Robotica (2006) volume 24, pp. 447–453.
doi:10.1017/S0263574705002444 Printed in the United Kingdom

Predictive display and interaction of telerobots based on augmented reality

Youjun Xiong*, Shiqi Li* and Ming Xie†

(Received in Final Form: September 30, 2005)

SUMMARY

A predictive display method and man-virtual robot interaction based on augmented reality are applied to control a telerobot. We first discuss the process of the augmented reality environment development. Then, we present the advantages of predictive display. Simulation of virtual robot's tasks in the augmented environment improves the safety of the telerobot when it executes the planned tasks. In addition, the immediate feedback from the virtual robot avoids the exacerbation of maneuverability caused by time-delay. For a more natural operation process, we apply multi man-virtual robot interactive methods. Lastly, the experiment of pick & place is conducted to validate the system.

KEYWORDS: Telerobot; Predictive display; Augmented reality.

I. INTRODUCTION

The development of telerobotics system has gained considerable attention all over the world in recent years with numerous new application areas, such as nucleare decommissioning, inspection, waste handling in hazardous environments, deep space exploration, sub-sea pipline inspection in unreachable environments or medical applications in which humans adversely affect the environement. Important efforts have been devoted to the objective of developing telerobots and impressive results have been obtained.[1,2] The first telerobotic systems with a web-based interface were presented by researchers from the University of West Australia, which lets the user control an industrial robot to manipulate objects distributed on a table through an HTML interface.[3] In the USA, the Mercury Project[4] led to the development of a system in which the manipulator was a robotic arm equipped with a camera and a compressed air jet, and the interface consisted of a web page that could be accessed using any standard browser. In Japan, Susumu Tachi *et al*. developed a mutual telexistence system using retro-reflective projection technology.[5]

In a conventional telerobot control, the human operator communicates with the robot through local control inputs, such as mouse and keyboard or joysticks. For instance, in Japan, Neo Ee Sian *et al*.[6] developed a teleoperation system for whole body motion of a humanoid robot using a simple joystick master device. This way of operating a telerobot will keep the operator continually occupied which not only can cause cognitive fatigue[7] during an extended period of operations but also make some precise operations rather cumbersome. Furthermore, because of the inevitable time-delay, the operator has to wait for an unpredictable delay in order to get the real results of his operations on the real robot, which thus can cause teleoperation performance to deteriorate significantly, even if the time-delay is small. In the University of Michigan, Kang G. Shin and Xianzhong Cui[8] discussed the effects of time-delay on real-time control systems. In 2002, J. Corde Lane *et al*.[9] found any time-delay in the human/robot interaction could significantly degrade the effectiveness of operator control. Moreover, time-delay will also greatly decrease the maneuverability of the telerobotic system and the safety of the telerobot.

In order to avoid the above-mentioned problems, one solution is to provide more intelligence to the robot and let the operator specify tasks at a higher level of interaction. However, due to the limitation of artificial intelligence, we are still far away from developing a truly intelligent robot. Alternatively, some researchers devote to the use of virtual reality to improve the human/robot interaction by an immersive interactional environment. For example, Lim Ser Yong *et al*.[10] designed a telepresent robot controlling system using virtual reality instruments. In Swiss, Lorenzo Fluckiger[11] proposed a robot interface using virtual reality for high-level control of robot in 1998. Although virtual reality technology can greatly improve the interactivity in an immersive environment, limitation still exists in many situations. For example, in order to simulate the telerobot's working environment, the remote environment should be simple, or structured. Unfortunately, many teleoperation tasks are carried out in relatively unstructured environments. And, unstructured environments are difficult to characterize because of unavailability of the necessary information for quantitative modeling, or the high cost in obtaining numerical data.[12] Also, unstructured environments typically present all kinds of uncertainty due to the changes in the environment. And, the consideration of uncertainty usually results in the need for flexibility in task planning which must accommodate these changes. Without sufficient feedback from both the actual robot and the remote site, it will be difficult or even dangerous to operate a telerobot. Therefore, in order to

* School of Mechanical Science & Engineering, Huazhong University of Science & Technology Wuhan, Hubei Province, 430074 (China).
† Nanyang Technological University, Singapore-MIT Alliance, Block N3 Nanyang Avenue, 639798 Singapore (Rep. of Singapore).
Corresponding author: Youjun Xiong. E-mail: x_youjun@163.com

overcome the limitations of virtual reality, it is necessary to introduce other forms of interactivity.

