A robot arm/hand teleoperation system with telepresence and shared control

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Jiawei Li
University of Nottingham Ningbo China

Hong Liu
Harbin Institute of Technology

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A Robot Arm/Hand Teleoperation System with Telepresence and Shared Control [1]

Haiying Hu, Jiawei Li, Zongwu Xie, Bin Wang
Robot Research Institute
Harbin Institute of Technology (HIT)
150001 Harbin, P.R. China
huhaiying @hit.edu.cn

Hong Liu, Gerd Hirzinger
Institute of Robotics and Mechatronics
German Aerospace Center, DLR
82230 Wessling, Germany
hong.liu@dlr.de

***Abstract*—This paper describes a master-slave teleoperation system which is developed to evaluate the effectiveness of teleopresence in telerobotics applications. The operator wears a dataglove augmented with an arm-grounded force feedback device to control the dexterous hand and utilizes a Spaceball to control robot arm. Contact forces measured by the finger sensors can be feedback to the operator and visual telepresence systems collect the remote operation scenes and display to the operator by a stereo helmet. A primitive autonomous grasp system based on parallel joint torque/position control is developed. The experimental results show that this teleoperation system is intuitive and productive and the primitive autonomous grasp is feasible and efficient.**

I. Introduction

THE goal of teleoperation is to allow a human to control a robot in a situation where it is inconvenient or unsafe to place a human and difficult to program a robot to autonomously perform complex operations. Now many teleoperation tasks demand the robot to perform more complex and difficult works. Dexterous telemanipulation is an extension of the field of teleoperation. Michael Turner and Mark Cutkosky define dexterous telemanipulation as teleoperation where the end effector of the robot is a dexterous hand, and the robot finger motions are controlled by motions of the operator's fingers [1]. In recent years, many researchers have devoted their attention to create teleoperation system with highly dexterous masters and slaves that give the overall system operator-centered control and intuitive feedback. In some of these systems, the robot arms are operated by joysticks or space ball [2][3], while others are controlled by moving the operator's arm with tracker mounted on the wrist [1][4][5]. Some systems track the human hand through use of a vision system, which has the advantage of being non-intrusive at a penalty of cost and complexity [6]. Most of dexterous hands are teleoperated by dataglove [1][2][3][4][5] with kinds of mapping method[7] [8][9].

In these remote teleoperated circumstances, the operators would wish to input body motions (legs, arms, hands and head) which the robot would duplicate, and receive from the remote sensors full visual, audio and tactile feedback [4]. This forms a domain known as telepresence or tele-existence. It can provide useful information to enhance operator perception of the task environment and aid task completion. Telepresence techniques include haptic feedback, vision feedback and audio feedback. A good overview and introduction of haptic interfaces can be found in [10]. Many teleoperation systems have implemented and tested the force feedback devices [11] [12]. In many cases, a stereo vision feedback is implemented in teleoperation system.

Telepresence is no way to preclude sensible automation. Shared control is actually one of the most important features. In many instances it makes sense for the robot to have reflex actions, such as local force torque compliance or protection, or be able to perform tedious holding object tasks that may tire an operator. A set of primitive autograsps have been developed in our teleoperation system. In this way, the teleoperator can relax his fingers while dexterous hand maintains a firm grasp.

This paper attempts to set up a teleoperation system with high robot dexterity and deep human immersive control. The following sections firstly introduce the system architecture, and then detail the arm/hand robot system and their control methods, the human interface and force, vision telepresence. Then this paper details the primitive autograsp. In the last, this paper gives the results of the teleoperation experiments.

II. System Architecture

Fig.1 shows a teleoperation scene: this teleoperation system can be divided in to three main parts: human operation interface, telerobot system and local network communication system. In human operation interface side, there are kinds of

