Development of a six DOF haptic master for teleoperation of a mobile manipulator

Dongseok Ryu\textsuperscript{a}, Jae-Bok Song\textsuperscript{b,*}, Changhyun Cho\textsuperscript{c}, Sungchul Kang\textsuperscript{d}, Munsang Kim\textsuperscript{d}

\textsuperscript{a}Department of Mechanical Engineering, Texas A\&M University-Corpus Christi, TX, United States
\textsuperscript{b}School of Mechanical Engineering, Korea University, Seoul, South Korea
\textsuperscript{c}Department of Control, Instrumentation, and Robot Engineering, Chosun University, Gwangju, South Korea
\textsuperscript{d}Center for Cognitive Robotics Research, Korea Institute of Science and Technology, Seoul, South Korea

\textbf{A R T I C L E   I N F O}

Article history:
Received 20 February 2007
Accepted 4 November 2009

Keywords:
Haptic master
Teleoperation
Parallel mechanism
Force-feedback

\textbf{A B S T R A C T}

An intuitive controller is needed for easier teleoperation of a slave robot. The mobile manipulation task requires three DOFs for planar mobility and six DOFs for 3-D manipulation. Since existing six DOF haptic devices have not been adequately developed for mobile manipulation, they are inefficient for planar three DOF motion. In this paper, a design for a six DOF haptic master suitable for tasks involving mobile manipulation is presented. The proposed device adopts a separable structure composed of lower and upper mechanisms. The lower parallel mechanism offers three DOFs for planar motion, and the upper parallel mechanism mounted on the lower mechanism provides the remaining three DOFs for a total of six DOFs; thus, the workspace can be extended into a full six DOF representation. This separable feature provided efficient actuation and reduced computational burden since only three actuators were involved in the planar task. Moving bodies should have low inertia to improve the back-drivability and transparency; therefore, all actuators were placed at the base, and torques were delivered via wire-driven transmission. A kinematic analysis was performed, and design parameters were determined through workspace analysis. Various experiments demonstrated that the proposed mechanism was efficient for a planar task, and also adequate for a full 3-D task.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Over the past several decades, various models of field robots have been developed to take the place of humans in dangerous tasks such as rescue missions, Mars exploration, airport patrols, and missions in war [1–4]. The ultimate goal of such field robot systems is to perform tasks autonomously using their own intelligence. Unfortunately, this level of independence is beyond the current state-of-the-art, and human intervention is still needed. Therefore, most field robot systems are designed to use a teleoperation control scheme.

A field robot needs to meet appropriate performance criteria (e.g., accuracy, reliability, dexterity, and various sensing abilities) to complete assigned missions. Some robots have been equipped with a manipulator to handle objects for certain missions [4]. Mobile manipulation tasks require three DOFs (x and y translation, and yaw rotation) for mobility and six DOFs for manipulation. A joystick-type device, which is commonly used for teleoperation, is adequate for navigation, but is inadequate for controlling the manipulator because it does not have an adequate number of degrees of freedom [5]. Therefore, six DOF haptic devices are often applied to a mobile manipulation task because haptic features allow easier operation of this type of task [6].

Various six DOF haptic devices have recently been developed. In particular, parallel mechanisms have been widely used for high performance haptic devices because they provide multiple degrees of freedom, low inertia, high stiffness, and high accuracy with relative ease. Siva [7] introduced the Gough Stewart mechanism in which all active joints of the haptic device were composed of prismatic joints. In designing haptic devices, revolute joints have been preferred over prismatic joints because the revolute joint is readily back-drivable. Long and Collins [8] and Iwata [9] proposed similar six DOF parallel haptic devices using revolute joints. The parallel mechanisms in their devices are composed of three pantograph linkages connected from the base to each vertex of the trinodal end-effector. For easier construction, Woo et al. [10] improved the pantograph linkage into five-bar connections. All of their devices permitted the actuators to move along the linkages so that inertia would degrade the transparency of the devices. Yoon et al. [11] suggested a parallel mechanism in which all the actuators were located at the base, thereby leading to low inertia of the moving bodies. Similar six DOF parallel haptic devices have been proposed in which all the actuators are fixed at the base frame [12, 13, 15].
Even though six DOF parallel devices have greatly improved, they have not been optimized for teleoperation of a mobile manipulator. Existing six DOF parallel haptic devices often activate all six actuators for simple force sensation because the Cartesian space and joint space are closely coupled. A teleoperation task requires planar three DOF motion for navigation and full six DOF motion for manipulation. Therefore, if a conventional six DOF device is used to control a mobile manipulator, it would be useless for controlling the redundant three joints during navigation. This type of device, therefore, is not desirable for the task, which spends most time on navigation. The dominant motion, such as planar motion of a mobile manipulator, should be independently controlled by a separate mechanism to achieve high efficiency.