Summarizing, earlier telerobotic systems always let the users send simple commands to the telerobot and slow progress was made to reduce the effect of cognitive fatigue or time-delay. It is also difficult to intuitively teleoperate a robot in unstructured environment.

In our case, we develop a telerobotic system to implement a task in unstructured work environment and take several measures, as follows, to avoid the problems mentioned above.

Firstly, we apply augmented reality, which is an advanced man-machine interaction technology, to locally provide the operator with a natural sensation of presence as if the operator felt directly on the remote site. In fact, telerobotic and telepresence systems can be greatly extended and enhanced by overlaying computer generated 3D graphics onto the images that are coming from the remote environment. The augmented reality is an extension of virtual reality. In a virtual reality system, the user is completely immersed in a virtual world. However, in an augmented reality, the operator sees the real world with virtual objects superimposed on it. In this way, the augmented reality supplements the real world rather than replacing it. Later recently, R. Marin *et al.*[13] developed a high level interface based on augmented reality to the teleoperate a robot via web, and this kind of user interaction allows user specifying a task into a 3D model and sending commands to the real robot.

Secondly, on telerobot is controlled by means of predictive display[14] which has been defined as using a computer for extrapolating displays forward in time.[15] A local model can be used to predict and render the remote scene in response to operator motor command. It replaces the delayed video feedback with immediate synthesized images and enables local operators to perform operations normally. Noyes[16] developed one of the first telemanipulator predictive displays, in which Operators were asked to control an arm to perform a manipulation task and a path tracing task. A performance increase from 50–150% was found with subjects using the predictor display compared to the delayed video alone. Mar[17] used a predictive display to overcome varying levels of time-delay for a manipulator task. The predictive display provided a 15–25% improvement when working with 1.5, 3, and 5 second time-delays.

Thirdly, for more natural operation process, we apply multi man-virtual robot interactive manners, including voice control.

In this paper, we present a telerobot which has 6 degrees of freedom (DOF) and is controlled by a predictive display approach in an interactive environment that is based on augmented reality. This paper is organized as follows: Section II details the development of an augmented reality environment. Section III discusses the advantages of the predictive display in our telerobot system. Section IV presents multi man-virtual robot interaction system. Section V discusses the communication module between virtual robot and telerobot. Section VI describes the overall system architecture. Section VII presents the experiments and results. Conclusions and discussion of possible future directions are shown in section VIII.

II. DEVELOPMENT OF AN AUGMENTED REALITY

II.1. Augmented reality

Augmented reality is an advanced human-machine interactive technology and is concerned with the enhancement of visual information about a real scene through the embedding of one or more 3D computer-generated virtual objects and text superimposed in real-time. An augmented reality system has three properties as follows: Combines real and virtual objects in a real environment; runs interactively and in real time; registers (aligns) real and virtual objects with each other. It can be thought of as an intermediary point not only on the spectrum from telepresence (completely real) to virtual reality (completely compute-generated), but also on the spectrum from autonomous robotics to manual teleoperation.

Augmented reality environment has useful application on telerobotics. It can greatly enhance the man-machine interface and this can be implemented at a variety of levels of complexity. It also has the ability to present information not otherwise available to the operator. For instance, at a basic level, virtual modeling can be combined with the video stream to provide the user with additional information, such as the robot position and orientation, heading, gaze angle, etc. This may be thought of as a virtual instrument panel. At a higher level, the user might, for instance, position a 3D stereo cursor on part of the real world scene. Provided that the real and virtual worlds are calibrated and registered, the (x, y, z) position of the cursor in real world coordinates would be available. This is a very powerful capability which would enable the robot or manipulator to move to that point, to measure the distance between two such points, and even to interactively build, or modify, a nominal 3D virtual model of the real world. In unstructured remote environments virtual objects from a toolbox could be attached to the real world. For instance virtual information may be placed to hint the operator how he can do better; markers and labels could be left on objects for further processing and even virtual trajectories could be defined for the robot or manipulator to follow.

In our augmented reality environment, the real scene is the telerobot worksite environment feedback video stream by cameras whereas the virtual information is virtual robot which is the replica of the telerobot. As shown before, to form an augmented reality environment, the virtual robot should be aligned with the telerobot in the real scenario, including original position and orientation. We accomplish the process by virtual robot registration.

II.2. Registration of virtual robot

It is crucial that the characteristics and pose of the camera relative to the real robot be precisely known. The computation of the camera intrinsic and extrinsic parameters, which constitutes the registration process, is the purpose of the work of registration. Figure 1 presents the schema-bloc of the proposed registration flow.