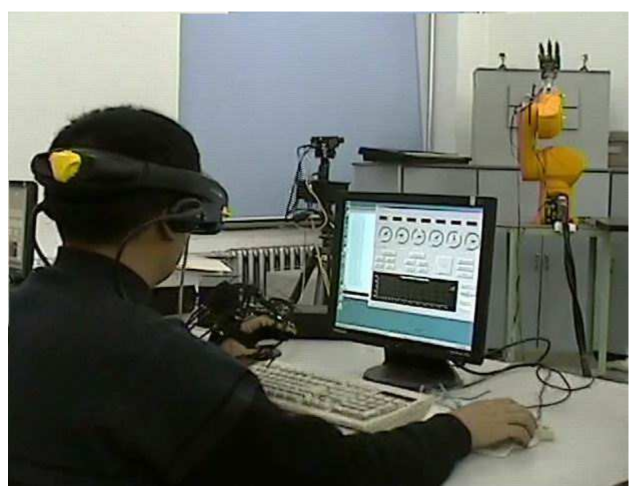

Fig.1 a robot arm/hand teleoperation system with telepresence

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input devices like Space Mouse, dataglove and the teleopresence devices like the force feedback device: CyberGrasp, vision feedback device: helmet. In the telerobot system, there are an arm/hand robot system, table, parallel hand-eye cameras system and world cameras system. The robot arm is a Staubli RX60 robot and the hand is HIT/DLR dexterous hand. The local network communication system is based on the TCP/IP protocol and the Sever/Client mode which connects the human operation interface system and the telerobot system. Because time delay caused by the local network communication is very little, all the experiments in this paper ignore the effect of time delay.

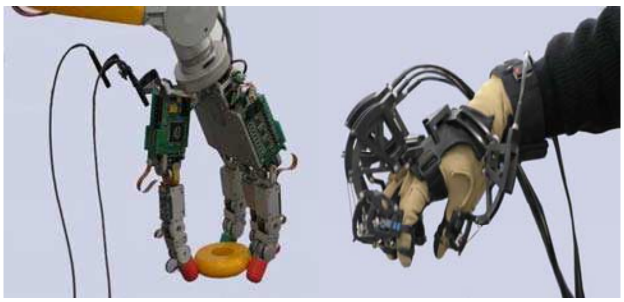


Fig.2 HIT/DLR hand with dataglove and CyberGrasp

III. TELEROBOT SYSTEM AND HUMAN INTERFACE

A. Dexterous Robot Hand and its Position Control System

The HIT/DLR hand is a multi-sensory and integrated four fingers with in total thirteen degrees of freedom (DOFs), which is approximately 1.5 times that of a human hand, as shown in Fig. 2. Each finger has three DOFs and four joints; last two joints are mechanically coupled by a rigid linkage (1DOF). The thumb has an additional DOF to realize the motion relative to the palm. This enables to use the hand in different configurations. In this hand, 13 commercial brushless DC motors with integrated analog Hall sensors systems as well as more than 100 sensors are integrated in the fingers and palm. DSP based control system is implemented in PCI bus architecture and the high speed serial communication between the hand and DSP needs only 3 cables. The high degree of integration and low weight (1.5kg for whole hand) make the HIT/DLR dexterous hand can be completely mounted on a robot arm. The HIT/DLR hand has an abundant sensor system: in a finger, the base joint has a two dimensional torque sensor, middle joint has a one dimensional torque sensor and the fingertip has a six dimensional force/torque sensor.

Teleoperation of dexterous robot hand requires continuous and accurate control of finger positions. The robot finger joints are controlled by a proportional and derivative control law about desired positions and velocities. The desired joint positions and velocities are calculated from fingertip mapping method; detail information is described in reference [13].

Fig.3 shows the diagram of the PD position controller. In the diagram, where θ_{d1}, $\dot{\theta}_{d1}$ are the corresponding desire joint angle and velocity of base joint 1 getting from joint space

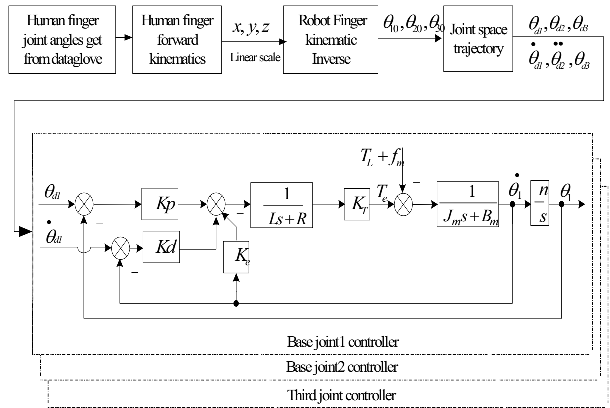


Fig.3 diagram of joint position control

trajectory generation. θ_1, $\dot{\theta}_1$ are the actual joint angle and velocity measured by the sensors. K_p, K_d are corresponding coefficient factors of proportional and derivative.

