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Posture-Based Virtual Force Feedback Control for Teleoperated Manipulator System

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***Abstract* - Operability/transpancy is of vital importance in telerobotic systems. For fear of collision between the end-effecter and the objects, human operator must make strict observation on the visual image and carefully plan small pieces of motion of the robot at a time. This makes operability worse. Good force telepresence can reduce the workload of human operator, overcome the limitation of vision information, and improve the operability performance of teleoperation system. In this paper, we describe a novel virtual force feedback control approach to enhance force telepresence and then make operability better. Based on accurate measurement of relative posture with a monocular vision, we first perform camera calibration to detect the relationship between pixel points in the image and points in the real object. Secondly, with the information transformation technique, the virtual reflective force is generated. Finally, virtual force feedback is used to improve the performance of operability. Experiments are made to demonstrate the effectiveness of posture-based virtual force feedback guided control method in telerobotic system.**

Index Terms - Telerobotic systems. Virtual force feedback. Force telepresence. Operability. Information transformation.

I. Introduction

With the rapid growth of the internet, the application of robots has been extended to many scenes, such as home appliances and recreation, dangerous and unexpected situations [1]. In such environments, highly intelligent decisions are needed to make dynamically to cope with the unexpected events. However, since it is hard to achieve robot completely autonomous now, this makes the robot itself is not reliable any more. Therefore, it is believed that human operator should not be excluded from the robotic systems. Correspondingly, bilateral telerobotic system has become the hottest topic of research.

Bilateral telerobotic system is effective to reproduce the force sensation of contact force at master side and then transmit it to the remote robot [2] [3]. Governed by such force sensation, robot can undertake precise tasks in many territories from traditional applications in the space, underwater environment monitoring surveillance, military operations and nuclear industries to new applications such as telesurgery and telelearning.

Fig. 1 shows a typical bilateral telerobotic system [4] [5] [6], which comprises five components: human operator, human-system interface, communication channel, teleoperator, and environment.

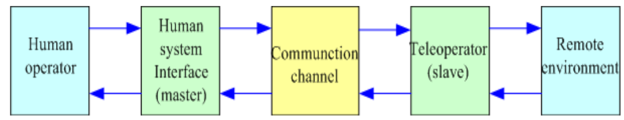

Fig. 1. Bilateral teleoperation system

For bilateral telerobotic systems, telepresence [7] is the ultimate factor for the reliable and skillful operations. Telepresence is a class of important virtual environment that stands for a special reality strengthening technique, by which the users, though being far away from a certain real site, can bind the virtual objects generated by the computer to the three dimensional images of the real physical entities from the remote site. By this way, the human operator obtains adequate feeling on the real target surroundings where they feel themselves as stepping into it. The telepresence can be achieved naturally and accordingly the performance of the telerobotic system can be enhanced. The telepresence is usually divided into two types, namely visual telepresence and force telepresence [8]-[13].

Because the information that human operator can percept comes mostly from vision, human operators rely mainly on visual message to direct the remote robot to move properly in conventional telerobotic systems. However, this approach has an ultimate shortcoming.

Without force telepresence, the error between actual position and reference position of end-effecter will cause relatively large force unnecessary, and then make the teleoperation system free of security and stability. However, force feedback can help to overcome this issue with great flexibility and high efficiency. It is proved that force feedback can enhance telepresence and improve the performance of the teleoperation system with or without visual feedback. So, force feedback is a critical factor that affects severely the performance of teleoperation.

When only visual information is offered, the human operator cannot acquire comprehensive information of interaction, such as starting time, the size of contact force, between robot and environment and then the quality of operability is becoming worse.

Due to the complexity of environment and tasks, human operator has to take strict inspections about the video stream to prevent collision between robot and environment. These will raise greatly the workload for human operator and may cause losses. So, human operator is forced to carefully plan

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small pieces of motion of the robot at a time, and execute them in a stop-and-go manner [14]. The result is a very slow and cumbersome system that is still prone to operator error and costly collisions.

Since human operators are more sensitive to haptic/force information than to visual information [14], the performance of a teleoperation system can be greatly enhanced when the contact force information is also provided to the human operator, i.e. the human operator is kinesthetically coupled to the remote environment [13].

Model-based position/posture estimation based virtual force feedback control is a very important research problem applicable to bilateral telerobotic system. Model-based position estimation based virtual force feedback control has been stated in [13]. In this paper, we will settle the problem of posture-based virtual force feedback control. Its aim is to generate a virtual reflective force according to the relative posture between the end-effecter and the object using information transformation technique. As a result, the virtual attractive force will make the end-effecter be in a good posture to finish the grapping task.