Since it seems difficult to rely on automatic feature extraction to deal with real images of a manipulator in unstructured environment, mark is defined beforehand in the

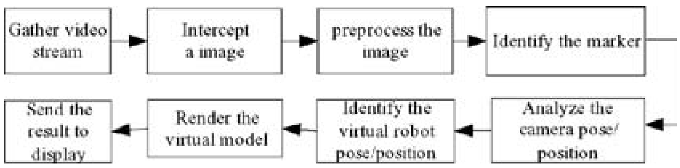

Fig. 1. Virtual robot registration flow.

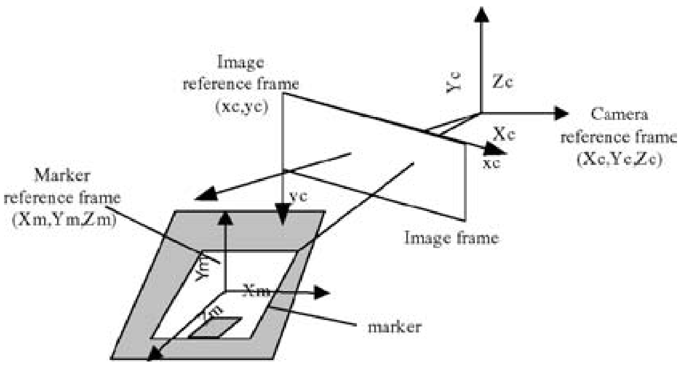

Fig. 2. Coordinate transforms.

remote worksite as the characteristic element to associate the cameras and the worksite environment. After the image intercepted from the video stream in the host computer buffer is preprocessed (such as decompress and revise), the registration program should identify the marker by pattern recognize and image match.[18] We now turn our attention to the determination of the camera's intrinsic and extrinsic parameters by coordinate transforms, which is the core content of registration.

Let $P_m = [X_m, Y_m, Z_m, 1]^T$ represent the coordinates of a marker in the marker reference frame of the remote environment and $p_c = [X_c, Y_c, Z_c, 1]^T$ be the same marker's coordinates in the camera reference frame. Let $p_i = [u, v, 1]^T$ represent the corresponding image projection of P_c. they are shown in Fig. 2. The coordinate transform from P_m to P_c is given by equation (1)

$$P_c = \begin{bmatrix} V_{11} & V_{12} & V_{13} & W_x \\ V_{21} & V_{22} & V_{23} & W_y \\ V_{31} & V_{32} & V_{33} & W_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \bullet$$

$$P_m = \begin{bmatrix} V_{3\times 3} & & & W_{3\times 1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \bullet P_m \qquad (1)$$

where we call $V_{3\times 3}$ as a rotation matrix and $W_{3\times 1}$ a translation vector.

The camera-to-image transform is given by the homogeneous perspective projection matrix $P_{3\times 4}$ described in equation (2):

$$P_{3\times 4} = \begin{bmatrix} s_x f & 0 & 0 & 0 \\ 0 & s_y f & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

where f is the camera's focal length and s_x, s_y are the proportionment factor of x and y axis respectively. These parameters value will be computed during the calibration of the camera. The complete transform from marker reference frame to image frame is:

$$w \bullet \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} s_x f & 0 & 0 & 0 \\ 0 & s_y f & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\bullet \begin{bmatrix} V_{11} & V_{12} & V_{13} & W_x \\ V_{21} & V_{22} & V_{23} & W_y \\ V_{31} & V_{32} & V_{33} & W_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \bullet P_m \qquad (3)$$

Each marker M_i and its image m_i corresponding provides two linear equations parameterized by the coordinates of the marker:

$$F_i(V_{11}, V_{12}, V_{13}, V_{21}, V_{22}, V_{23}, V_{31}, V_{32}, V_{33}, W_x, W_y, W_z) = m_i \qquad (4)$$

The twelve pose components are then computed using a linear algorithm that minimizes the sum of squared errors in the image plane.[19]

III. PREDICTIVE DISPLAY IN THE AUGMENTED REALITY ENVIRONMENT

The traditional telerobotic system is a loop, shown in Fig. 3, in which both the commands from the operator to the telerobot and the feedback from the telerobot to the operator are affected by variant time-delay during the course of the communication. Research has shown how time-delay can significantly degrade operating performance.[20–22] Fortunately, combination of predictive display and augmented reality can significantly reduce the effect of time-delay.