In this study, a new six DOF haptic master for teleoperation of a mobile manipulator was designed and tested. The proposed haptic master consists of two separable mechanisms: one has three DOFs for planar motion \((x, y, \theta)\) and the other has three DOFs for spatial motion \((z, \phi, \psi)\). As a result, operational efficiency and a simplified control system were achieved during the navigation of the mobile manipulator because only three actuators were involved for planar motion. Each separable mechanism adopted parallel linkage to achieve high performance. The proposed haptic master demonstrated lower inertia and higher transparency since all of its actuators are located at the base frame by means of a unique power transmission design.

We report on the derivation of the kinematics of the developed mechanism, and on the analysis of a workspace for determination of proper link parameters. The design of the actual system, including its controller, is described, and our results can be used to evaluate a system with teleoperation of a mobile manipulator in both virtual and real environments. The various experiments described in this work demonstrate that the proposed six DOF haptic master was efficient for a planar task and also adequate for a full 3-D task. The remainder of this paper is organized as follows. In Section 2, the design of a proposed haptic device is introduced briefly. Section 3 describes the kinematic constraints and the Jacobian of the device. Section 4 describes dexterous workspace and link parameters. The actual integration of the system to tele-operate a mobile manipulator is described in Section 5, and Section 6 shows experimental results of the integrated system. Section 7 presents our conclusions.

2. Design concept and structure

Teleoperation for mobile manipulation is composed of navigation and manipulation. Even though manipulation requires six DOF motion, navigation is restricted within three DOF planar motion. Thus, the mechanism for planar motion is considered first. The other spatial mechanism, which provides the remaining three DOFs, is designed to extend the degrees of freedom. A new six DOF haptic master that mounts the spatial mechanism on the planar mechanism is proposed, as shown in Fig. 1. Parallel structures were adopted for both mechanisms to achieve high precision and a large feedback force.

2.1. Lower mechanism for planar motion

For a planar three DOF parallel manipulator with three identical limbs, seven combinations of RRR, RRP, RPR, RPP, PRR, PRP, and PPR are possible [16,17]. In a parallel manipulator such as the Stewart–Gough platform, prismatic joints (e.g., a linear ball screw) are employed to deliver a large force to the moving platform. In contrast to a manipulator, a haptic device should be back-drivable. Since the back-drivability of a revolute joint is better than that of a prismatic joint composed of a linear ball screw, we adopted an RRR structure in the lower mechanism, as shown in Fig. 2. Active joints \(A_i (i = 1, 2, 3)\) controlled the triangular end-effector for three DOF motion of \((x, y, \theta)\), and the other passive joints (i.e., \(B_i\) and \(C_i\)) constrained the planar motion.

2.2. Upper mechanism for extending degrees of freedom

The proposed upper mechanism offered auxiliary degrees of freedom that the lower mechanism does not provide. The upper mechanism was designed as a spatial three DOF parallel mechanism with three RRS limbs, as shown in Fig. 3. The actuation of the active joints \(A_i (i = 4, 5, 6)\) enabled the triangular end-effector to perform a three DOF motion of \((z, \phi, \psi)\).

