Tele-Manipulation of ROBHAZ-DT2 for Hazard Environment Applications

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Abstract: In this paper, a tele-manipulation in explosive ordnance disposal(EOD) applications is discussed. The ROBHAZ-DT2 is developed as a teleoperated mobile manipulator for EOD. In general, it has been thought that the robot must have appropriate functions and accuracy enough to handle the complicated and dangerous mission. However, the research on the ROBHAZ-DT2 revealed that the teleoperation causes more restrictions and difficulties in EOD mission. Thus to solve the problem, a novel user interface for the ROBHAZ-DT2 is developed, in which the operator can interact with various human senses (i.e. visual, auditory and haptic sense). It enables an operator to control the ROBHAZ-DT2 simply and intuitively. A tele-manipulation control scheme for the ROBHAZ-DT2 is also proposed including compliance control via force feedback. It makes the robot adapt itself to circumstances, while the robot faithfully follows a command of the operator. This paper deals with a detailed description on the user interface and the tele-manipulation control for the ROBHAZ-DT2. An EOD demonstration is conducted to verify the validity of the proposed interface and the control scheme.

Keywords: Tele-manipulation, explosive ordnance disposal, mobile manipulator, compliance control

1. INTRODUCTION

Recent rapid improvement of robot and control technology makes a robot take the place of human in dangerous work. In order to execute a mission in war, several robots for EOD have been developed [1-3].

The goal in the EOD mission is that the robot autonomously accomplishes all EOD processes by itself. Unfortunately, it is beyond the state of the art, and human intervention is still needed to handle explosive ordnances. Therefore, most EOD robots have been developed based on a teleoperation scheme. In this scheme, the robot is a slave to face with the dangerous environment, while the operator is to be a master who manages the slave from a distance. Not only to design the robot but also to make the user interface becomes an essential technology.

The ROBHAZ-DT2 is a teleoperated mobile manipulator developed for EOD. A mobile base of the ROBHAZ-DT2 is designed to get high adaptability to uneven terrain with passive double tracks, and a manipulator is equipped on the mobile base. The robot has nine dof including the mobile base and the seven dof manipulator with gripper. Various sensors(e.g. sonar sensor, inclinometer) are installed to gather environment information [4]. Through nine degrees of freedom, a dexterous motion can be performed, and the robot can be aware of the situation in detail with attached sensors. On the contrary, there is some trade off. The dexterous motion means that a complex command for the operation is required. The more information is gathered, the more confusion comes to the operator. How to present information clearly is as important as how much information to be gethered. It becomes more serious problem to design the user interface of the teleoperation system.

The user interface carries out two functions: to get the command from the operator, and to report the situation of the robot to the operator. Existing most EOD robots use a joystick-type device for the command, and each axis of the joystick directly connects to a motion of each joint of the robot. Because the degrees of freedom of the joystick are too low for proper control, all joints of the robot can not be controlled at a time [5, 6]. Furthermore, the operator would sometimes be confused how to move the joystick as a result of the command not in Cartesian space but in the joint space. A main view monitor and a few auxiliary indicators are used for reporting. The dispersed indicators cause inattentiveness and the user cannot grasp the situation immediately. For this problem, not only vision sense but also various human senses should be used. All commands and reports should be simple and intuitive in order to concentrate the operator's attention on a given mission. The next section presents the teleoperation system of ROBHAZ-DT2 as an advanced approach for EOD robot system. The remainder is organized as follows. In Section 3, the design of a user interface is introduced. Section 4 deals with robot control including arm compliance control. Section 5 shows EOD experiments. Section 6 concludes the research results.

2. THE ROBHAZ-DT2 TELEOPERATION SYSTEM

Fig.1 shows the block diagram of the ROBHAZ-DT2 teleoperation system. The user interface is composed of three components. The first one is a visual interface, and the second one is a speech and auditory interface, and the last is a haptic interface. Commands are inputted by speech or operation of the haptic device. While the robot moves by a set of commands, it interacts with environment and gathers data with installed sensors (e.g. ultrasonic sensor, inclinometer). When the robot reports the sensed data via a wireless LAN, the environmental information is inferred from the data. All information is displayed on single scene of HMD and some information is represented as a force feeling or audio. In this manner, the operator interacts with the user interface intuitively.