Unlike a conventional telerobot to which an operator directly sends the command, our telerobot system can obviate the effect of time-delay. Shown in Fig. 4, it consists of two closed loop, in which virtual robot in the augmented reality

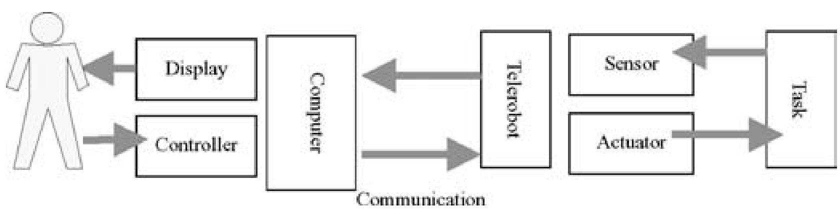

Fig. 3. Traditional system.

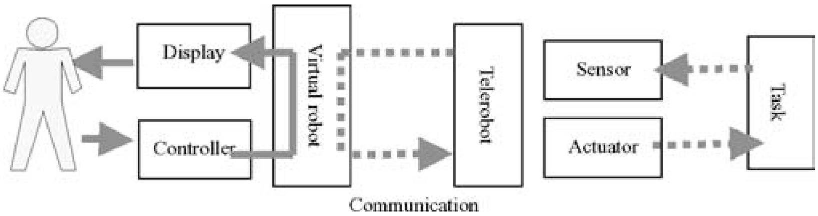

Fig. 4. Telerobotic predictive display system.

environment acts as an interface between the operator and the telerobot. When the calibrated virtual robot is registered on the camera image of the worksite, the virtual robot can be operated in real-time on the monitor. It will show in real-time the consequences of a command action before the real action takes place at the remote worksite and before it becomes visible on the monitor. Thus, the operator does not have to "move and wait"; He can "move" more and "wait" less since he has now more quantitative confidence in the command's consequences in the real world. So, operator, interface and augmented environment form a close loop in which operator can smoothly accomplish a task without any interruption by the limited communication bandwidth.

The other closed loop includes the augmented environment, communication module, the telerobot and remote environment. The virtual robot will record the commands sent by the operator in the former loop. Once the simulation presents the operation is safe and feasible, the virtual robot will transfer a series of commands to the telerobot. Because of the invariant time-delay in the communication process, the telerobot maybe accomplish the task following the instructions intermittently. However, for the operator, the intermission will not decrease the maneuverability or deteriorate safety.

Besides, for those complex or precise task, considering feasibility and safety, the operator must often be trained several times. Predictive display allows the operator controlling the virtual robot freely in the augmented environment without leading to any serious impact until the optimum control method is found.

Therefore, in our system, predictive display implements in three steps as follows. Firstly, the virtual robot implements the task under the operator control. It is also a task simulation in the real scenario instead of a virtual environment. The purpose is to optimize the process or eliminate any dangerous operation. Secondly, the system will form a series of optimum commands approved by the operator. Thirdly, the telerobot follows the virtual robot to implement the task with the operator's admission.

IV. MULTIPLE MANNERS OF MAN-VIRTUAL ROBOT INTERACTION

Another problem is to find a way to manipulate a virtual robot more efficiently and obtain an immersed interaction in the augmented reality environment to help the operator accomplish a task smoothly. The interactive system has to integrate different sensors and devices, such as position sensor, force sensors as well as visualize tools and etc. Some researchers have studied the interactive by mouse, keyboard or joystick. For example, Otto J.Rosch tried to improve the remote control performance by the use of a joystick, whereas other researchers operate the robot by keyboard and mouse. As it is not a natural way of interaction, the operator is required to have more professional skills.

As we know, hand and arm, which are the most dexterous apparatus of humans, are of great importance in the everyday work and life. They can accomplish many complex actions such as to grasp and hold an object in a very direct way. Therefore, we explore how the hand and arm could be used to interact with virtual robot. In gesture recognition, it is very common to use a camera in combination with an image recognition system. These systems have the disadvantage that the image/gesture recognition is very sensitive to illumination, hand position, hand orientation and etc.

In order to solve these problems, we used data gloves and the Flock of Birds (FOB) position and orientation measurement system as input devices. The data gloves consist of a lycra glove with embedded 16 fiber optic sensors. These sensors are linked to the computer via an optoelectronics unit, a ribbon cable and an interface box. The data glove measures finger flexure and orientation (pitch and roll) of the operator's hand. The FOB is a six DOF measuring device that can be configured to simultaneously track the position and orientation of multiple sensors. Each sensor is capable of making from 20 to 144 measurements per second of its position and orientation. The FOB works by transmitting a pulsed DC magnetic field that is simultaneously measured by all sensors in the Flock. From the measured magnetic field characteristics, each sensor independently computes its position and orientation and makes this information available to the host computer. To measure the head orientation, a sensor is attached at the back of head. Other sensors are at the shoulder, elbow and wrist. Figure 5 shows the kinematic definition of the telerobot. Each joint angle is calculated form the following equation.