2.3. Power transmission

The proposed haptic device has a separable structure consisting of lower and upper mechanisms. Both mechanisms moved independently in each workspace, and this feature was important for
Although the power transmission inevitably generated another coupled motion as described in Eq. (1), the main idea of the proposed device was still preserved; that is, only three actuators were activated for the planar motion. This finding was verified as described in Section 3. Note also that the benefit of the transmission (i.e., an increase in back-drivability) was enough to outweigh the disadvantage from the constraint of the aforementioned coupled motion.

3. Jacobian analysis

To operate a haptic device, kinematic equations relating joint angles to Cartesian variables are needed. Let the pose (i.e., position and orientation) of the end-effector be described by a vector $x$ and the actuated joint angles by $q$ as follows:

$$
x = \{ \begin{array}{c} x_1 \\ x_2 \\ \vdots \\ x_6 \end{array} \} \quad (2)
$$

where

$$
x_i = [x \ y \ \theta]^T, \quad x_a = [z \ \phi \ \psi]^T
$$

and

$$
q = \{ q_1 \ q_2 \ q_3 \}^T, \quad q_u = \{ q_4 \ q_5 \ q_6 \}^T
$$

where the subscripts $l$ and $u$ denote the lower and upper mechanisms, respectively. (Note that all the variables are shown in Figs. 2, 3 and 5.) The kinematic relations written in vector notation for the lower and upper mechanisms are given by

$$
A_iG_l + G_lC_l = A_iB_l + B_lC_l, \quad i = 1, 2, 3 \quad (4)
$$

$$
A_iG_u + G_uC_u = A_iB_u + B_uC_u, \quad i = 4, 5, 6 \quad (5)
$$

Since the length of each mechanism is constant at $l_i$, the following constraint can be derived:

$$
f_i(x, y, \theta, q_i) = (x + x_{GC} \cdot c\theta - y_{GC} \cdot s\theta - (x_a + l_1c(q_i)))^2 + (y + x_{GC} \cdot s\theta + y_{GC} \cdot c\theta - (y_a + l_1s(q_i)))^2 - l_i^2 = 0 \quad (i = 1, 2, 3) \quad (6)
$$

Similarly, for the upper mechanism,

$$
f_i(z, \phi, \psi, \theta, q_i) = (x_{GC} \cdot c\theta - y_{GC} \cdot c\phi + y_{GC} \cdot s\phi - c\theta \cdot s\phi + c\phi \cdot s\phi + s\phi \cdot c\phi + s\phi \cdot s\phi) - (l_1c\phi)q_i(x_a) - c\phi \cdot s\phi \cdot s\phi) + (l_1s\phi)q_i(y_a) - c\phi \cdot s\phi \cdot s\phi + y_{GC} \cdot c\phi - y_{GC} \cdot s\phi - c\phi \cdot s\phi + s\phi \cdot c\phi + s\phi \cdot s\phi - l_is(q_i))^2 - l_i^2 = 0 \quad (i = 4, 5, 6) \quad (7)
$$

where all the variables are shown in Figs. 2 and 3, and $s\theta$ and $c\theta$ denote $\sin\theta$ and $\cos\theta$, respectively. Referring to Eq. (1), the relation between actual joint variables $q_i$ ($i = 4, 5, 6$) and the three DOF motion of $(z, \phi, \psi)$ can be derived from Eqs. (1) and (7). Substituting $q_i$ ($i = 4, 5, 6$) from Eq. (1) into $q_i$ ($i = 4, 5, 6$) from Eqs. (6) and (7) leads to the following differential relations between the joint and the Cartesian vectors for each mechanism:

$$
f_{ql} \cdot dq_l = f_{zl} \cdot dx_l + f_{xl1} \cdot dx_a \\
J_{zu} \cdot dq_u = f_{zu} \cdot dx_u + f_{xz2} \cdot dx_l
$$

Fig. 3. Schematic of the upper mechanism.