The rest of the paper is organized as follows: Section II presents a reflective force control structure. Section III gives technical implement of a specific system control structure. Relative posture estimation between end-effecter and object and information transformation will be discussed in section IV. Section V computes the virtual force. Section VI demonstrates experimental results. Section VII concludes this paper with some remarks.

II. Framework for Reflective Force Control

Due to the advantages of Force-Position/Posture control architecture in the stability and operability/transparency [15] [16], we adopt this structure in the telerobotic system. The Force- Position/Posture control architecture is shown in Fig. 2.

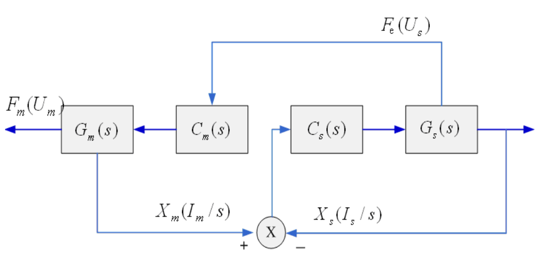

Fig. 2 Force-Position/Puosture control architecture

where F_m and F_s signify the forces exerted by human operator and environment separately. $G_m(s)$ and $G_s(s)$ represent the open-loop transfer functions of master device and slave robotic manipulators respectively. While $C_m(s)$ and $C_s(s)$ indicate the transfer functions of master and slave controllers respectively. X_m and X_s express the movement of the controller in the master side and environment respectively.

According to the equivalent simulation of mechanical systems, virtual impedance $Z_v(s)$ and environment impedance $Z_e(s)$ are defined as follows:

$$\begin{aligned} Z_v(s) &= F_m(s)/X_m(s) \\ Z_e(s) &= F_e(s)/X_e(s) \end{aligned} \qquad (1)$$

If the condition in (2) is satisfied, ideal telepresence will be acquired.

$$Z_v(s) = Z_e(s) \qquad (2)$$

A two-port hybrid matrix model is used to describe the relationship between forces and velocities at the input and output ports.

$$\begin{bmatrix} F_m \\ \dot{X}_e \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \cdot \begin{bmatrix} \dot{X}_m \\ F_e \end{bmatrix} = H(s) \cdot \begin{bmatrix} \dot{X}_m \\ F_e \end{bmatrix} \qquad (3)$$

The elements of h, which are frequency-dependent, are well-understood quantities such as gains, impedances, and admittances. The two-port hybrid matrix parameters can be derived from the system architecture and thus can be used to relate components or parameters of the system to overall system performance.

From (1), (2), and (3), the relationship between environmental impedance and perception impedance is descripted as:

$$Z_v(s) = \frac{h_{11} + (h_{12}h_{21} - h_{11}h_{22}) \cdot Z_e(s)}{1 - h_{22}Z_e(s)} \qquad (4)$$

Let $\dot{X}_m = \dot{X}_s, F_m = F_s$, we can get the hybrid parameters matrix (5):

$$H(s) = \begin{bmatrix} 0 & G_m(s)C_m(s) \\ \dfrac{G_s(s)C_s(s)}{1 + G_s(s)C_s(s)} & 0 \end{bmatrix} \qquad (5)$$

Correspondingly, the virtual impedance is

$$Z_v(s) = \frac{C_m(s)G_m(s)C_s(s)G_s(s)}{1 + C_s(s)G_s(s)} \cdot Z_e(s) \qquad (6)$$

The ideal condition that the telepresence should satisfy is

$$G_m(s) = 1 + \frac{1}{G_s(s)} \qquad (7)$$

If $Z_e(s) \to 0$ and then $Z_v(s) \to 0$, then the telerobotic system has a perfect operability/transparency.

III. System Set Up

A. *Hardware Architecture*

This section introduces the hardware implementation of experimental system. The hardware is mainly composed of maser sub-system, slave sub-system, and communication sub-system. Communication sub-system is charge of the exchange of information from all sub-systems.