Let S_i ($i = 0, 1, 2, 3, 4$, represent the sensors from the head, shoulder, elbow, wrist and hand, respectively) is the

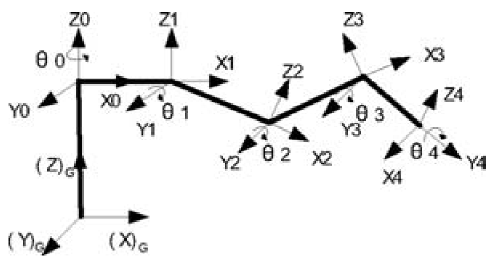

Fig. 5. Kinematic definition.

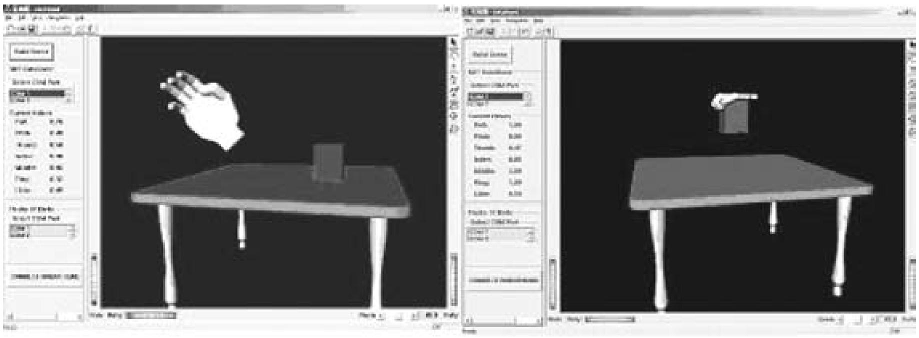

Fig. 6. Use the FOB and data glove to pick a cube in the virtual space.

i-th sensor reading, which is a 6×1 vector, $[x, y, z, azimuth, elevation, roll]$.

$$\theta_0 = roll(\overrightarrow{s_0}) \tag{5}$$

$$\theta_1 = elevation(\overrightarrow{s_2 s_1}) \tag{6}$$

$$\theta_2 = \cos^{-1}\left(\frac{\overrightarrow{s_3 s_2} \cdot \overrightarrow{s_2 s_1}}{\left|\overrightarrow{s_3 s_2}\right| \cdot \left|\overrightarrow{s_2 s_1}\right|}\right) \tag{7}$$

$$\theta_3 = \cos^{-1}\left(\frac{\overrightarrow{s_4 s_3} \cdot \overrightarrow{s_3 s_2}}{\left|\overrightarrow{s_4 s_3}\right| \cdot \left|\overrightarrow{s_3 s_2}\right|}\right) \tag{8}$$

$$\theta_4 = azimuth(\overrightarrow{s_4}) \tag{9}$$

From equation (5) to (9), all the necessary joint angles of the arm are derived. The end executor of the telerobot is driven by data glove which can operate more flexibly. To get accuracy readings, all sensors are calibrated beforehand.

The host computer extracts the parameters and sends to the actuator units of virtual robot arthral node. Thus, without using iterative inverse kinematic computing, the virtual robot can implement a task under the operator control in a virtual space before the telerobot starts to act.

In the earlier stage we have developed a virtual hand as the redivivus of human hand to operate objects in the virtual space showed in Fig. 6. Once the user takes control of the virtual hand, the FOB and the glove data will track the user's hand position and orient in the magnetic field and send these data to corresponding virtual hand arthral nods in the host computer. The user can pick and transfer the virtual cube easily.

For those situations where the remote environment is well structured and the aim object is isolated, or the task is easy enough for the telerobot to accomplish, the system afford operator a more flexibility interactive manner: voice control.

As presented in Fig. 7, before we control the robot by voice, the voice template library should be built. The process of template match is to search the template library and find the least distort template compared with the voice command. Some of the voice control commands are summarized in Table I. With the time passing, more and more templates will be exuberated and the robot can respond to more voice commands.

