to hold the hand at the same position and generate the force feedback. Adding the force feedback to the interactive force obtained from the visual tracking system, the combined force feedback will be sent to notice the operator. The control flow of the arm server is shown in Figure 12.

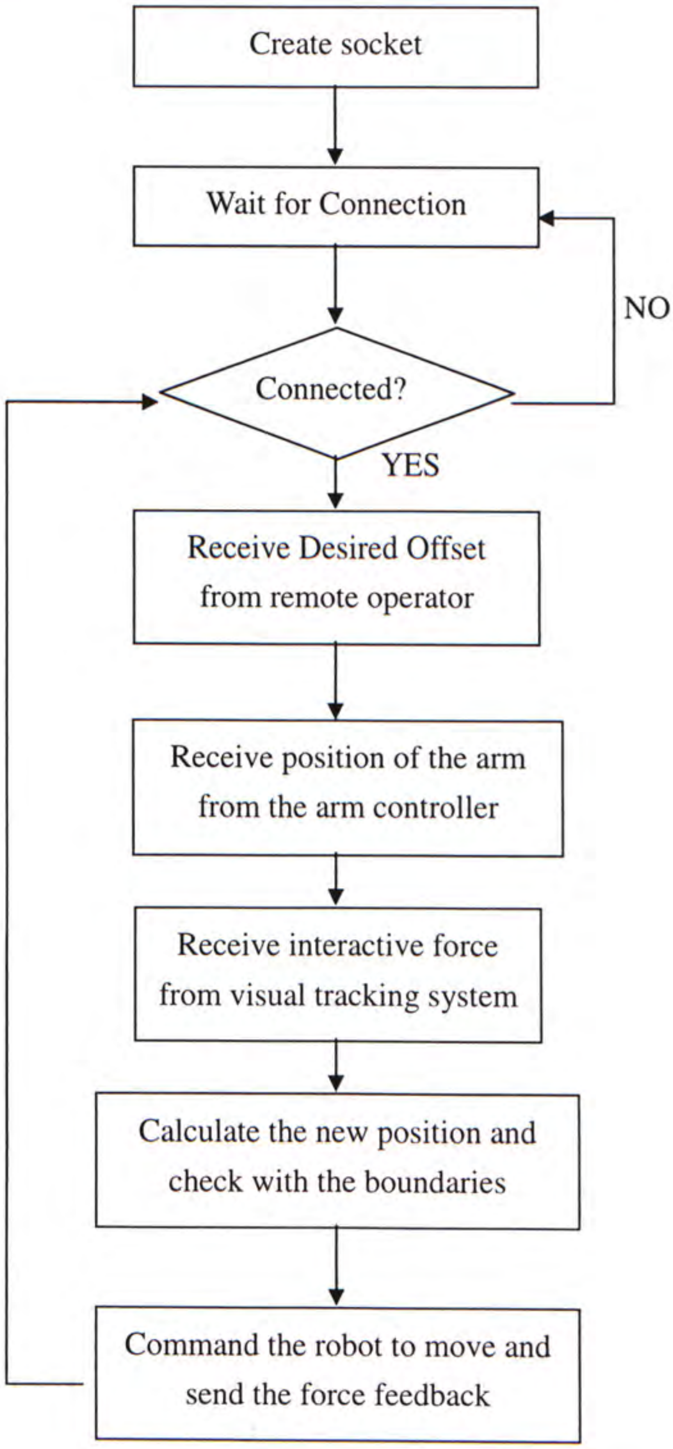

Figure 12. The control flow of the arm server

2.3.5 Arm Controller

After the desired offset in x, y, z directions from the arm server have been received through the serial communication, the arm controller calculates the required joint angle offset of each joint by inverse kinematics, and then moves the end effector of the robot hand to the desired position.

2.3.6 Finger Server

The finger server written in Lisp connects the finger controller to remote site. In the server, the predefined joint angles of each finger in grasping and ungrasping gesture are stored. The joint angles of grasping or ungrasping are forwarded to the finger controller based on the grasping signal received.

2.3.7 Finger Controller

The controller receives a set of joint angles of the each finger from the finger server, and controls the finger gesture according to the joint angles obtained.

2.3.8 Robot Tracker

The tracking program is developed in Visual C++ with the Matrox Imaging Library. The program gets the real time image of the workspace from the CCD camera and selects the patterns needed to be tracked. In our case, the patterns are the markers placed on the mobile robot and the robot hand. By locating the markers, the distance between the mobile robot and the robot hand is known. The interactive force is then obtained based on the intermediate distance and categorized into four types according to the relative position of the robots. The result will be transferred to the communication part through I/O card.

2.3.9 Interaction Forwarder

The forwarder is connected to the servers as a client. It gets the result of interactive force from the robot tracker through I/O card and then forwards this information to the robot server and the arm server.

Chapter 3

Event-based Control for Force Reflecting Teleoperation

3.1 Modeling and Control

Time delay is always the problem of teleoperation. This problem becomes more critical when the control commands and the feedback information are transmitted through the Internet in real time. As Internet is a global networking connected by a million of computer, communication over Internet from one point to another point involves a number of connection nodes. The performance of the each connection node has a direct effect on the whole communication process, and all the nodes share the same importance. However, the connection node is unable to be controlled even it is a part of the system. Due to the network congestion and the different data transmission rountine, the time delay over the Internet is not constant or upper bounded, but varying and unpredictable. To illustrate the randomness of the time delay, Figure 13 and Figure 14 show the round trip delay between Hong Kong and USA, and that between Hong Kong and China. The random time delay, in fact, may not affect the transfer of the data, but it will make the system instable and unreliable.

The varying time delay makes the traditional control law, which taken time as the reference variable, inapplicable to the internet-based teleoperation system. To solve this problem, several new control methods are presented. One of the effective approaches is to use a non-time based controller.

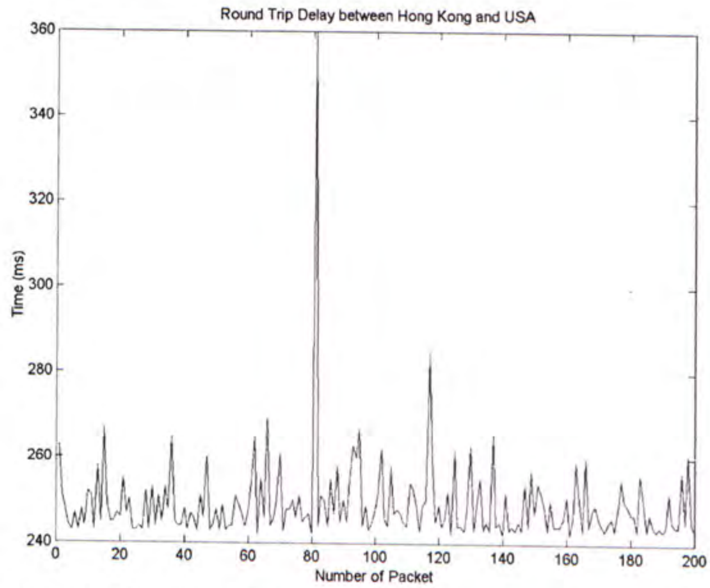

Figure 13. The round trip delay between Hong Kong and USA

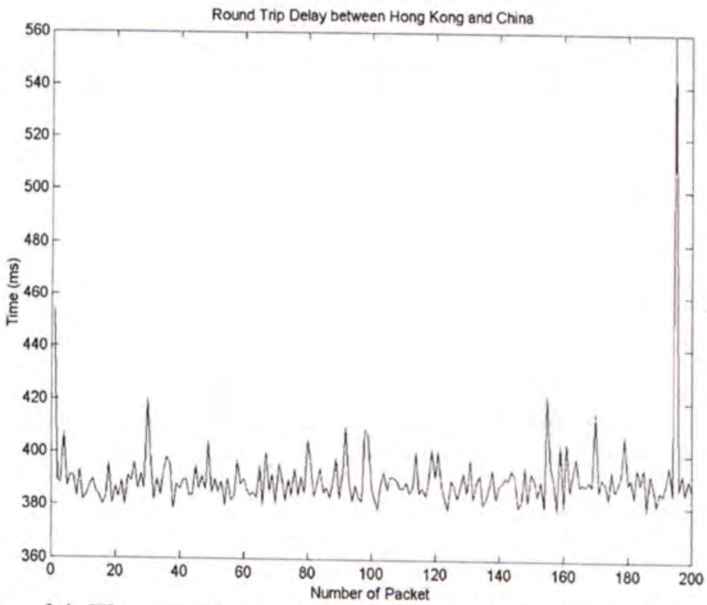

Figure 14. The round trip delay between Hong Kong and China

Event-based controller is a non-time based controller. The basic idea of the theory is to takes an event, instead of time, as the action reference parameter. The event parameter is the physical output of the system, and it is not necessary to have a physical meaning. As the system is now no longer related to the time, it can be free from the random time delay problem.