B. Industrial Robot Arm and Spaceball

The dexterous hand is mounted on the wrist of a Staubli RX60 robot arm. The RX60 robot has a positional repeatability of ± 0.02 mm and maximum speed of 8m/s. In this system, we use the "Alter" command (a real-time path modification command) to implement the path modification. The use of the "Alter" command is summarized below:

Alter ( ) DX DY DZ RX RY RZ

The command makes the robot translate DX,DY,DZ along the X,Y,Z axes and rotate RX,RY,RZ about the X,Y,Z axes. The modified desired positions are from the output of Space Mouse through the local network communication. We use the Space Mouse as the 3D input device, which has six DOFs and can control the end position and orientation of the Staubli RX60 robot. The displacement range of the Space Mouse is fairly small. Therefore, the Space Mouse values are not interpreted as absolute position commands, but as velocity commands.

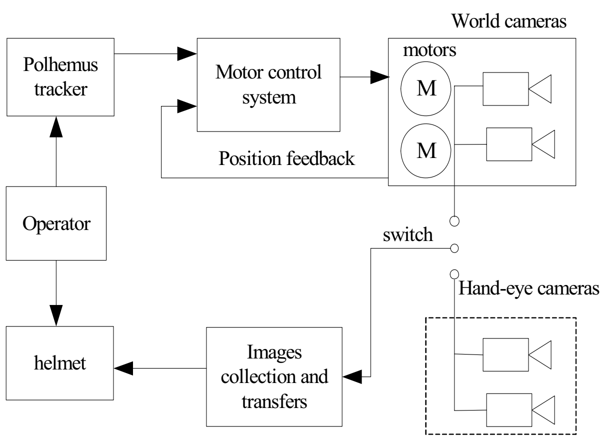
C. CyberGlove and CyberGrasp

Using human action to guide robot execution can greatly reduce the planning complexity. The most intuitive way to control a dexterous robotic hand is to make it follow the movements of a human hand, e.g. by the use of a dataglove. As shows in fig.2, we use CyberGlove® as a hand input device, which is constructed with stretch fabric and 23 resistive bend sensors that describe the five fingers' joint angles and the orientation of the hand. CyberGlove® is shipped with calibration software, but the human hand fingertip positions obtained through this way are not precise enough to control a dexterous robot hand. So we calibrated human hand with the glove based on a vision system [13]. In our teleoperation system, there are two ways to map the human hand motion to robot hand: joint space mapping and Cartesian space mapping. The former is more suitable for enveloping (or power) grasps and the later is more suitable for fingertip (or precision) grasps.

A Cybergrasp exo-skeleton is used to create one dimensional force feedback per finger, a cable driven device designed for use with the CyberGlove. The forces applied to the finger are unipolar, since the cable can only pull along a single axis, and are grounded to the back of the user's hand, so no forces restrain arm motion. The motors can apply force up to 12 N and are updated at 1000 Hz to appear smooth and continuous to the user. Generally, the feedback force should be measured by the fingertip force/torque sensor. But now we only have two six dimensional force/torque fingertip sensors. So in this system, we use the joint torque sensor to calculate the force in the fingertip coordinate and feedback the calculated one to the CyberGrasp controller. The basic relation between joint torques and the generalized force in the fingertip coordinate system could be written in the form of:

$$F_{ext} = J_F^{-T} \cdot \tau_{ext}$$

where $\tau_{ext} = [\tau_1 \quad \tau_2 \quad \tau_3]^T$ is a 3×1 vector representing joint torques in the base joint and the third joint and $F_{ext} = [F_x \quad F_y \quad F_z]^T$ is a 3×1 vector representing the generalized external forces in the fingertip coordinate system. J_F is the finger force Jacobian matrix.