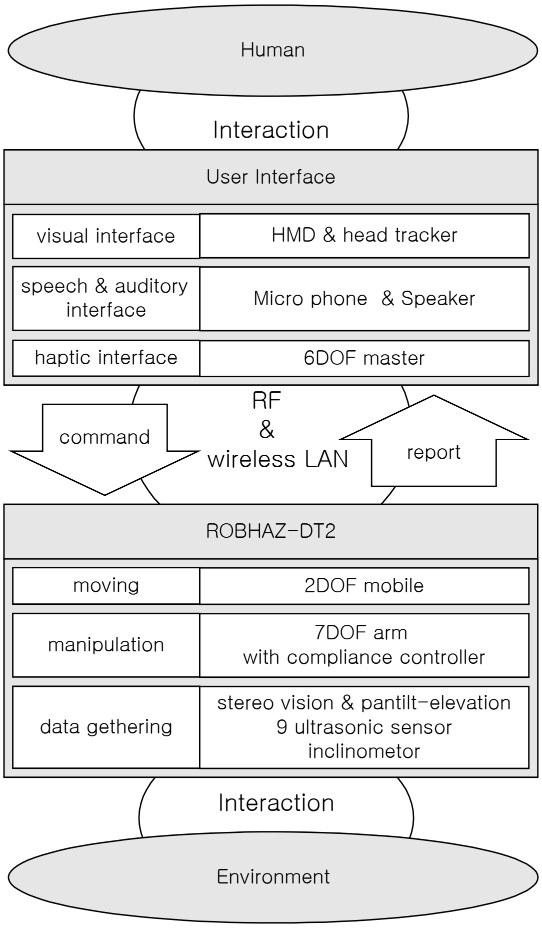


Fig. 1 Teleoperation system for ROBHAZ-DT2.

Compliance control is applied to manipulation tasks. Not only it can protect the manipulator from the contact with environment by improper command or unexpected trouble, but also it is adequate for some dexterous tasks (e.g. opening door, writing on the board, wall scratch).

3. USER ORIENTED INTERFACE

The operator wears the HMD, head tracker and headset in the user interface system. He grips the handle of the 6-dof haptic master, as shown Fig. 2. A keyboard, button, switch or any other display devices are not needed during the operation. Following subsections describe how it works.

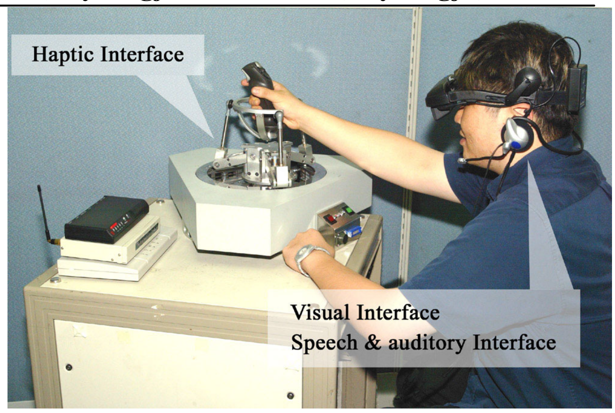
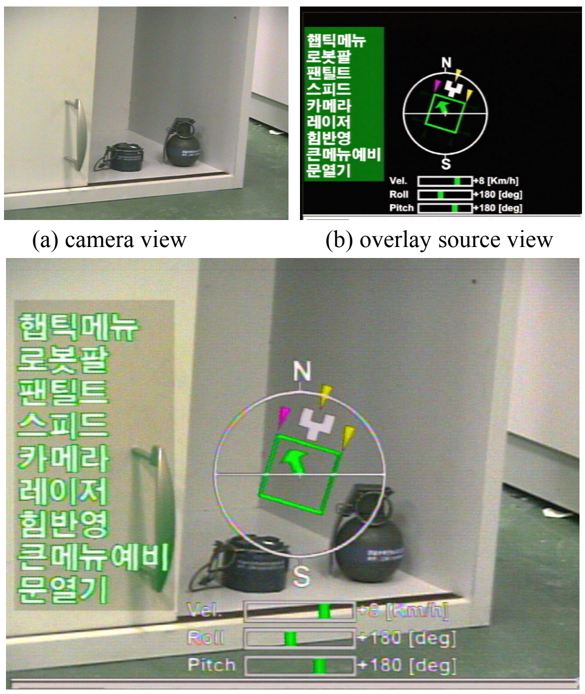


Fig. 2 The user interface of ROBHAZ-DT2.

3.1 Visual interface

The visual interface shows the robot's view, the status of sensed data, and the status of speech commands. A stereo camera and pan/tilt mechanism are installed on the ROBHAZ-DT2. The operator wears the head tracker and it generates a pan/tilt command. Thus the stereoscopic camera moves along the direction of his head. As a result, the operator looks at the view he wants to see as shown in Fig. 3(a). The vision information is sent via a RF channel while the sensed data is reported via an independent wireless LAN channel to reduce the traffic in data communication. A source for overlay is prepared with the reported data, as shown Fig. 3(b). It is overlaid on the pictures and unified both as one scene. Finally the operator sees the stereoscopic picture and the status of the robot at a glance on the HMD. It is shown as Fig. 3(c).