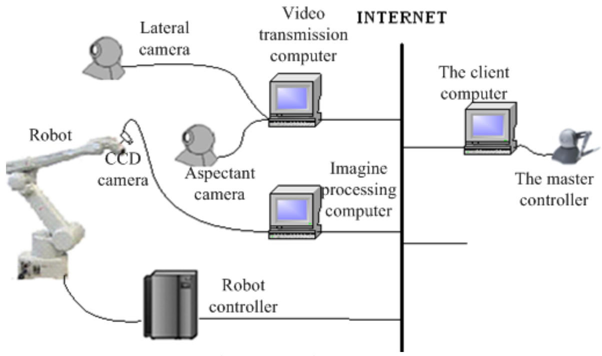

Fig. 3. Hardware setup

1) Master Sub-system: When the relative position/posture between the end-effecter and the object is received， force will be shown on the master device. Communication between the client PC and the master device is achieved with the IEEE 1394 interface.

The screen display interface is composed of two parts: the first part offers comprehensive video information about the scene using the aspectant and the lateral cameras; the second part shows control mode of robotic position/posture on a control panel.

In the client side, a PHANTOM Omni model from Sensable Technologies is employed as master device. It can provide high quality haptic/force feedback effect. It is illustrated in Fig. 4.

Fig. 4. A PHANTOM Omni force feedback device

2) Slave Sub-system: Six degrees of freedom MOTOMAN industrial robot is employed as the slave robot. The robot controller runs under a real-time operating system.

3) Communication Sub-system: Communication sub-system consists of video transmitting unit and imagine processing unit.

Video transmitting unit has three parts. Two video cameras, one presents lateral view and the other gives aspectant view, are mounted in the work scene to provide comprehensive scene information for human operator. A PC is charge of transmitting visual message from the slave side in the remote place to the client side via internet.

Imagine processing unit consists of a CCD camera and a PC. The CCD camera is mounted on the robot wrist to detect the relative position/posture between the end-effecter and the object. A PC is used as to deal with the video information from the CCD camera, and then transmit it to the master side via internet. In order to enhance the performance of force feedback, the multi thread technology is introduced in the imagine processing.

B. *Software Architecture*

The entire software has been written in Visual C++. The operation is described as follows: when the relative position/posture is obtained between the end-effecter and the object, the force will display on the PHANTOM Omni device. Meanwhile, state data is turned into control command and conveyed to the robot through internet.

Processes running in the system include: (1) an image processing task; (2) a communication task; (3) a java application managing a client interface window; (4) serial communication line front-end processes; (5) communication server. Among these processes, (1) and (2) are running on a real-time controller, while (3)-(5) are running on workstations.

Communication tasks are connected to the communication server running in a workstation using a socket over a TCP/IP network. It handles output and input data. The client interface is written in Java and is connected to the communication server using the socket.

IV. Posture Estimation Between End-Effecter and Object

A. *Posture Estimation Scheme Based on Monocular Vision*

The Perspective-3-Point (P3P) problem is originated from camera calibration, also known as posture/position estimation. The P3P problem is to determine the position and posture of the camera with respect to a scene object from three correspondent control points. It concerns many important fields such as computer vision, automation, robotics, and model-based machine vision system, etc [17] - [19].

The P3P problem is shown in Fig. 5.

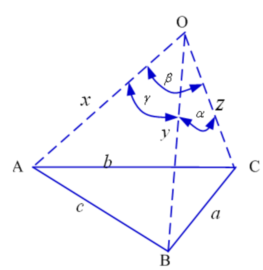

Fig. 5. The P3P problem

where O is the center of the perspective, A,B,C are three control points. Let

$$|OA| = x, |OB| = y, |OC| = z,$$
$$|AB| = c, |AC| = b, |BC| = a. \tag{8}$$
$$\angle BOC=\alpha, \angle AOC=\beta, \angle AOB=\gamma,$$

The question is to compute x, y, z and the equations can be described as:

$$\begin{cases} x^2 + y^2 - 2xy\cos\alpha = c^2 \\ x^2 + z^2 - 2xz\cos\beta = b^2 \\ y^2 + z^2 - 2yz\cos\gamma = a^2 \end{cases} \quad (9)$$

An important application of P3P problem is to locate the posture of the object with respect to the camera by using the image coordinate system of three control points. But the application of the method is limited because of the multi-solution problem of P3P. Zhou Xin made the research on how to set up the location relationship between three control points and the camera to assure the unique solution of P3P problem in [17]. It was reported that when three control points form an isosceles triangle, some special regions could be found and that once the camera appears in these particular regions, unique solution to the P3P problem could be obtained. In Fig. 6, triangle ABC is an isosceles triangle. The strict proof can be found in [8].