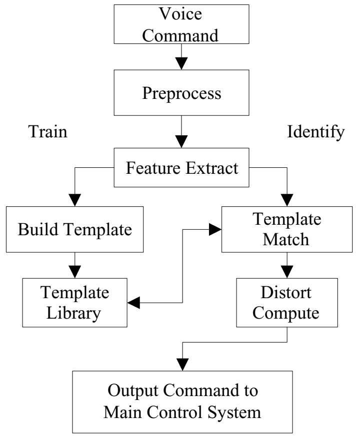

Fig. 7. Voice control process.

Table I. Examples of voice commands.

Voice command	Detail
Turn {x}	Robot turns {x} degree reference its origin position clockwise
Move to{x, y, z}	{x, y, z} is the world coordinates position
Grasp the {object}	This command is valid when the object is isolated
Put down	Put the object on the platform
Back	The gripper go back to the initial position

V. COMMUNICATION BETEEN A VIRTUAL ROBOT AND TELEROBOT

The communication module consists of two socket connection channels. These socket channels cope with two tasks such as remote work scene transmission and interaction between the virtual robot and the agent of telerobot. Because of the huge data of the work scene video, the communication channel used to be crowded. To avoid data loss and exaggerated time-delay, we take several measures. 1) Double buffer areas are introduced in the data resource port and the accepter. To the data resource port, the scene photo will not be send out if it is the same with the photo in the buffer and the buffer will not refresh. To the accepter, buffer will only be refreshed after new image is received. 2) An image compress algorithm will be adjusted with the changing volume of the data steam through the resource port.

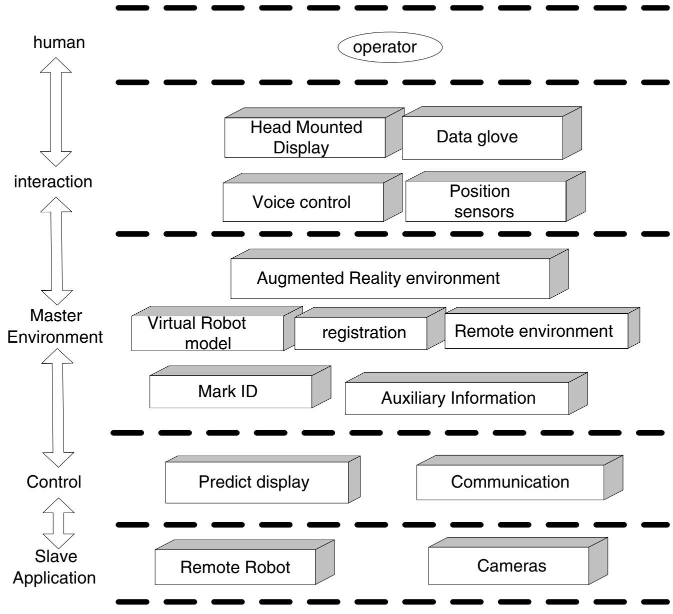

Fig. 8. System architecture.

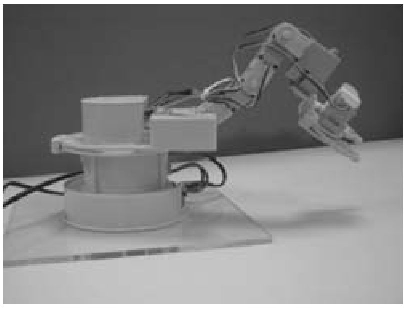

Fig. 9. The six DOF telerobot.

Double buffer areas are also introduced into operation command channel between virtual robot and telerobot. According to the command priority level, a queue is created by link list in the buffer under the following rule: those with high priority level will be in the top of the link list and be implemented at first while those with low priority level will be in the bottom of the link list and be implemented in the end; commands with the same priority level will array and be implemented according to the order of received. The telerobot agent receives commands from the buffer and driver the actuator until the link list is empty.

VI. SYSTEM ARCHITECTURE AND ITS IMPLEMENTATION

The telerobotic system based on augmented reality consists of several parts as follows: human operator, man-virtual robot interactive system, local control environment based on augmented reality, control and communication system between the master and the slaver robot. Figure 8 presents the schema-bloc of the proposed system configuration.