Fig. 4. Schematic of wire-driven mechanism for power transmission.
where \(J_q\) and \(J_u\) are the Jacobian matrices of the lower mechanism and \(J_{qu}\) and \(J_{xu}\) are the Jacobian matrices of the upper mechanism. \(J_{xc1}\) and \(J_{xc2}\) are the coupling relation between the lower and the upper mechanisms. Eq. (6) shows that \(q_i\) \((i = 4, 5, 6)\) does not affect the lower mechanism, and hence, \(J_{xc1}\) becomes the zero matrix in Eq. (8). However, some elements of \(J_{xc2}\) in Eq. (9) still exist because the rotation of the lower mechanism \(\vartheta\) is involved in the upper mechanism, as shown in Eqs. (1) and (7). Using the definitions of Eqs. (2) and (3), Eqs. (8) and (9) can be integrated into a single

\[
\begin{align*}
J_q \cdot dq &= J_x \cdot dx \\
\text{where}
J_q &= \begin{bmatrix} J_{q1} & 0 \\ 0 & J_{qu} \end{bmatrix} = \text{diag}[J_{q1}, J_{q2}, J_{q3}, J_{q4}, J_{q5}, J_{q6}], \\
J_x &= \begin{bmatrix} J_{xl} & 0 \\ 0 & J_{xu} \end{bmatrix} = \begin{bmatrix} J_{xl} & 0 \\ J_{xc2} & J_{xu} \end{bmatrix}.
\end{align*}
\]

The matrix \(J_x\) becomes a lower triangular matrix which implies that only three actuators can be used for planar forces. From Eq. (10), the overall Jacobian matrix \(J\) can be defined as

\[
dq = Jdx
\]

where

\[
J = \begin{bmatrix} J_{cl} & J_{cu} \end{bmatrix}
\]

The relationship between the joint torque vector \(\tau\) and the force/moment vector \(F\) at the end-effector is given by

\[
F = J^T \tau
\]

or, equivalently,

\[
\tau = J^{-T} F
\]

Singularity analysis of a robotic device is important during the design process. The two Jacobians in Eq. (10) need to be analyzed. First, matrix \(J_q\) becomes singular when \(\det(J_q) = 0\). Since \(J_q\) is a diagonal matrix, singularities occur when one of the diagonal elements
vanishes whenever the device reaches its workspace boundary. If this type of singularity occurs, the device can resist forces or moments in some directions for zero joint torques. Second, the matrix $J_x$ becomes singular when $\det(J_x) = 0$. In this case, the device cannot resist forces or moments in some directions, even for large joint torques. Since $J_x$ is a lower triangular matrix, its determinant becomes

$$\det(J_x) = \det(J_{xl}) \det(J_{xu}) = 0$$

(19)

Therefore, $J_x$ becomes singular when either $J_{xl}$ or $J_{xu}$ or both are singular. This condition implies that the whole mechanism does not need to be analyzed at once, and that singularities can be easily investigated in each separate mechanism.

Another important feature of the proposed design is the simplified computation of the inverse Jacobian matrix. In Eq. (16), $J^{-T}$ must be obtained to compute the joint torques required for the desired end-effector force $F$. From Eq. (14), $J^{-T}$ becomes

$$J^{-T} = J_x^{-T}$$

(20)

From Eq. (12),

$$J_{x} = \begin{bmatrix} J_{xl} & J_{xc} \\ 0 & J_{xu} \end{bmatrix}$$

(21)

Since Eq. (21) is an upper triangular matrix, its inverse can be computed by the matrix inversion lemma as follows:

$$J_x^{-T} = \begin{bmatrix} J_{xl}^{-1} & J_{xc}^{-1} J_{xu}^{-1} \\ 0 & J_{xu}^{-1} \end{bmatrix}$$

(22)

Note that the inversions involved in Eq. (22) for $3 \times 3$ matrices are much simpler than those for $6 \times 6$ matrices. Hence, the computational load of the inverse Jacobian is significantly reduced in comparison with that of six DOF devices of a similar type.