To achieve the stability and synchronization, the concept of event-based control law is applied to the developed telerobotics system. The selection of the event s, in our case, is the number of the executed cycle. As a consequence of applying the event-based controller, the model of all the components in the developed system will be a function of the event. The modeling of system is discussed in detail as follows.

3.1.1 Model of Client System

The operator will move the joystick to a new position according to the forces he felt, and so the joystick position can be described as:

For the mobile robot client,

$$P_m(s+1) = K_m(F_m(s) + I_m(s)) \tag{1}$$

For the robot arm client,

$$P_a(s+1) = K_a(F_a(s) + I_a(s)) \tag{2}$$

where K_m and K_a are the scaling constant of the joystick. P_m and P_a are the position of the joystick, and $F_m(s)$ and $F_a(s)$ are the reflected force from the robot server and ar server respectively. $I_m(s)$ and $I_a(s)$ is the interactive force between the mobile robot and the robot arm obtained by the visual tracking system. $I_m(s)$ is s ent to mobile robot client while $I_a(s)$ is sent to the robot arm client. $P_m(s)$, $P_a(s)$, $F_m(s)$, and $F_a(s)$ are in the form of 3×1 vector as

$$P_m(s) = \begin{bmatrix} P_{mx}(s) \\ P_{my}(s) \\ P_{m\theta}(s) \end{bmatrix}, \qquad P_a(s) = \begin{bmatrix} P_{ax}(s) \\ P_{ay}(s) \\ P_{a\theta}(s) \end{bmatrix} \tag{3}$$

$$F_m(s) = \begin{bmatrix} F_{mx}(s) \\ F_{my}(s) \\ F_{mz}(s) \end{bmatrix}, \qquad F_a(s) = \begin{bmatrix} F_{ax}(s) \\ F_{ay}(s) \\ F_{az}(s) \end{bmatrix} \tag{4}$$

As the interaction force is found with a two dimensions image, only forces in x and y direction can be determined. Therefore, $I_m(s)$ and $I_a(s)$ are a 2×1 vector,

$$I_m(s) = \begin{bmatrix} I_{mx}(s) \\ I_{my}(s) \end{bmatrix}, \qquad I_a(s) = \begin{bmatrix} I_{ax}(s) \\ I_{ay}(s) \end{bmatrix} \tag{5}$$

The dynamics of the joysticks are:

Mobile robot operator,

$$M_{mj}\dot{V}_{mj}(s) = F_{mp}(s) + F_{mj}(s) \tag{6}$$

$$F_{mj}(s) = F_m(s) + I_m(s) \tag{7}$$

Robot arm operator,

$$M_{aj}\dot{V}_{aj}(s) = F_{ap}(s) + F_{aj}(s) \tag{8}$$

$$F_{aj}(s) = F_a(s) + I_a(s) \tag{9}$$

where M_{mj} and M_{aj} are the mass of the joystick and $V_{mj}(s)$ and $V_{aj}(s)$ are the velocity of the joystick movement. $F_{mp}(s)$ and $F_{ap}(s)$ are the forces applied by the operator. $F_{mj}(s)$ and $F_{aj}(s)$ are the forces generated by the installed motors. $F_m(s)$ and $F_a(s)$ are the forces fed from the servers as in equation *(4)*. $I_m(s)$ and $I_a(s)$ are the interactive forces described by equation *(5)*.

Once the position of the joystick has been obtained, the input data will be derived by following equation:

$$V_d(s) = K_v \times P_m(s) \tag{10}$$

$$L_d(s) = K_l \times P_a(s) \tag{11}$$

where K_v and K_l are the positive scaling constant. $V_d(s)$ and $L_d(s)$ are the desired velocities of the mobile robot and the desired offsets of the r obot hand respectively. They are three-dimensional where

$$V_d(s) = \begin{bmatrix} V_{dx}(s) \\ V_{dy}(s) \\ V_{d\theta}(s) \end{bmatrix}, \qquad L_d(s) = \begin{bmatrix} L_{dx}(s) \\ L_{dy}(s) \\ L_{dz}(s) \end{bmatrix} \tag{12}$$

3.1.2 Model of Mobile Robot System

After the robot server has received the desired velocity $V_d(s)$, the mobile robot will be commanded to move at this velocity. However, due to the obstacle algorithm and the design of the motion controller, the robot may not be able to move exactly with the desired velocity. In fact, the robot will move at $V_a(s)$, which is the actual velocity of the robot. Therefore, the dynamic of the mobile base is written as following:

$$M_m \times \dot{V}_a(s) = F_m(s) + T_m(s) \tag{13}$$

where M_m is the mass of the mobile robot. T_m is the driving force of the motor, and F_m is the reflected forces obtained based on the environmental information.

3.1.3 Model of Multi-fingered Robot Hand System

The end effector of the robot hand will move to a new position once the desired offset $L_d(s)$ is received. Each joint will displace for a certain offset in order to achieve the desired position. The dynamics equation of the robot hand can be described as following:

$$H(q)\ddot{q} + (\frac{1}{2}\dot{H}(q) + S(q,\dot{q}))\dot{q} + G(q) = T_a(s) + J^T F_a(s) \tag{14}$$

where q is the generalized coordinates of the robot hand, and $H(q)$ is a symmetric and positive definite inertial matrix. $S(q, qdot)$, $G(q)$, and J are the skew-symmetric matrix, the gravity force, and the Jacobian matrix of the manipulator respectively. T_a is the torque applied by the actuators and F_a is the feedback forces obtained based on the shortest distance between the end effector of the arm and the boundaries of the workspace.

3.2 Force Feedback Generation

To control a robot remotely, it is better if the operator can get more information about the robot's work place. Besides the visual information, force feedback also plays an important role in teleoperation. With the force feedback, the operator can have a better understanding on how the robot interacts with the remote environment, and therefore increase the dexterity of teleoperation.

In this project, force feedback is applied on three different aspects: obstacle avoidance, singularity avoidance, and rendering the interaction between the mobile robot and the robot hand.

3.2.1 Obstacle Avoidance

The force feedback algorithm designed for obstacle avoidance is applied on the mobile robot system. The sonar sensors around the mobile robot are used to detect the existence of obstacles, and get the obstacle distance. According to the sensor reading, the reflected force will be generated.

If the obstacle is 50cm away from the mobile robot, no force will be generated and the robot can be controlled to move freely. However, when there is a detected obstacle closer than 50cm, the robot server will send the feedback force to the operator to alert him the existence of the object. And, at the same time, the speed o the robot will be slowed down by half of the desired velocity to allow the operator to have more time to response. Furthermore, if the distance between the robot and the object detected is less than 30cm, the robot will be stopped to prevent from damaging itself and the working environment.

The direction of the feedback force will tell the operator the position of the object relative to the robot, and the magnitude of the for ce is related to the desired velocity of the robot. The relation between the desired translation velocity and the reflected force can be written by following equations,

$$F_m(s) = \begin{bmatrix} F_{mx}(s) \\ F_{my}(s) \\ F_{mz}(s) \end{bmatrix}, \tag{15}$$

$$F_{mx}(s) = V_{dy}(s) \times \cos\theta \times r \times C_m \tag{16}$$

$$F_{my}(s) = V_{dy}(s) \times \sin\theta \times r \times C_m \tag{17}$$

$$F_{mz}(s) = 0 \tag{18}$$

F_{mx} and F_{my} are the force feedback in the direction of x and y respectively. V_d is the desired velocity and θ is the orientation of the obstacle relative to the heading of the mobile base. C_m is the scaling constant. r is a variable depended on D_m which is the distance between the robot and the obstacle in c , where

$$r = \begin{cases} 0 & D_m > 50 \\ 0.5 \quad for & 30 < D_m < 50 \\ 1 & D_m < 30 \end{cases} \tag{19}$$

In our case, the minimum distance between the mobile robot and obstacles is 30cm and the minimum distance for force generation is 50cm. Both distances will be increased if the robot is allowed to move at higher speed. Because the mobile is unable to move up and down, the value of $F_{mz}(s)$, which is the force feedback in z direction, is always equal to zero.