(a) visional telepresence diagram

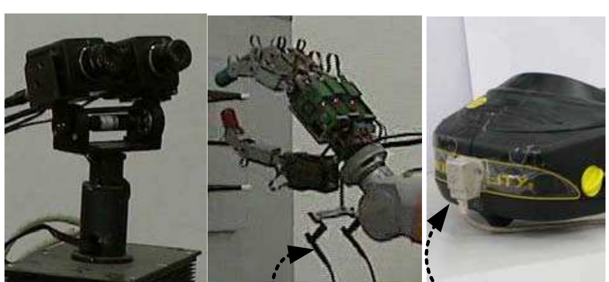

(b) world cameras and its platform (c) hand-eye cameras (d) tracker and helmet

Fig.4 vision telepresence system

D. Visual Telepresence

Fig.4 (a) is a diagrammatic picture of the visional telepresence system. Stereo video collection part consists of a stereo world camera system and a stereo hand-eye camera system. A helmet is used as the stereo video display device. The world camera system provides the whole operation scene and the hand-eye camera system provides local scene of the hand dexterous manipulation. These two kinds of vision feedback can be smoothly switched: when the operator uses the Space Mouse to control the RX60 robot, the world vision system provide the whole scene to the helmet; when the operator uses the dataglove to control the dexterous robot hand, the hand-eye system feedback the hand manipulation scene to the helmet. In each vision system, there are two parallel CCD cameras. The baseline of world cameras is 12cm and the baseline of the hand-eye cameras is 8cm.

In order to extend the vision field, we have developed a motional platform and put the world cameras on it. The platform has two degrees of freedom: pan and tilt. The each axis moving range is $\pm 180^\circ$ and is driven by a DC motor. A four axis servo-controller for DC motor has been developed to control this platform. We put a Polhemus tracker on the helmet which can measure pan and tilt motion of the operator's head. So it can map the motion of the operator's head to the platform. In this way, the operator can freely see the scene where he is interested.

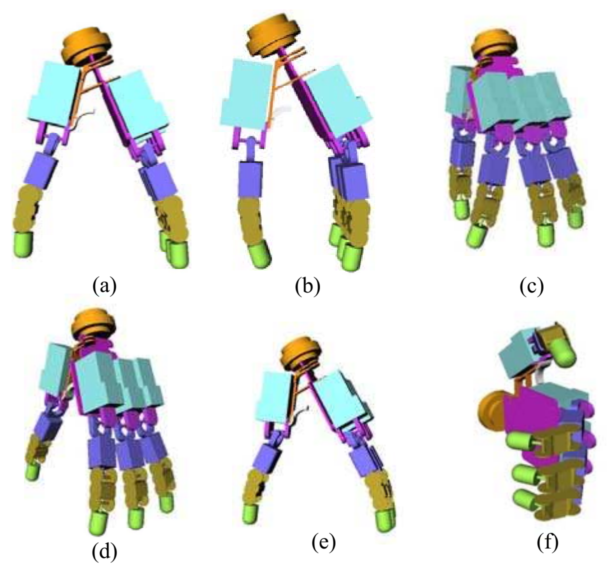


Fig.5 grasp preshape: (a) large precise grasp. (b) Little precise grasp (c) sphere precise grasp (d) sphere power grasp (e) cylinder power grasp (f) side opposition grasp

IV. Primitive Autograsp

A. Primitive Autograsp and Preshapes

Because the kinematic difference between the human hand and the dexterous robot hand, the motion mappings especially based the joint space mapping are not very intuitive, in some tasks, the human grasp pose is very unnatural. Also, it is much tired work for the teleoperator to keep a stable grasp pose in order to hold an object for a long time. Especially if the teleoperator has little move with his fingers when the dexterous hand is holding an object, the object will drop and the teleoperation task may be failed.

In this paper, we defined and fulfilled six representative autograsp: small and large precision grasp, sphere precise grasp, cylinder power grasp, sphere power grasp and side opposition grasp. Given predefined angle of flexion and abduction, this paper presents six corresponding preshapes: Fig.5 shows the preshape configuration.

B. Parallel Joint torque/Position Control

Successful control of contact transitions is an important capability of dexterous robot grasp; Hong Liu [14] proposed a parallel torque/position control strategy for the transition phase in the DLR hand. This strategy combined simplicity and robustness of the impedance control and sliding mode control with the ability to control both torque and position. The kernel of the strategy is the design of a parallel observer which determines which control mode should be active. In this paper, we implement this control strategy to HIT-DLR hand joint control, pure PID position control systems will follow the commanded position trajectory and impedance joint torque control is introduced for the motion control in the constrained environment by tracking a dynamic relation between the active force and impedance.