4. Design parameters and workspace analysis

To determine adequate design parameters, the characteristics of the mechanism (e.g., workspace, force capacity, position accuracy, and isotropy of the Jacobian) must be examined. Figs. 2 and 3 reflect many of the design parameters for the developed device such as the length of the links and the initial configuration. It is difficult to optimize these parameters because the characteristics of the mechanism are complementary or contradictory to each other. These parameters were selected specifically to meet the purpose for which the device is being designed, rather than to optimize the performance of the device. Thus, we present a guideline for determining some specific parameters for the lower mechanism. The workspace of the lower mechanism is the main focus of this section, even though other performance indices such as the global
A haptic device should have a continuous reachable workspace without singular position. For the lower mechanism, there are various configurations for creating a solid workspace that excludes non-reachable holes in the workspace [22]. In this study, all links in the limbs of the lower mechanism, as shown in Fig. 2, were set to the same length \((l_2 = l_3)\). To achieve a solid workspace, the circle of radius \(R_l\) shown in Fig. 2, where \(A_i (i = 1, 2, 3)\) is located, should also be the same length as link \(l_1\). As a result, a continuous reachable workspace was obtained, and the limbs could access all locations in the circle. The remaining parameter to be determined was the radius of the end-effector for the lower mechanism \(r_l\). This remaining parameter and the initial configuration are determined from workspace analysis, and the dexterous workspace discussed in this research generally excludes a singular pose. Even in the reachable workspace, a parallel mechanism may include a singular pose. For this reason, the dexterous workspace, which is the region where the mechanism actually performs a given task, was suggested \([18,23]\). As shown in Fig. 5, the reachable and dexterous workspaces of the lower mechanism were analyzed with respect to the three cases of \(r_l\).

In Fig. 5a–c, the outer hull, which is enveloped by lines, represents the reachable workspace, and the mesh inside of the hull displays the dexterous workspace. As reflected in the figures, the dexterous workspace was investigated with the condition number since the condition number of a Jacobian matrix properly represents the kinematic characteristics. The figures show that the dexterous area is much smaller than the reachable area. This indicates that even in some regions in the reachable area, performance is poor because the limbs are nearly folded or stretched in those regions. When the radius \(r_l\) increased, the reachable workspace was reduced. On the other hand, the dexterous workspace was extended when the radius \(r_l\) increased. From these workspace analyzes, the actual parameter \(r_l\) was determined to be 0.4\(l_1\) for implementation purposes.

Fig. 5 also suggests two important insights: (1) the dexterous workspace is vertically split and does not include the neighborhood of angle \(\theta = 0\) and (2) the upper region, characterized by a positive angle, is larger than the lower region. Consequently, it was desirable to use the continuous area in the upper dexterous area and not to continue operating the mechanism near the origin \((\theta = 0)\). For these reasons, the rotation was restricted to the upper dexterous area, and the initial configuration was set in the middle of this area.

### 5. Development and performance evaluation

An experimental system was developed in this study. Fig. 6a shows the developed mechanism, and Fig. 6b shows a picture of the power transmission. As shown in Fig. 6b, the bevel gears in Fig. 4 were replaced by a wire-driven mechanism to minimize backlash. Fig. 7 shows a block diagram illustrating the control system of the developed haptic master. To provide feedback force, the main controller calculates the desired joint torque \(\tau_{d} \) with respect to the given force command \(F_d\) using the Jacobian analyzed in Section 3. Joint torque \(\tau_{d} \) was converted to the desired current \(i_d\) by multiplying the torque constant \(K_t\), and the motor driver regulated the desired current to exert joint torque \(\tau_{e} \). The encoder measured the angles of the active joints \(q\), and pose \(x\) described in Eq. (2) was computed from the measured data by a pulse counter and kinematic analysis.