The generation of the feedback force in obstacle avoidance are shown in Figure 15.

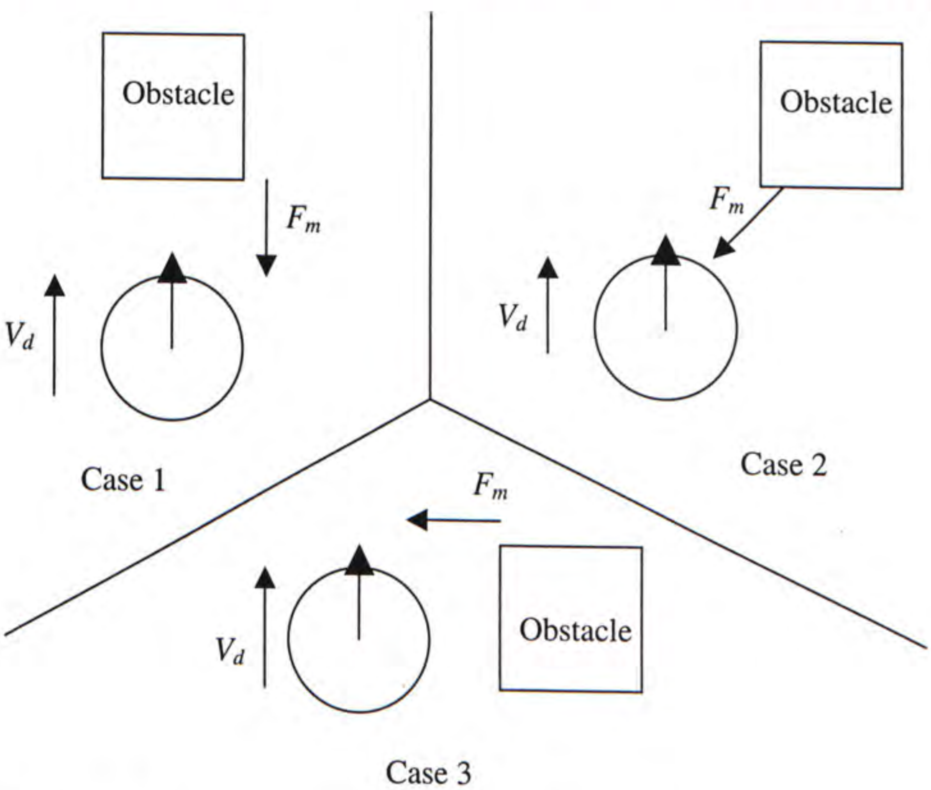

Figure 15. The generation of the feedback force in obstacle avoidance

3.2.2 Singularity Avoidance

In the multi-fingered robot hand system, a workspace in the shape of rectangular box is defined to avoid the arm reaching the singular position. By the built in encoder, the position of the end effector is known. When the arm is near the boundaries, the reflected force is generated to notice the operator.

When the end effector is away the boundaries 5cm or more, the operator will not feel any force, and he can control the arm to move in all directions. But, if the shortest distance between the arm and the boundaries is less than 5cm, the operator wil receive the feedback force from the arm server to prevent him from driving the arm to the workspace limit. And, the robot hand will stop moving if it reaches the boundary of the workspace.

The direction of the reflected force is opposite to the motion of the arm, and so the operator will know which direction he should move to keep the arm away from the boundary. The Forces can be represented as follows,

$$F_a(s) = \begin{bmatrix} F_{ax}(s) \\ F_{ay}(s) \\ F_{az}(s) \end{bmatrix} , \qquad (20)$$

$$|F_{ax}(s)| = |F_{ay}(s)| = |F_{az}(s)| = \begin{cases} C_a & for \quad D_a < 5 \\ 0 & ,otherwise \end{cases} \qquad (21)$$

where C_a is the force constant, D_a the shortest distance between the end effector and the workspace boundaries in cm. F_{ax}, F_{ay} are the force feedbacks in the direction of x and y respectively. As the joystick can only generate forces in x and y direction, F_{az}, the force generated when the arm is reached the upper or lower limit, will be a vibration force.

The generation of the reflected force in singularity avoidance are shown in Figure 16.

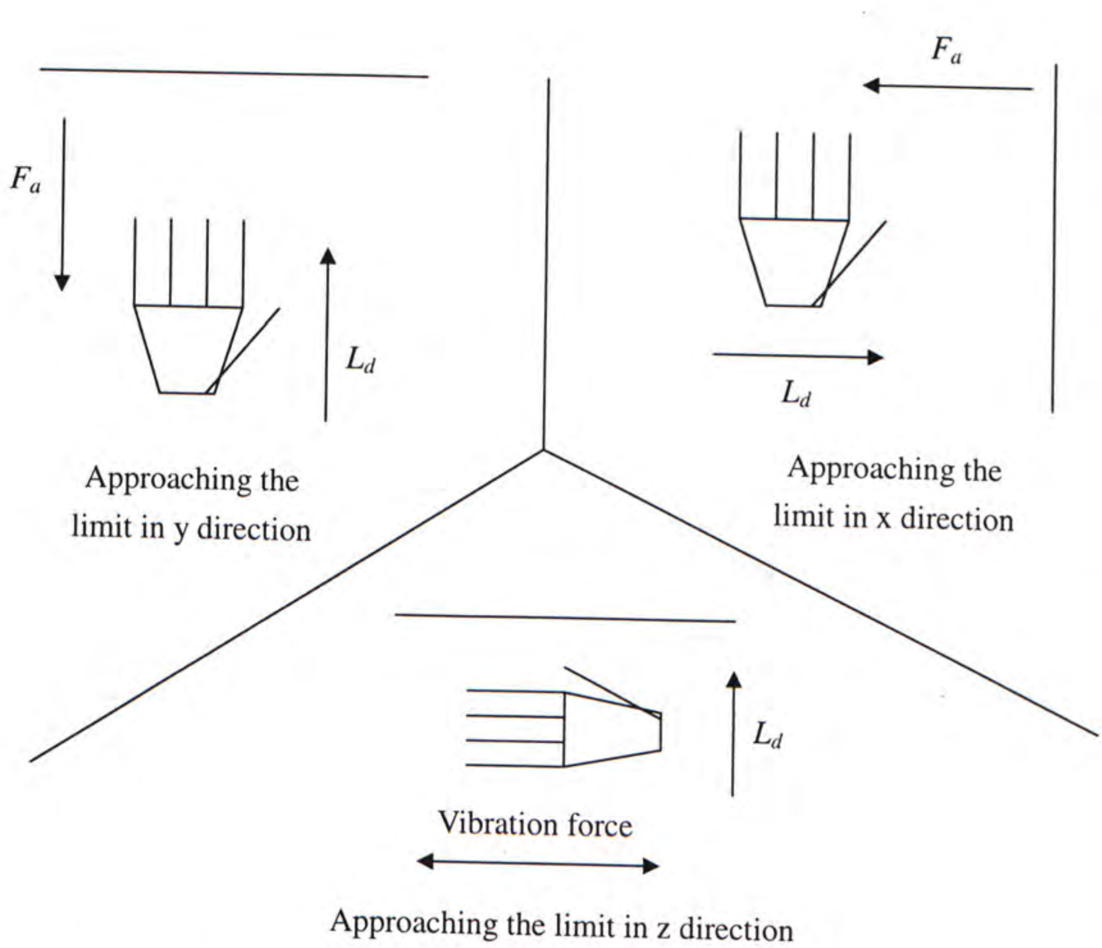

Figure 16. The generation of the reflected force in singularity avoidance

3.2.3 Interaction Rendering

In order to explore the working environment with a better view point, the mobile robot sometimes may need to enter the workspace of the robot arm. The robot hand is different from other stationary obstacle or moving object since it can move in both x, y, z direction. Therefore, the end effector may escape from the detection of the sonar sensor and collie with the mobile robot. To prevent the collision, the visual tracking system is introduced to find out the interaction between the end effector and the mobile robot.