Fig.6 shows the block diagram of impedance torque control and Fig.7 shows the diagram of the parallel torque/position control. In the diagram, where θ_d, $\dot{\theta}_d$ are the corresponding desired joint angle and speed determined by the trajectory. θ_m, $\dot{\theta}_m$ are the actual joint angle and speed measured by the sensors. τ_d is desired joint torque, τ_{ext} is actual joint torque. The parallel observer control mode switching to contact motion is only determined by contact torque: when $\tau_{ext} > \tau_{th}$, the mode switches from PID position control to the impedance joint torque control, where τ_{th} is threshold torque.

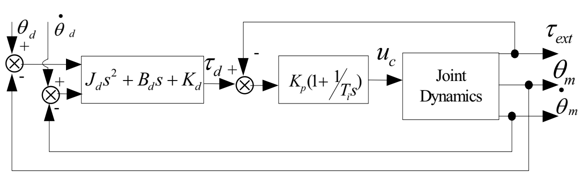


Fig.6 Block diagram of impedance torque control

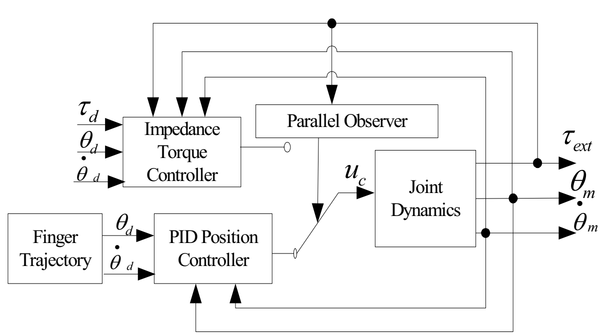


Fig.7 Block diagram of parallel torque/position control

In the autonomous grasp, each joint reference angle θ_d is difficult to be definitely settled because of uncertainty of the object. In the impedance force control mode, we let the current reference joint angle

$$\theta_d^i = \theta_d^{i-1} + \Delta\theta_i$$

$$\Delta\theta_i = \frac{\tau_d - \tau_{ext}}{J_d s^2 + B_d s + K_d}$$

Where θ_d^{i-1} is previous reference joint angle, $\Delta\theta_i$ is the adjustment value of reference angle. J_d, B_d, K_d are the desired target impedance parameters of the robot finger joint, τ_d is the desired joint torque. The two equations mean that if τ_{ext} is not equal to τ_d, current reference angle will be adjusted by the $\Delta\theta_i$ in order to get the desired joint torque.

C. Control Modes Switching

Control modes switching is for the fully teleoperation based on the dataglove and autonomous grasp; for the dexterous hand, the joint control mode switches between pure position control mode for fully teleoperation and parallel joint torque/position control mode for autonomous grasp. In the experiment, three functional buttons in the Space Mouse are set for the control mode switching: the first button is set for the switch between fully teleoperation to autonomous grasp, the second button is set for execution of preshape of dexterous hand, and the third button is set for the execution of autonomous grasp.

For example, if the active mode is fully teleoperation at present, when the first button is pushed, the joint control model switches to parallel joint torque/position control; when the second button is pushed, the system control the hand to the predefined position of corresponding preshape which is selected by the operator. The preshape parameters are chosen in order to make the estimated distance-to-contact possible small and stratify the precondition of obstacle avoidance. When the third button is pushed, the dexterous hand executes the corresponding autonomous grasp, and then it encloses each finger and finish the grasp based on the force/torque sensors.

V. TELEOPERATION EXPERIMENTS AND RESULTS

A. Fully Teleoperation Experiment: Draw a Drawer and Put in a Ball

Task descriptions: As show in fig.8, this teleoperation task can be divided in to three steps: 1) Draw a drawer in front of the robot;2) Grasp and pick up a ball in its right side; 3) Put the ball in the draw and close the drawer.