(a) camera view (b) overlay source view

(c) user view

Fig. 3 The visual interface for ROBHAZ-DT2.

3.2 Speech and auditory interface

In this research, the operator sends two types of commands to the robot. The one is a selection command and the other is a continuous command. For example, the selection between moving and manipulation mode, the reset of the robot arm and mobile base, the on/off and reset of pan-tilt motors, the speed selection of the mobile, the selection among installed cameras are defined the selection commands. These commands implemented through the speech recognition.

When the operator says a word which has been defined as a selection command, the speech interface can be aware of the word. If the interface successfully recognizes what he says, it notifies him of the recognized command, the command pops up on the HMD and the command is overlaid on the background picture. Thus the operator would decide to execute or cancel the command with the button on the haptic master.

A speech synthesis engine can synthesize the human voice. The auditory interface can warn of the approach of obstacle by sound.

3.3 Haptic interface

In most 6-dof haptic devices, all six actuators are activated to create force feedback even when only simple motion is desired, since Cartesian space and the joint space are closely coupled in the device. It is desirable, therefore, that a haptic device is designed so that only necessary dofs are activated while other dofs remain unactivated depending on the situations. This strategy has several advantages. First, mass and moment of inertia of the moving parts are reduced, which leads to the improved backdrivability and transparency. Second, computational burden needed to solve kinematic and static equations involving all dofs for determination of the end-effector posture and the required force reflection are greatly reduced. Third, it is energy efficient because only necessary actuators are activated.

In this manner, a new 6-dof haptc device is designed for the ROBHAZ-DT2 [7]. The haptic master is composed of upper and lower mechanisms in the consideration of the manipulator and the mobile, as shown Fig. 4. The lower mechanism is designed to be a planar 3-dof parallel manipulator and the planar 3-dof (x, y translation, z rotation) exactly matches the motion of mobile. While the mobile is moving, only the lower mechanism is activated for force reflection. The upper mechanism is designed as a spatial 3-dof (x, y rotation, z translation) parallel manipulator and it is attached on the lower mechanism, as shown Fig. 4. Finally, the proposed haptic device has totally 6-dof. Once the robot reaches the goal, it performs a given task using the manipulator, using its full 6-dof motion.

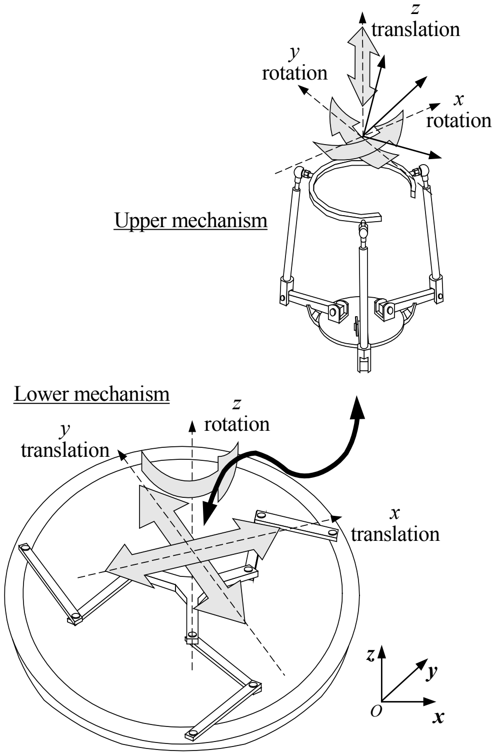


Fig. 4 Structure of the proposed haptic master.

The complex motions of the ROBHAZ-DT2 are easily commanded by the haptic interface. The continuous command mentioned above, such as the velocity of mobile and the position of arm, is ordered with the haptic master. The operator grips the handle of the haptic device and moves his hand, and the robot exactly moves along the direction. The mobile moves intuitively with the moving mode. In this case, only the 3-dof of the haptic device is used. The manipulator is operated in manipulation mode with full 6-dof of the haptic device.

Another feature of the haptic interface is that it exerts the forces on the operator. Thus the operator can notice the situation of the robot with feeling the forces that indicate the distance from obstacles or the inclination of robot.