In the real time image, the mobile robot and the robot hand is being tracked, and the position and the intermediate distance of the robots are found. The operators will not feel the feedback force until the distance between two robots is less than 60cm. And, the force will increase linearly when the mobile robot approaches to the robot hand. The reflected force is only used to alert the operators and will not affect the motion of the robots.

Both operators receive the feedback force with the same magnitude but in different direction. The mobile robot is assumed that it is always pointing to the arm's workspace and keeps away from the end effector by moving backward, so its operator will get the backward reflected force. For the robot hand system, the operator can receive the feedback force in 4 directions depended on the region of the mobile robot located. The possible directions of the reflected force for th multi-fingered arm system are shown in Fig ure 17. The interactive force can be described as follows,

$$F_v(s) = \begin{bmatrix} F_{vm} \\ F_{va} \end{bmatrix} \quad , \tag{22}$$

$$|F_{vm}(s)| = |F_{va}(s)| = \begin{cases} C_v \times (60 - D_v) & \text{for} \quad D_v < 60 \\ 0 & ,\text{otherwise} \end{cases} \tag{23}$$

where C_v is the force constant and D_v is the distance between the mobile robot and the end effector. F_{vm} and F_{va} are the interactive force sent to the operator of mobile robot and that of the robot arm respectively.

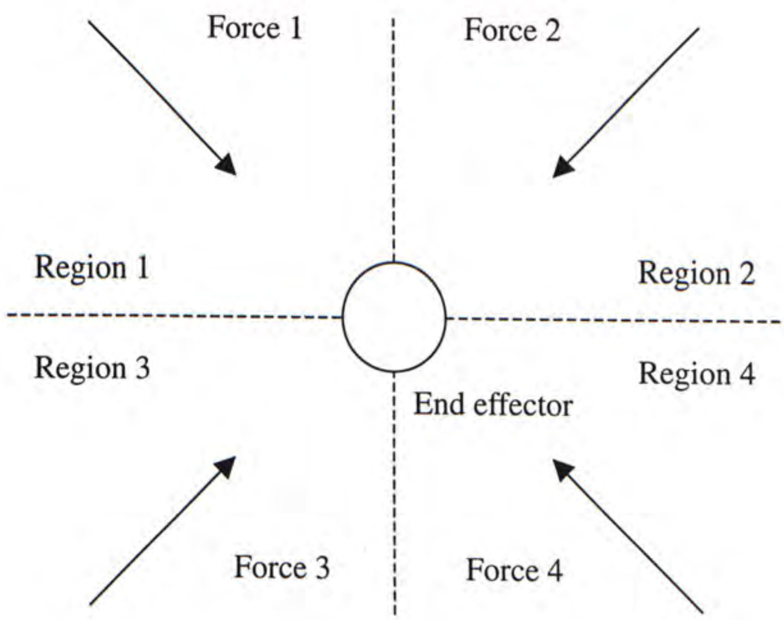

Figure 17. The possible directions of the interactive force

Chapter 4

Experiments

To evaluate the developed system, several experiments were carried out among the Mainland China, Hong Kong, USA to verify its performances. Described here are two of the experiments in which the mobile robot and the mutifingered robot hand are located in Hong Kong, and the operators from China and USA are cooperated to complete the specific task. The mobile robot system is controlled by the operator in Shenyany, China, and the multi-fingered arm system is operated by the operator in Michigan State, USA

4.1 Experiment 1

This experiment is aimed to verify the feasibility of the developed system and test the cooperation between the operators based on different visual information.

In this experiment, two robots are controlled independently. The operator at China moves the mobile robot around the working environment based on the images of entire working environment captured by an over-head camera, while the operator at USA controls the robot hand with the images captured by the CCD camera mounted on the mobile robot. At the beginning, the mobile robot is located far away from the robot hand. The mobile robot operator needs to move the robot to approaches to the robot hand. Also, the operator needs to keep the pan tilt head pointing to the robot arm's workspace. Once the operator notices that the arm start moving, he will stop moving the mobile robot and keep it remain stationary. For the operator in USA, he is waiting for the image of the hand's workspace to perform the grasping task. And, he will not start moving the arm until he finds that the image he obtained is good for him to do the manipulation. Based on the image, he operates the manipulator to grasp an object and puts it into a box. In this case, a small ball is used.

During the experiment, both operators will get the force feedback from the robots. The mobile robot operator receives the feedback force for obstacle avoidance, so that he can explore the working environment without collision with objects. The robot arm operator will obtain the reflected force for singularity avoidance to prevent him from moving the arm to the workspace limited

In Figure 18 and 19, the plots of the actual velocity, the desired velocity and the velocity error of the mobile robot in translation and rotation are shown respectively. As shown in the graph, the motion of the mobile robot follows the motion commands. The variation between the actual motion and the desired motion is mainly due to the controller design. The communication delay is the other cause of the variation.

And, Figure 20 to Figure 22 show the desired path and the actual path of the end effector, and the position error in the direction of x, y, z respectively. The graphs show that both the mobile robot and the robot arm are moved corresponding to the motion command and the response of the robots is fast and synchronized. The occurrence of the error is due to the delay between the remote and local site.

This result indicated that the system is able to achieve the stability and synchronization even the time delay in communication is existed, and the feasibility of the developed approach for internet based teleoperation is proven.

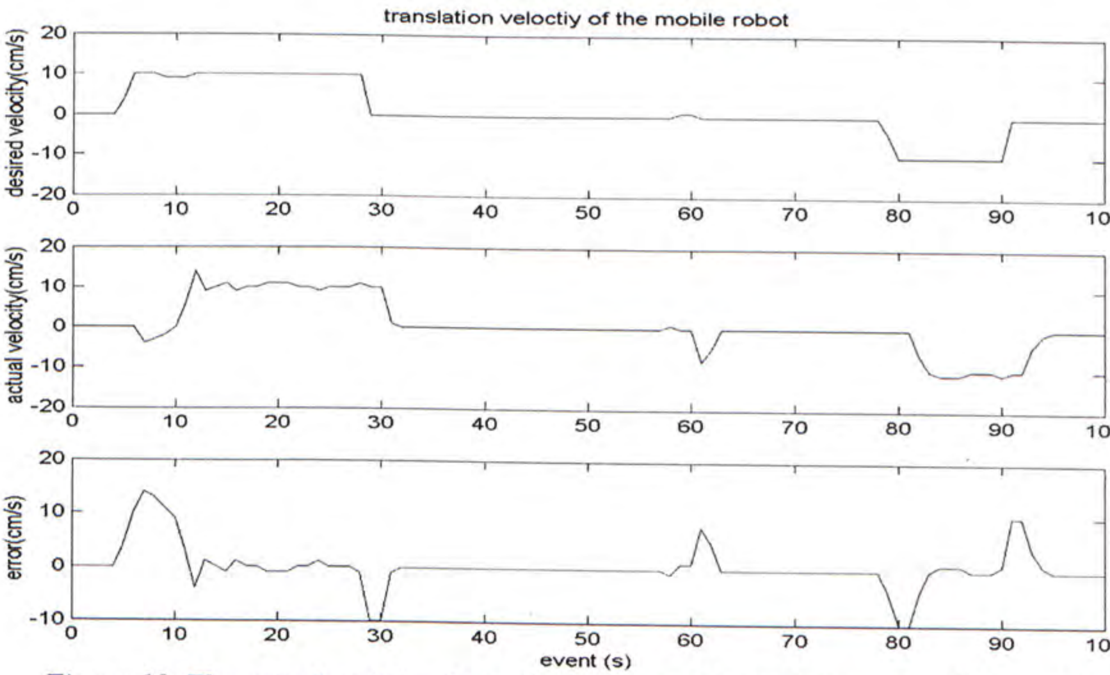

Figure 18. The actual and the desired velocity and the velocity error of the mobile robot in translation