- Interaction: discarding the unnatural interactive devices, several virtual reality interactive devices are adopted such as Head Mounted display, data glove as well as Flock of Birds (FOB) position and orientation measurement system, etc. For those simply task, the operator even can set their task commands by voice.
- Local control environment based on augmented reality: Fabricated in the local computer, this environment consists of the virtual robot and the video stream feedback from the remote worksite. The virtual robot is registered into the video stream by registration and then augmented reality environment comes into being. The operator can control the virtual robot in real-time and get quick feedback without obvious time-delay.
- Controlling system: the local controlling system include predictive display control and communication between the virtual robot and the telerobot. By means of cooperating with the virtual robot, predictive display control method can eliminate the affection of time-delay and improve the maneuverability and the safety. In order to avoid data error of operational command and feedback, special communication model is developed.
- Remote telerobot: our telerobot is a six degrees-of-freedom (DOF) robot, shown in Fig. 9, with two cameras to obtain visual feedback.

VII. EXPERIMENTS AND RESULT

A pick & place task operation experiment is accomplished in our system. The set-up is showed in Fig. 10, in which remote server and local control station are connected by local area network. A 43 seconds time-delay occurs by setting by software.

It can be observed in Fig. 11, where a toolbox is placed on the floor board and the telerobot should pick a pincher (hint is given by the additional virtual information) and place it in the position of the virtual. Firstly, we connect the control

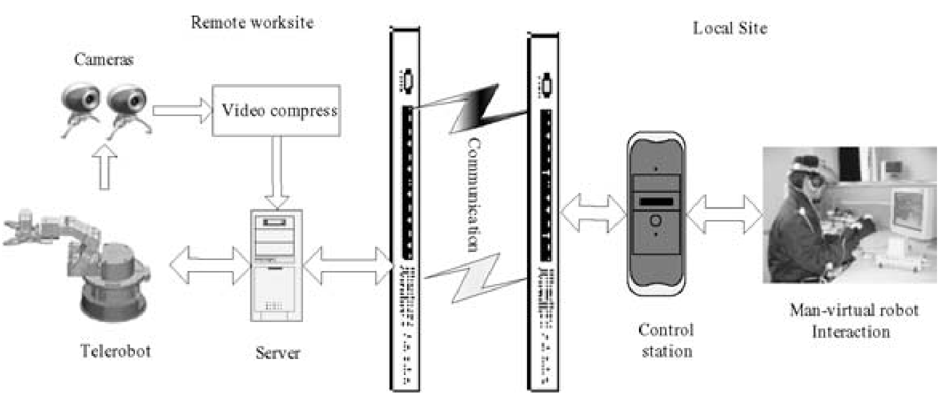

Fig. 10. Prototype system setup.

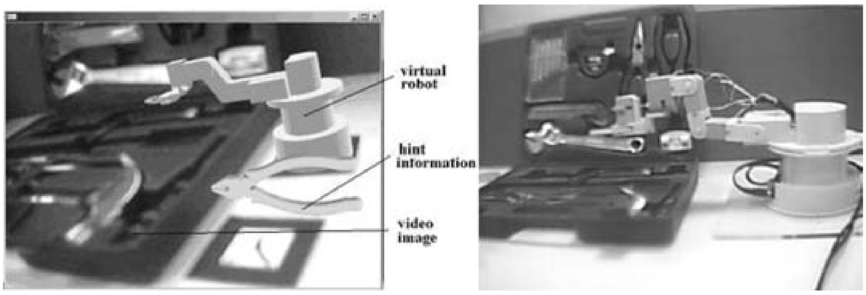

Fig. 11. Augmented reality environment and the telerobot worksite.

station and the remote server to build the control environment based on augmented reality where not only the telerobot scenario is monitored but also the virtual robot is registered. As the working environment is relatively unstructured and the pick task needs precise control, operation training is required before the telerobot implements the tasks directly. With the data glove and the FOB, the operator can control the virtual robot in the simulation mode by multi interactive manner. The virtual robot will record the action and wait for the operator approve of communication with the telerobot. Secondly, the telerobot will implement the task with intermission.

VIII. CONCLUSION AND FUTURE WORK

This paper presents a telerobot system in unstructured environments, which applies prediction display and augmented reality to improve the maneuverability and safety. A virtual robot is registered to the real video image and becomes an interface between the operator and the telerobot, thus the time-delay is separated from interactive of the human-virtual robot. By training the virtual robot in the real scenario, error or dangerous action can be eliminated.

In the future, we will improve the module of multiple operator-virtual robot interaction, especially the voice control. In addition, force feedback should be combined in the system so that a more precise teleoperation can be accomplished.