We design three kinds of situations for this task: 1) both world stereo vision and hand-eye stereo vision feedback and the two kinds of vision feedback can be switched as needed. 2) Only world stereo vision feedback. 3) Only local hand-eye

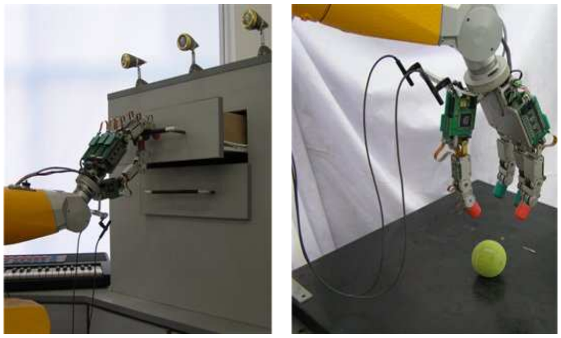


Fig.8 drawer a drawer and put a ball experiment

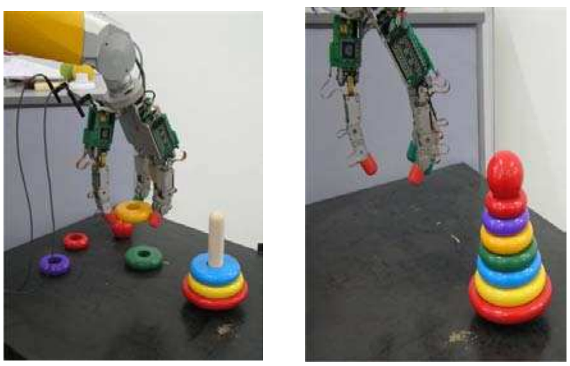


Fig.9 place a tower with a circle block experiment

stereo vision feedback. Three situations are all with force feedback and in the same other conditions.

Experimental results: the operator performed this task threes times for each situation. The operator can successfully complete the task in the first and second situation, but can't finish the task in the third situation. In the first situation, the average time for complete this task is about 16 minutes; for the second situation, it is about 20 minutes.

Observations: In third situation, because there is no world vision feedback, the operator can not see the RX60 robot and don't know the joint configuration of the robot, so the operators can't avoid the collision between the robot joint and obstacle. In some cases, the robot joints are out of the range but the operators don't know. In the second situation, because of the resolution limit of the helmet, the operator can't clearly see the local operation scene only based on the world vision feedback. For instance, when the operator control the robot arm/hand to approach to the drawer, the operator is difficult to judge whether the robot hand is on the right place or whether the fingers touch the handler only based on the world vision feedback. In this situation, the operator should be very carefully and rely on force feedback to complete the operation. In the first situation, because it can switch the vision feedback between the world cameras and hand-eye cameras, the operator can clearly see the local operation scene based on the hand-eye vision feedback and finish the operation quickly.

B. Fully Teleoperation Experiment: Stacking a Tower

Three operators after 5 minutes training were asked to perform this task who never be trained before. As shows in fig.9, the arm/hand telerobot system were controlled to grasp and pick up seven circular block spreading on the table and construct a tower as quick as possible. If all of the seven circular blocks were stacked up as a tower, the task will be considered as success. The block dropping is granted in the procedure of grasping, moving, and stacking.

Experimental results: all three operators can complete this task after 5 minutes training. The first operator completed the task in 26 minutes; the second one finished this task in 22 minutes and the last one finished this task in 30 minutes. These experiments show that the telepresence control was found to reduce training time. Typically, a new operator can perform some simple teleoperation task like picking up a ball using the system after less than 5 minutes of training

C. Primitive Autograsp Experiments

We set up several experiments to verify primitive autonomous grasp. The experiment follow the steps formulated as following: firstly, the operator gets the information about the object through the vision feedback and controls the dexterous hand to the corresponding preshape. Next, the operator controls the robot arm to the appropriate position for the right grasp and adjusting the hand palm's position and orientation. Lastly, the dexterous hand performs the autonomous grasp following the predefined finger trajectory and encloses the grasp with the joint torque/position control. As show in Fig.10, this paper gives the three experiment results: precise grasp for small size object (1),