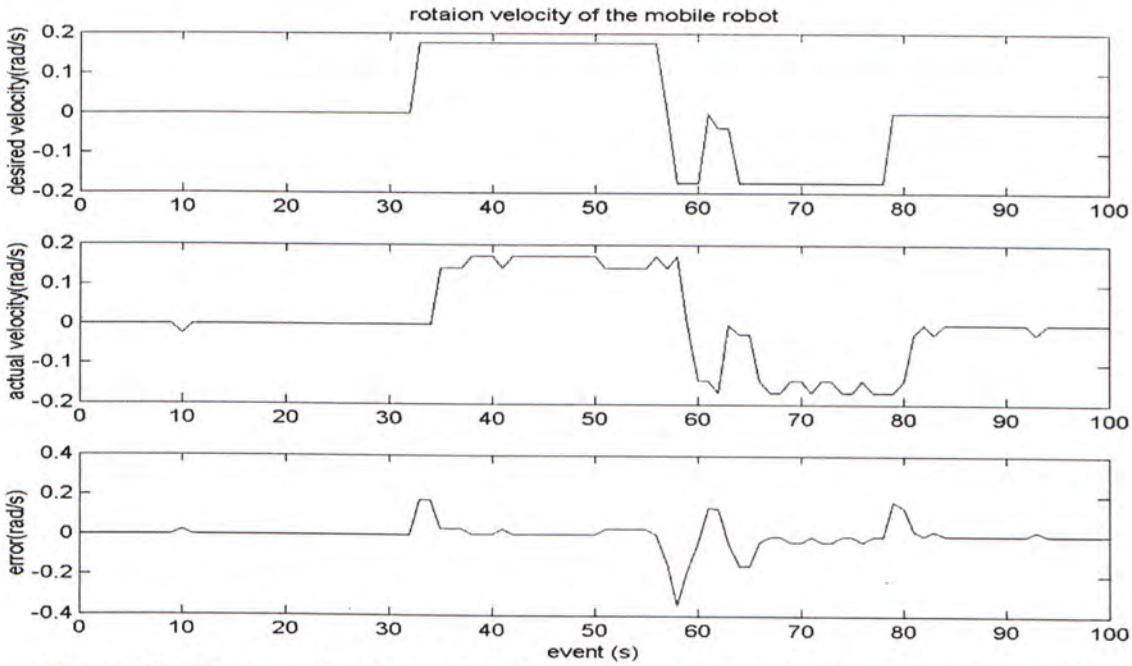

Figure 19. The actual and the desired velocity and the velocity error of the mobile robot in rotation

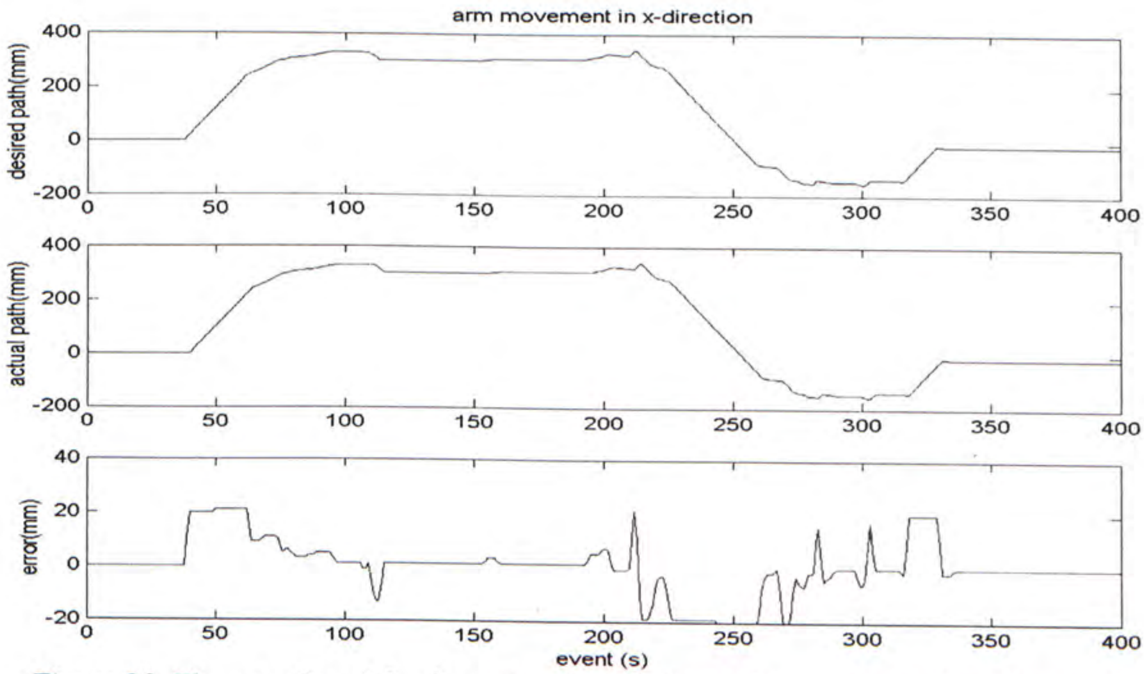

Figure 20. The actual and the desired path, and the position error of the robot arm in x direction

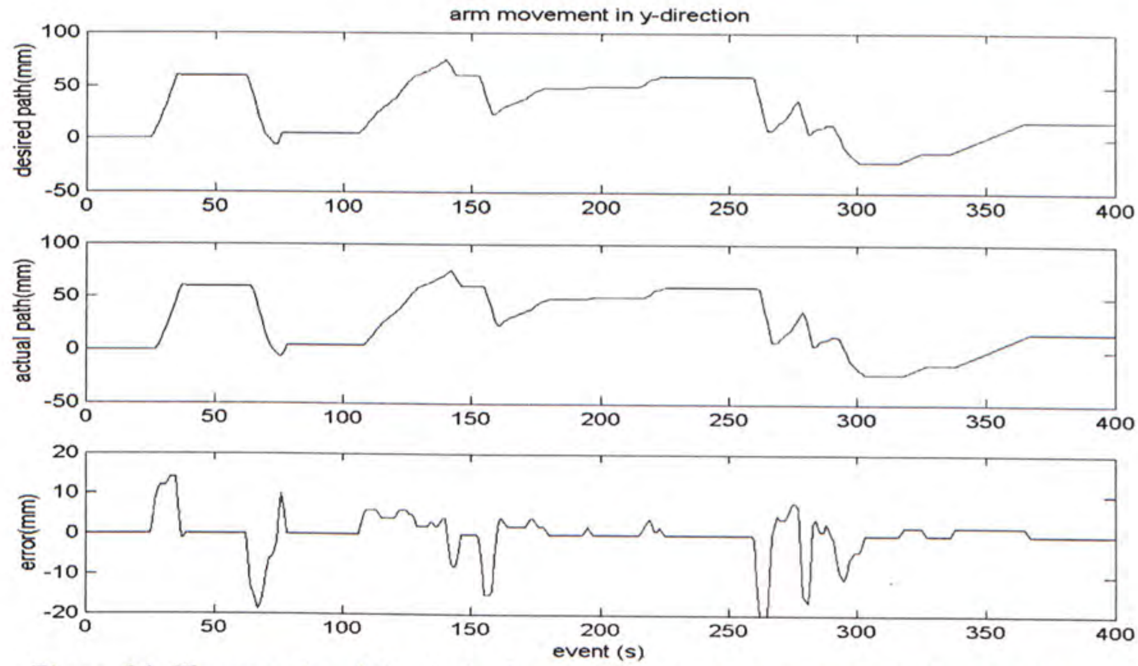

Figure 21. The actual and the desired path, and the position error of the robot arm in y direction