References

1. A. Casals, J. Fernandez and J. Amat, "Augmented reality to assist teleoperation working with reduced visual conditions", *Proceedings of the 2002 IEEE International Conference on Robotics & Automation* (May 2002) **1**, pp. 235–240.
2. K. Yerex, D. Cobzas, and M. Jagersand, "Predictive display models for telemanipulation from uncalibrated camera capture of scene geometry and appearance", *IEEE International Conference on Robotics and Automation (ICRA)* (2003) **2**, pp. 2812–2817.
3. R. Marin, P. J. Sanz and A. P. del Pobil, "A predictive interface based on virtual and augmented reality for task specification in a web telerobotic system", *Proceedings of the 2002 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems EPFL* (October, 2002) **3**, pp. 3005–3010.
4. K. Goldberg, *The Robot in Garden: telerobotics and telepistemology in the age of the internet* (The MIT Press Cambridge, Massachussets, ISBN 0-262-07203-3, 2000).
5. S. Tachi, N. Kawakami, M. Inami and Y. Zaitsu, "Mutual telexistence system using retro-reflective projection technology", *International Journal of Humanoid Robotics* **1**, No. 1, 45–64 (March, 2004).
6. Neo Ee Sian, Kazuhito Yokoi and Shuuji Kajita, "Whole body teleoperation of a Humanoid Robot-Development of a Simple Master Device using Joysticks", *Proceedings of the 2002 IEEE/RSJ, Intl. Conference of Intelligent Robot and Systems EPfl* (October, 2002) **3**, pp. 2569–2574.
7. R. R. Murphy *Introduction to AI Robotics* (The MIT Press, 2000).
8. Kang G. Shin and Xianzhong Cui, "Computing time-delay and its effects on real-time control systems", *IEEE Transactions Control Systems Technology* (June, 1995) **3**, No. 2, 218–224.
9. J. Corde Lane, Craig R. Carignan and Brook R. Sullivan, "Effects of time-delay on telerobotic control of neutral buoyancy vehicles", *IEEE International Conference on Robotics and Automation* (May, 2002) **vol. 3**, pp. 2874–2879.
10. Lim Ser Yong, Wong Hong Yang and Marcelo Ang Jr., "Robot task execution with telepresence using virtual reality technology", *1998 International Conference on Mechatronic Technology*, Hsinchu, Taiwan, R.O.C, (1998) pp. 1–8.
11. Lorenzo Fluckiger, "A robot interface using virtual reality and automatic kinematics generator", *Proceedings of the 29th International Symposium on Robotics 1998 (ISR98)*, Birmingham (UK) (April, 1998) pp. 123–126.
12. Paul Milgram, Anu Rastogi and Julius J. Grodski, "Telerobotic control using augmented reality", *Proceedings 4th IEEE International Workshop on Robot and Human Communication* (July, 1995) pp. 21–29.
13. R. Marin, P. J. Sanz and J. S. Sanchez, "A very high level interface to teleoperated a robot via web including augmented reality", *Proceedings of the 2002 IEEE International Conference on Robotics & Automation* (May, 2002) **vol. 1**, pp. 2725–2730.
14. T. Sherindan, *Telerobotics, Automation, and Human Supervisory Control* (MIT press, 1992).
15. T. B. Sheridan, "Space teleoperation through time-delay: Review and prognosis", *IEEE Transactions on Robotics and Automation* (October, 1993) **9**, No. 5, 592–606.
16. Mark V. Noyes, "Superposition of graphics on low bit rate video as an aid in teleoperation", *M. S. Thesis* (MIT, 1982).
17. Linda E. Mar, "Human control performance in operation of a time-delayed master-slave telemanipulator", *B. S. Thesis* (MIT, 1985).
18. B. Jiang, S. You and U. Neumann, "Camera tracking for augmented reality media", *Proc. IEEE Int'l Conf. Multimedia Expo 2000, IEEE CS Press*, Los Alamos, Calif. (2000) pp. 1637–1640.
19. W. Kim, "Computer vision assisted virtual reality calibration", *IEEE T-RA* **15**, No. 3, 450–464 (June, 1999).
20. C. E. Garcia, B. Morales, R. Carelli and J. Postigo, "Stability analysis for a teleoperation system with time delay and force feedback", *Proceedings of the 39th IEEE Conference on Decision and Control* (Dec., 2000) **vol. 4**, pp. 3453–3458.
21. L. F. Penin, K. Matsumoto and S. Wakabayashi, "Force reflection for time-delayed teleoperation of Space robots", *IEEE International Conference on Robotics and Automation* (April, 2000) **vol. 4**, pp. 3120–3125.
22. S. Ushida and H. Kimura, "Adaptive control of nonlinear system with time delay based on the feedback error learning method", *IEEE International Conference on Industrial Technology* (Dec., 2002) **vol. 2**, pp. 706–711.