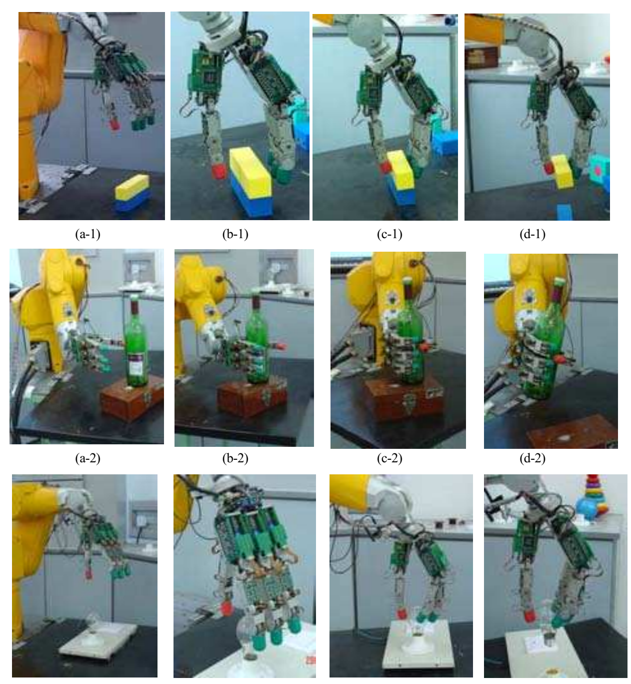


Fig.10 Experiments of precise grasp, cylindrical power grasp and sphere precise grasp

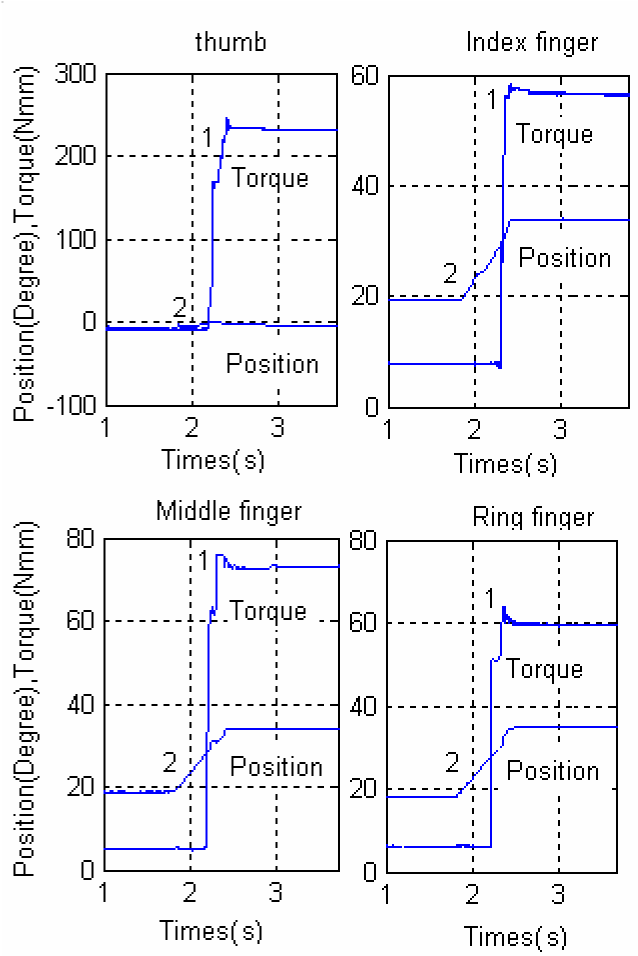


Fig.11 Joint positions and torques experimental results of the autonomous precise grasp.

cylindrical power grasp (2) and sphere precise grasp (3).

Fig.11 displays the joint angles and torques results of small precise grasp. Each finger's joint follows the trajectory and moves to the reference position until it detects a contact. The control mode is switched automatically from position control to torque control when the contact torque is greater than the threshold value of $\tau_{th} = 10Nmm$. The results shows that each finger can smoothly transfer from free space to constrained environment and holding a certainly contact force to maintain a stable precise grasp. From the experiments, we testified two main benefits of the autonomous grasp: the operator can have a natural hand pose and have rest when perform long time grasping and holding teleoperation tasks; the autonomous grasp can hold more stable joint torques than fully teleoperation mode.

VI. Conclusion and Future Work

A robot arm and dexterous hand teleoperation system is developed with force and visional telepresence. This teleoperation system allows an operator to control the telerobot in an intuitive manner to take full advantage of the operator's cognitive and skills. Several experiments were conducted to evaluate this system. Experimental results proved that this system has highly dexterous and fidelity. This system was able to be used with very little time required to train the operators. With the use of dexterous, intuitive control via telepresence technology, the efficiency and productivity of teleoperation tasks can be greatly improved.

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