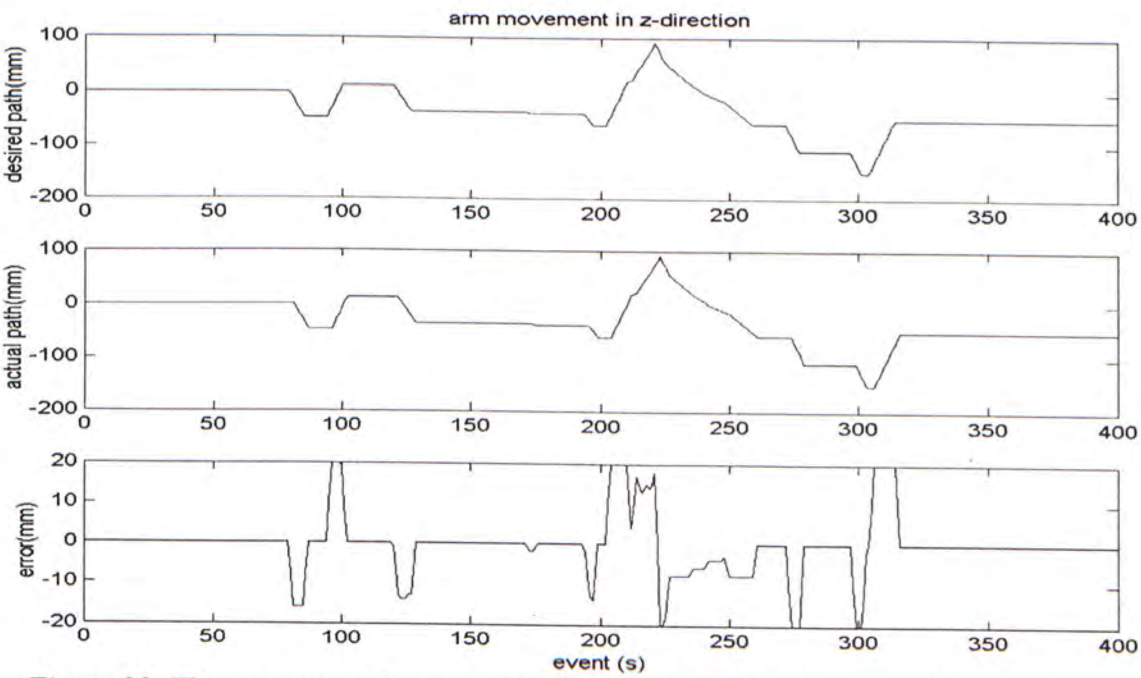

Figure 22. The actual and the desired path, and the position error of the robot arm in z direction

4.2 Experiment 2

This experiment is aimed to verify the performance of multiple clients of the system by adding the client of visual tracking system, and tests the cooperation of the operators with the similar video feedback.

In this experiment, two cameras mounted on the pan-tilt head are used to send image to China side and US side, and therefore both operators can get the similar image. The experiment starts with the mobile robot locating near the robot arm and looking at the arm's workspace. The operator at China controls the mobile robot to help the operator at USA in grasping the object by providing a better point of view of the robot hand's workspace. Next to the target object, there are two boxes. After the object is grasped by the robot hand successfully, the operator at China moves the mobile robot to view at either one of the boxes telling the operator at USA which box he should put the object. Based on the visual command sent by the China side, the operator at USA operates the robot hand to put the object into the specific box. In addition, the visual tracking system is used to determine the interaction between the mobile robot and the end effector of the robot hand, and the obtained force feedback will be sent to remote side to alert the operators if two robots are close to each other. Therefore the robots are not controlled independently but interact to each other mutually.

During the experiment, operators will not only receive the feedback force for obstacle avoidance and singularity avoidance, they will also obtain the interaction between the robot arm and the mobile robot. The interactive force can help the operators to keep a distance between two robots, and therefore the robot hand will not collide with the mobile robot even the mobile robot has entered to the robot hand's workspace.

In Figure 23 and 24, the plots of the actual velocity, the desired velocity and the velocity error of the mobile robot in translation and rotation are shown respectively. In the graph of the translation velocity, there is an inconsistence between the actual and desired velocity. This is due to the poor performance of the controller at slow speed, and the effect of obstacle avoidance algorithm. As the mobile robot is only allowed to move at half of the desired velocity if it is near an obstacle, the controller fails to move the mobile robot smoothly when the speed is slow. The inconsistence occurs when the mobile robot enter the robot arm workspace. However, the rotation of the robot does not affect by the obstacle avoidance algorithm, so the actual rotation velocity is at the same pattern as the desired one.

In Figure 25 to Figure 27, the desired path and the actual path of the end effector, and the position error in the direction of x, y, z are shown respectively. The graphs show that the robot arm's motion follows the command sent by the operators. However, the error shows that there is a delay between the desired path and the actual. It is believed that the delay is caused by the communication delay over the Internet.

With the obtained results, we find that the system is still stable and synchronized even the visual tracking system is implemented. As the visual tracking system is the second client of both robot server and arm server, this proves that the developed system is able to extend to multi clients approach and guarantees the communication between the server and different the clients.

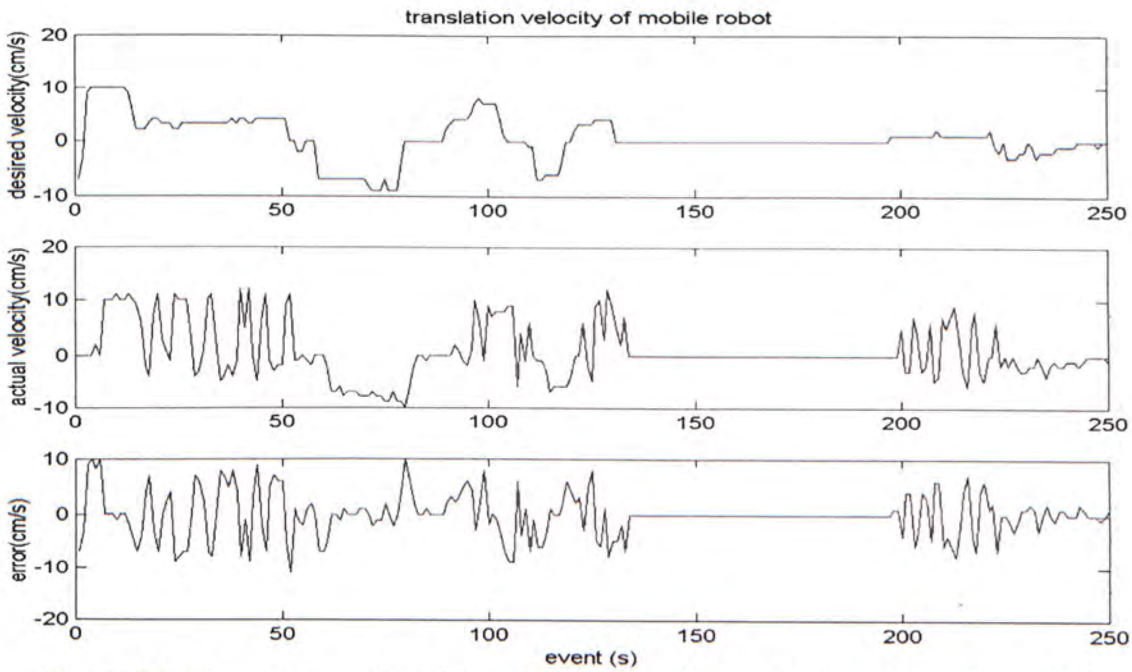

Figure 23. The actual and the desired velocity and the velocity error of the mobile robot in translation