4. CONTROL FOR TELE-MANIPULATION

4.1 Control for tele-manipulation

When the mobile base reaches in the vicinity of the target, the operator changes the operation mode from mobile mode to manipulation mode. In the tele-manipulation for EOD, a given task can be completed by simultaneously achieving the following two goals:

- According to haptic device command, the manipulator moves to target position for EOD.
- Explosion preclusion and manipulator protection from the unknown environment.

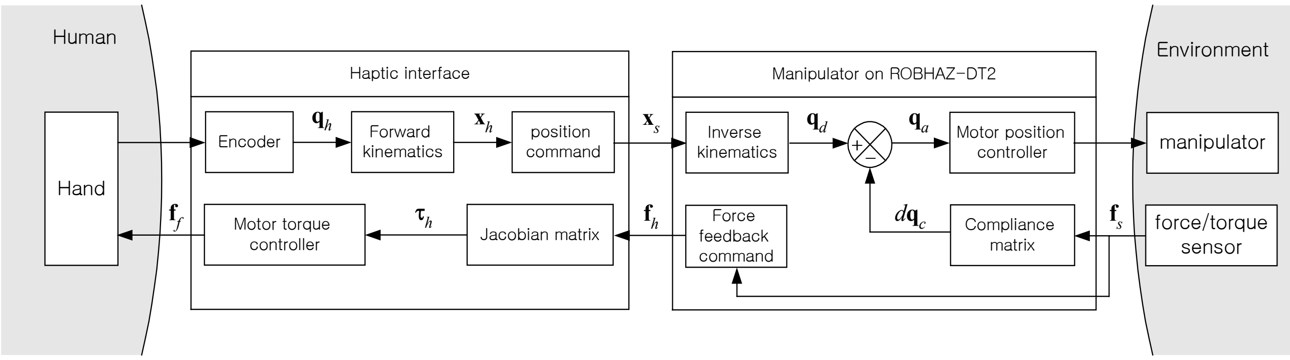


Fig. 5 Block diagram for tele-manipulation control of ROBHAZ-DT2.

To satisfy the goals, a tele-manipulation concept is proposed as shown in Fig. 5. The operator moves the handle carefully to the direction to the object, watching it through the HMD. The installed encoder reads the motion of a joint angle $\mathbf{q}_h$ and the haptic controller translate it to a pose $\mathbf{x}_h$ in Cartesian space with forward kinematic analysis. A local manipulator controller in the ROBHAZ-DT2 receives a scaled command $\mathbf{x}_s$ by the TCP/IP communication. After computing inverse kinematics of manipulator, the desired position of joints $\mathbf{q}_d$ is determined. It is modified to an adjusted position of joints $\mathbf{q}_a$ by compliance control.

The measured force is used not only for compliance control but also force feedback to the haptic device. The sensed force $\mathbf{f}_s$ translated to scaled force command $\mathbf{f}_h$, and joint torque τ_h is computed by Jacobian analysis of the haptic interface, then each motor installed haptic device is controlled to put force as much as the desired joint torque τ_h. As a result, the operator feels the feedback force $\mathbf{f}_f$.

In controlling a mobile manipulator, the interaction between the manipulator and the mobile base or uncertain environment is a very important issue. When a manipulator interacts with an uncertain environment, the control system should be able to estimate the unknown stiffness of the environment and control both the position and force of the manipulator simultaneously. There has been a growing interest in the research on the compliance control of a mobile manipulator. A compliance control strategy to protect serious damages in an unknown environment is proposed for the ROBHAZ-DT2. The details of control are a flow chart in Fig. 5.

4.2 Compliance control

A compliance control to enable contact tasks is proposed by employing a commercial 6-dof force-torque sensor. When an operator controls ROBHAZ-DT2 for given task, a desired manipulator posture is obtained, with which a desired compliance in the workspace could be computed to be achieved by given data.

In general, the m x 1 gripper displacement vector $d\mathbf{x}$ is related to the n x 1 joint displacement vector $d\mathbf{q}$ by the conventional m x n Jacobian matrix $\mathbf{J}$,

$$d\mathbf{x} = \mathbf{J}\, d\mathbf{q}\,, \qquad (1)$$

and the gripper output force-torque vector $\mathbf{f}$ is related to the joint torque vector $\boldsymbol{\tau}$ by the transpose of the Jacobian,

$$\boldsymbol{\tau} = \mathbf{J}^{\mathrm{T}}\mathbf{f}\,. \qquad (2)$$

With linear approximation, $\mathbf{f}$ and $d\mathbf{x}$ has a relation, as follows:

$$d\mathbf{x} = \mathbf{C}_x\mathbf{f}\,, \qquad (3)$$

where

$$\mathbf{C}_x = \mathbf{K}_x^{-1} \qquad (4)$$

is an m x m matrix called the *compliance matrix* [8] with respect to Cartesian coordinate. $\mathbf{C}_x$ is the inverse of stiffness matrix $\mathbf{K}_x$ which is denoted diag[k_1, k_2, ..., k_m] and k_i for i=1, 2,…, m is a stiffness constant with respect to each Cartesian axis. Eliminating $\boldsymbol{\tau}$ and $d\mathbf{x}$ from Eqs. (1), (2), and (3), we obtain

$$d\mathbf{q} = \mathbf{J}^{-1}\mathbf{C}_x\mathbf{f}\,, \qquad (5)$$

If the stiffness constants in $\mathbf{K}_x$ would be assumed that we want the manipulator to have, then we get the resultant joint displacement from Eqn. (5). The displacement means virtual offset with respect to the supposed stiffness by external force. After measuring exerted force and computing the virtual displacement, when we control the position of each joint to follow the virtual displacement, then the manipulator moves as if some springs are attached on the end-effector of the manipulator [9].

In this research, the exerted force $\mathbf{f}_s$ in Fig. 5 is measured by the commercial 6-dof force/torque. The sensor is mounted between the wrist of the manipulator and the gripper as shown in Fig. 6.

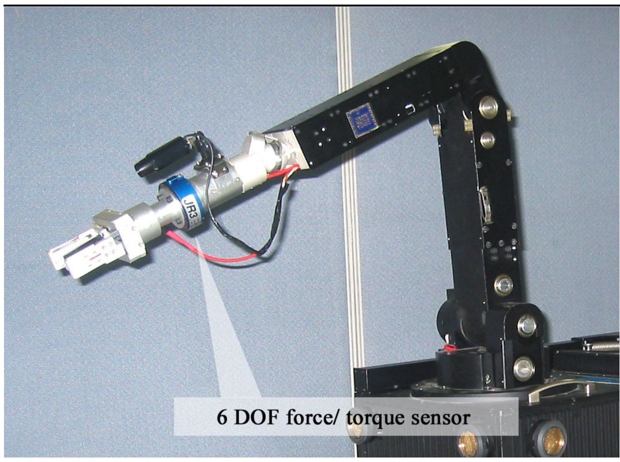


Fig. 6 The 7-dof manipulator for ROBHAZ-DT2

The force/torque signal is measured with respect to a sensor coordinate frame. Because the sensor is located between the gripper and the arm as shown in Fig. 6, the weight of the gripper must be compensated with respect to the configuration. The compensated signal is transposed from a local coordinate to Cartesian coordinate. The compliance control is applied with this signal.

Before calculating the virtual displacement with the force signal, the compliant direction would be decided. For example, when the robot opens a door, the manipulator must move compliantly not to exceed allowable forces, while the manipulator has stiffness in the direction of opening the door at the same time.

5. EXPERIMENT

5.1 EOD experiment

As a result of full integration of the system, a simple EOD demonstration task was successfully executed in real outdoor environment shown in Fig. 7. The demonstration setup for the EOD is artificially constructed. As shown in Fig. 7, an operator remotely controls the robot by means of the haptic device and a head mount display. First, he controls the mobile vehicle and manipulator to access the explosive ordnance. By means of the double-track mechanism, as shown in Fig. 7(a)-(c), the ROBHAZ-DT2 could easily travel over stairways and irregular surface. During the accessing motion, the operator could monitor the stereoscopic view transmitted from the pan-tilt stereo camera mounted in front of the robot. In manipulating the object lying in a car shown in Fig.7(d), the operator could approach, grip and pick up an imitated bomb by feeling the contact forces via the haptic interface and monitoring fine view transmitted from the camera equipped at the arm's gripper. Then it moved to a safe place for the disposal in.

(a) Start and climbing

(b) Running on irregular surface

(c) Approach

(d) Grip

(e) Moving for disposal

(f) Disposal

Fig. 7 Demonstration of explosive ordnance disposal.

6. CONCLUSION

In this research, a tele-manipulation method for EOD is presented. the user interface design and control for tele-manipulation is proposed and the following special features are summarized.

1. The operator makes the command by speech and a motion.
2. All information is shown on a unified scene.
3. The robot adapts itself to circumstances with compliance control, when it contacts with environment.
4. The operator feels the contact forces by the haptic feedback.

As a result, an intuitive and simple user interface in teleoperation for EOD is developed. An EOD experiment is performed to verify a validity of the proposed system, and its practical effectiveness has been successfully tested.

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