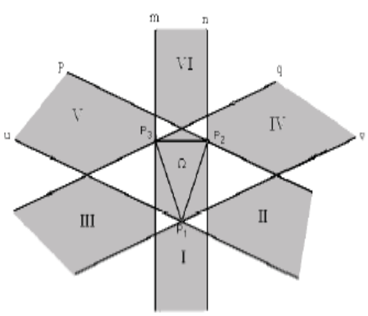

Fig. 6. Position of unique solution region of P3P problem

Based on monocular vision, the relative posture calculation is done between reference coordinate system and control points coordinate system. Therefore, the relative posture estimation between the end-effecter and the object can be acquired.

B. Relative Posture Estimation between End-effecter and Object

The relationships between coordinate systems are shown in Fig. 7. G represents the gripper coordinate system; R indicates the reference coordinate system; O means the coordinate system of the object grasped; B shows the coordinate system of the controlled points.

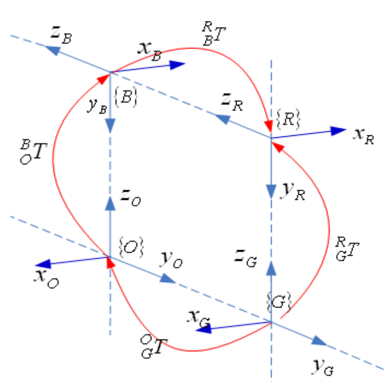

Fig. 7. Coordinate systems coordinate transformations

In Fig. 7, ${}^B_OT$ expresses the transformation from the object coordinate system $\{O\}$ to the control points coordinate system $\{B\}$

$${}^B_OT = \begin{bmatrix} & {}^B_OR & & {}^B\boldsymbol{p}_O \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (10)$$

where R represents rotation matrix, p is translation matrix.

${}^R_BT$ represents the transformation from control points coordinate system $\{B\}$ to reference coordinate system $\{R\}$

$${}^R_BT = \begin{bmatrix} & {}^R_BR & & {}^Rp_B \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

where R represents rotation matrix, p is translation matrix.

${}^R_GT$ shows a transformation from gripper coordinate system $\{G\}$to camera coordinate system $\{R\}$,

$${}^R_GT = \begin{bmatrix} & {}^R_GR & & {}^Rp_G \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

where R represents rotation matrix, p is translation matrix.

${}^O_GT$ is a transformation from gripper coordinate system $\{G\}$ to the object coordinate system $\{O\}$,

$${}^O_GT = \begin{bmatrix} & {}^O_GR & & {}^Op_G \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (13)$$

where R represents rotation matrix, p is translation matrix.

From Fig. 7, the following equation can be obtained

$${}^O_GT \cdot {}^B_OT = {}^R_GT \cdot {}^G_OT \quad (14)$$

From (14), we get

$${}^G_OT = \left({}^R_GT\right)^{-1} {}^O_GT \cdot {}^B_OT \quad (15)$$

where ${}^B_OT$ and ${}^R_GT$ need be determined in the experiment.

V. Virtual Reflective Force Computation Based on Posture Estimation

When human operator directs robot in the remote place to grasp the object, the gripper coordinate system $\{G\}$is expected to coincide with the object coordinate system $\{O\}$, as shown in Fig. 7. The transformation from virtual information, which describes the relative posture, to force message will help to guide human operator to drive the robot to approach the object properly.

When the remote robot is in posture control, angular velocity vector generated on the master device will control the end-effecter to adjust its attitude while its position is fixed.

Given the rotation matrix ${}^G_OR$ used to describe the attitude of the object coordinate system $\{O\}$ relative to the gripper coordinate system $\{G\}$

$$ {}^{G}_{O}R = \begin{bmatrix} n_x & o_x & a_x & 0 \\ n_y & o_y & a_y & 0 \\ n_z & o_z & a_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{16} $$

where (n,o,a) is a unit vector of coordinate system $o-xyz$.

The equivalent axle ζ and equivalent angle ψ which are described in $\{G\}$, will be derived, let

$$ {}^{G}_{o}R = Rot(\zeta,\psi) \tag{17} $$

where $s\psi = \sin\psi$, $c\psi = \cos\psi$, $vers\,\psi = 1-\cos\psi$,

$Rot(\zeta,\psi)=$

$$ \begin{bmatrix} \zeta_x\zeta_x vers\psi + c\psi & \zeta_y\zeta_x vers\psi - \zeta_z s\psi & \zeta_z\zeta_x vers\psi + \zeta_y s\psi & 0 \\ \zeta_x\zeta_y vers\psi + \zeta_z s\psi & \zeta_y\zeta_y vers\psi + c\psi & \zeta_z\zeta_y vers\psi - \zeta_x s\psi & 0 \\ \zeta_x\zeta_z vers\psi - \zeta_y s\psi & \zeta_y\zeta_z vers\psi + \zeta_x s\psi & \zeta_z\zeta_z vers\psi + c\psi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{18} $$