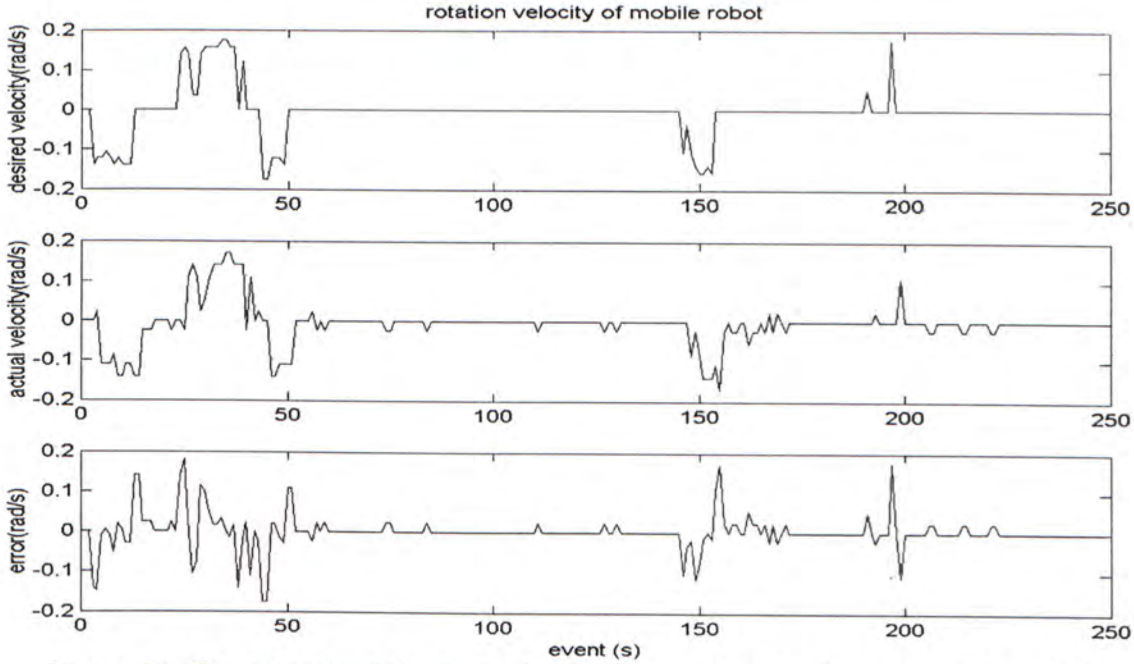

Figure 24. The actual and the desired velocity and the velocity error of the mobile robot in rotation

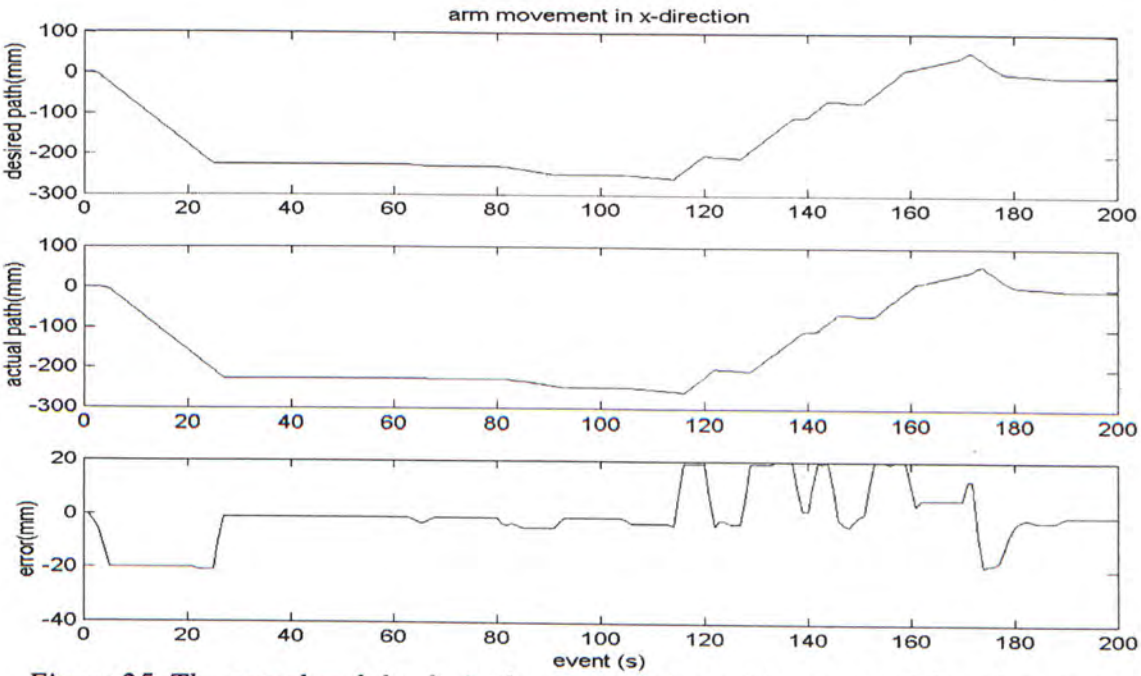

Figure 25. The actual and the desired path, and the position error of the robot arm in x direction

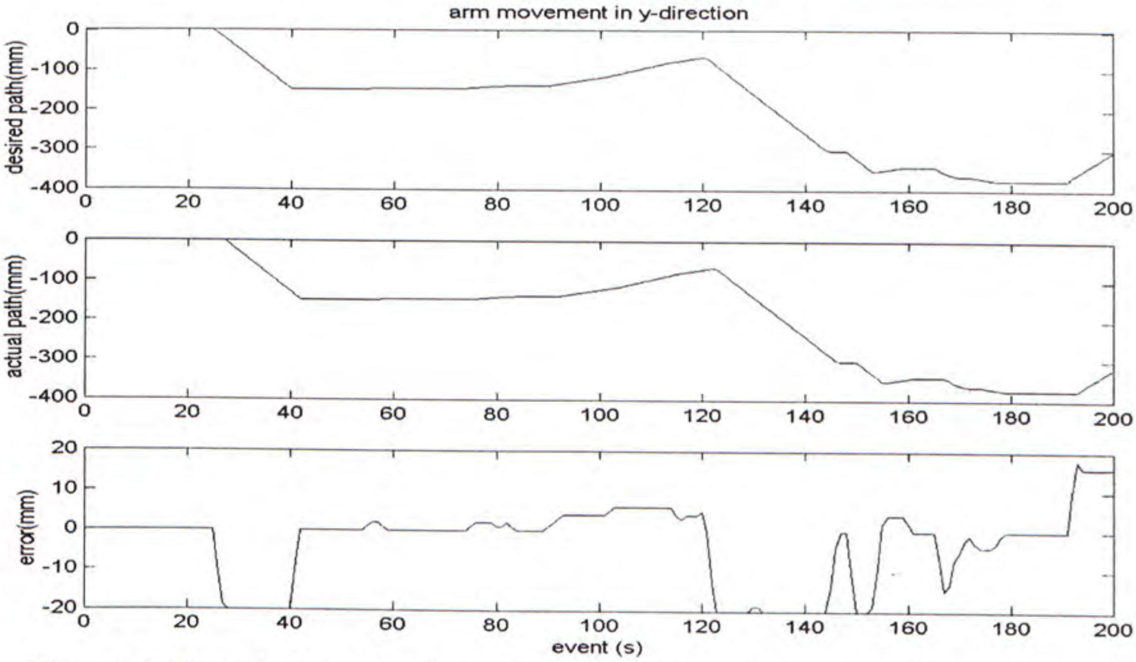

Figure 26. The actual and the desired path, and the position error of the robot arm in y direction

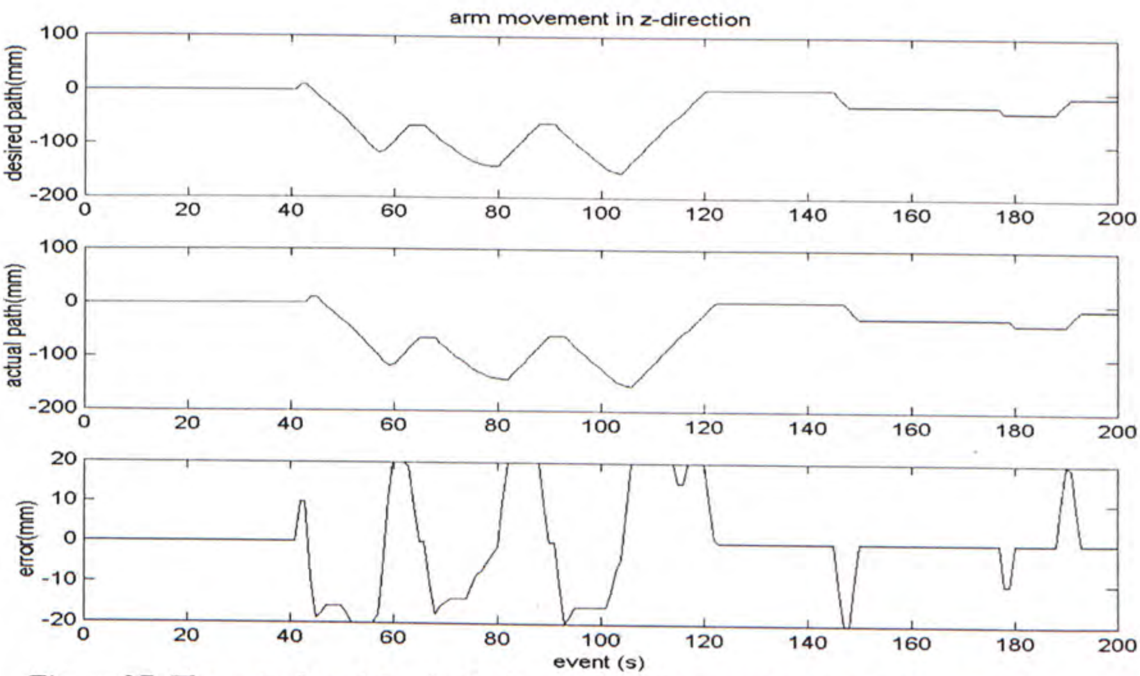

Figure 27. The actual and the desired path, and the position error of the robot arm in z direction

4.3 Experiment 3

Another experiment is carried out to verify the performance of orientation control of the robot hand. Besides the position, the orientation of the end effector about x and y axis can be controlled as well. As the fingers are connected with a number of cables, due to the safety reason, the orientation about the z axis is unable to be changed. The results are shown in Figure 28 and Figure 29. Figure 28 shows the desired orientation, the actual orientation and the orientation error about x axis and Figure 29 shows the same things about y axis. The plots show that the motion of the hand follows the commands sent by the operator and the system is stable.

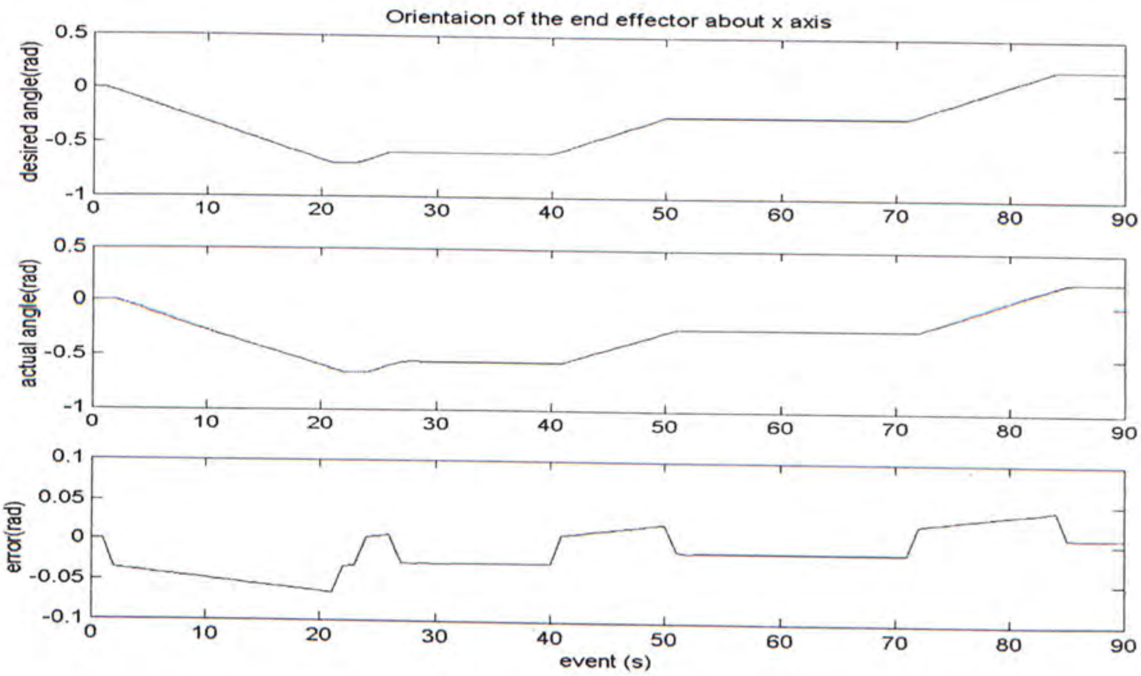

Figure 28. The actual and the desired angle, and the angle error about x-axis

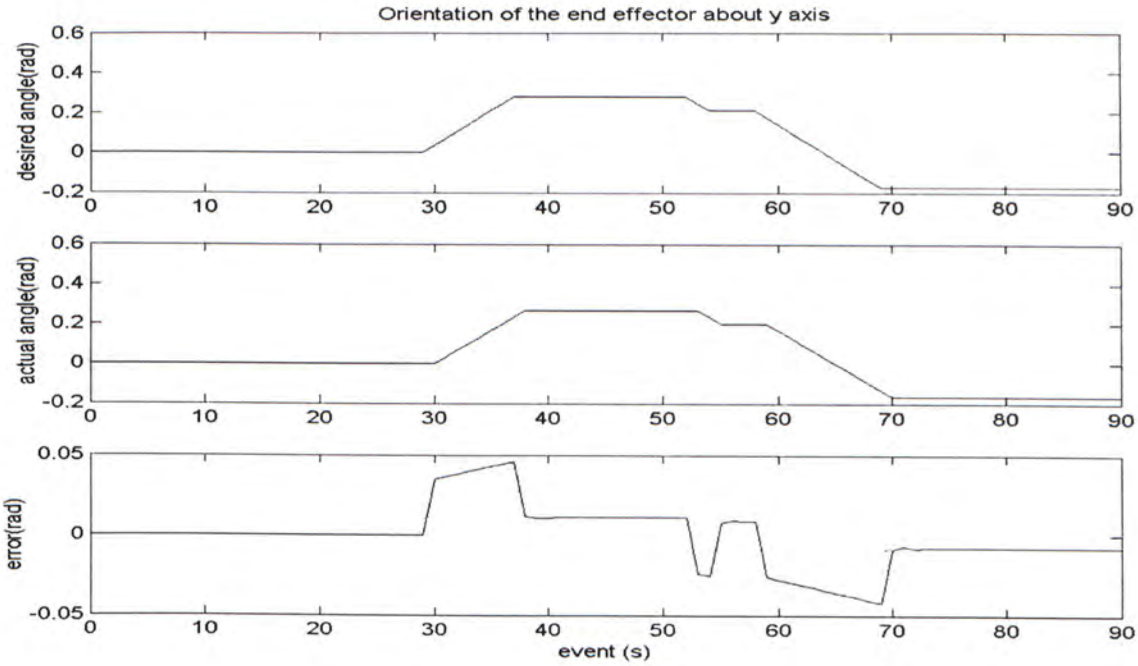

Figure 29. The actual and the desired angle, and the angle error about y-axis

Chapter 5

Future Work

A cooperative teleoperation of multiple robots, which has great potential in expanding to various applications, is an interesting research area. To enhance the ability of the presented system, several suggestions were given in different aspects as follows:

1. Using an input device with higher degree of freedom in controlling the manipulator is one of the suggestions. The flexibility of the input device has a direct effect on the operator's performance, and hence the performance of the whole system. Adopting a high degree of freedom input device such as PHANTtoM allows the operators have the better control on the manipulator and thus increase the dexterity of the operation.

2. The second suggested work is introducing new robots possessed different resources to the system. The participation of the new robot can bring new functions to the system and widen the implementation of the system on different

fields of automation. For example, the integrated system can be implemented in the cleaning procedure if a robot equipped with cleaning tools, liked water nozzle, is included.

3. Internet-based tele-cooperation is a fast growing remote control technique. A lot of investigations can be carried out on its application such as intelligent home and 'e- hospital'.

Chapter 6

Conclusions

Presented in this thesis is a cooperative control of multi robots for Internet-based teleoperation with force reflecting. A cooperative telerobotic system consisting of a mobile robot and a multi-fingered robot hand is developed to demonstrate the proposed approach. In addition, a visual tracking system is introduced to find out the interaction between two robots.

Concerning random time delay problem over the Internet, it is overcome by applying an event based controller. And, the performance of the presented system is verified by several teleoperation experiments carried out among China, Hong Kong, and USA with satisfactory result.

With such remote control technique, different operators at different location can collaborate concurrently all over the world via the Internet. This can help to reduce the cost of on-site operations which need the operator takes time to travel and can prevent human from exposing in some risky area such as unclear plant, underground mine, and underwater environment. And, it is hoping that such technique can be expanded to the general application such as intelligent home and 'e-hospital' in the future.

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