$$ s\psi = \pm\frac{1}{2}\sqrt{(o_z-a_y)^2+(a_x-n_z)^2+(n_y-o_z)^2} \tag{19} $$

If $0^\circ \le \psi \le 180^\circ$, then

$$ \tan\psi = \frac{\sqrt{(o_z-a_y)^2+(a_x-n_z)^2+(n_y-o_x)^2}}{(n_x+o_y+a_z-1)} \tag{20} $$

$$ \vec{\zeta} = (\zeta_x, \zeta_y, \zeta_z) \tag{21} $$

As a result, the reflective force in attitude control mode is

$$ {}^{M}F_w = c_a \cdot {}^{M}_{E}T \cdot {}^{E}_{G}T \cdot (\psi \cdot \vec{\zeta}) \tag{22} $$

where ${}^{M}_{E}T$,and ${}^{E}_{G}T$ are described in [11], c_a is the force coefficient.

VI. Experiments

In order to test the effectiveness of the virtual reflective force control system proposed, experiments are made. Since the MOTOMAN industrial robot has six degree of freedom and the PHANTOM Omni device has three dimensional data output, position and posture of the robot are controlled individually. The Phantom Omni device is used as a master device in local place. The MOTOMAN industrial robot is used as a slave device in a remote place. The master device is connected to control computer in slave side. The control computer transmits data generated by the imagine processing unit to the client side through internet.

In attitude control, angular velocity commands are transmitted to the remote robot while the virtual force which guides the human operator to give proper angular commands is generated according to (23). The human operator controls the remote robot to adjust its attitude. Figs. 8 though 10 show experimental results of the attitude control. Fig. 8 gives the posture of gripper coordinate system relative to the objective coordinate system. In Fig. 9, the angular velocity of the end-effecter is plotted. Fig. 10 depicts the force displayed on the master device.

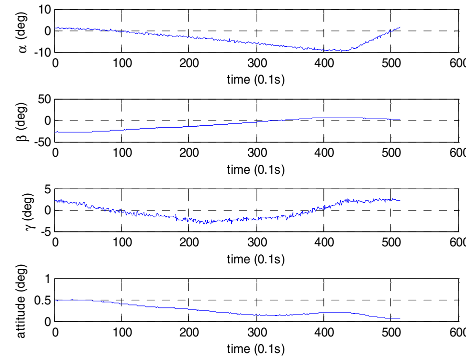

Fig. 8. Posture relationship of gripper coordinate system relative to the objective coordinate system.

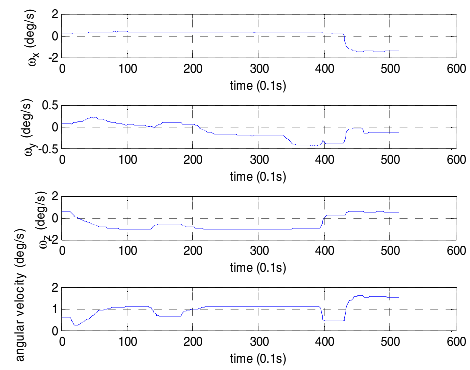

Fig. 9. Angular velocity of the end-effecter.

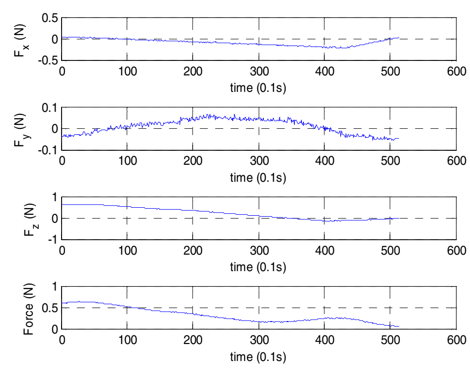

Fig. 10. Force displayed on the master device.

VII. Conclusions

In order to enhance telepresence in telerobotic system, this paper proposes posture-based virtual force feedback control scheme. Based on the precise measure of the relative posture between the end-effecter and the object, the visual message is converted into the force message using information transformation technique. This approach reduces the workload and anxiety of human operator for fear of collision between the end-effecter and the object. Experiments show that this method can improve the operability performance of telerobotic system greatly.

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