As shown in Fig. 8, the controller for the haptic system was integrated with an industrial PC, which provided sufficient computing power for the complex kinematic analysis. This controller also provided easier communication in either a virtual environment (VE) or a tele-operated robot system via a LAN. A multi-functional board was implemented to operate the motor driver with its counters and digital-to-analog/analog-to-digital converters. This board communicated with the industrial PC through a PC104 bus, which permitted a data rate of 8 Mbytes/s. Finally, the control period for the torque control and the kinematic calculation was set to 1 ms.

Fig. 9 shows measured force on the x axis during sinusoidal excitation with open loop control. The more frequent reference command makes the slower response follow the reference shown in Fig. 9, and finally the proposed device barely traces \(1/\sqrt{2}\) times
the commanded magnitude at 2 Hz as shown in Fig. 9d. This reveals that the mechanical bandwidth of the developed device is 2 Hz with open loop control which could be improved using feedback control.

It is difficult to compare the proposed haptic device with other haptic devices because they have different structures and features. Table 1 shows the comparative specifications among five haptic masters, and the superior specifications are denoted in bold on gray shading. The Phantom is a well-known serial haptic master proposed in [25]. It has a relatively larger workspace than other parallel masters, but other specifications are not as good as other haptic masters. The parallel haptic master described in [8] achieved six DOFs with high force capacity, but the actuators move with the linkages. Yoon and Ryu modified the master of Long and

Table 1
Comparative specifications among five haptic masters.

<table>
<thead>
<tr>
<th></th>
<th>Serial master, Phantom</th>
<th>Parallel master by Long and Collins</th>
<th>Paraller master by Yoon and Ryu</th>
<th>Hybrid master by Tsumaki et al.</th>
<th>Proposed new master</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOF</td>
<td>3/6 (6 inputs/3 outputs)</td>
<td>6 (6 inputs/6 outputs) (large)</td>
<td>6 (6 inputs/6 outputs)</td>
<td>6 (6 inputs/6 outputs)</td>
<td>6 (6 inputs/6 outputs)</td>
</tr>
<tr>
<td>Workspace (compare to device size)</td>
<td>Cube (80 \times 170 \times 250 mm) (small)</td>
<td>Max diameter 300 mm (small)</td>
<td>Max diameter 300 mm (small)</td>
<td>Sphere (150 mm diameter) (small)</td>
<td>Cylinder (110 mm diameter, 100 mm high)</td>
</tr>
<tr>
<td>Force capacity (compare to motor spec.)</td>
<td>Force: continuous 1.5 N, peak 10 N force (weak)</td>
<td>40 N(z), 20 N(x, y)</td>
<td>6 Nm(z), 3 Nm(x, y) (strong)</td>
<td>More than 10 N (strong)</td>
<td>Force: continuous 20 N, peak over 30 N (strong)</td>
</tr>
<tr>
<td>Complexity for control</td>
<td>3 actuators simultaneously</td>
<td>6 actuators simultaneously</td>
<td>6 actuators simultaneously</td>
<td>3/3 actuators separately (position/rotation)</td>
<td>3/3 actuators separately (planar/spatial)</td>
</tr>
<tr>
<td>Moving actuators</td>
<td>0/3 (3 for six DOF version)</td>
<td>6</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Note—Superior specifications are denoted in bold.
Collins so that all actuators were placed on the base frame [11]. However, it was difficult to control the actuators because they were all closely coupled in six DOF Cartesian space. Tsumaki et al. proposed a hybrid master using two parallel mechanisms [14] to improve the control problem. On the other hand, the moving inertia grows due to the moving actuators for the upper parallel mechanism. The developed device was designed to fix all actuators on the base frame, and it also adopted a hybrid concept for easy control. As shown in Table 1, the proposed device is better than other devices in four specifications excluding the workspace.

6. Experimental results

When a user performs a mission with a mobile manipulator, two operating modes are required. One is a navigation mode to move the mobile base, and the other is a manipulation mode to operate the manipulator. A mission usually starts with the navigation mode wherein the operator controls the mobile base to search for a target (or to explore an environment). When the robot detects an object to handle, the navigation mode is switched to the manipulation mode. The robot then executes various manipulation tasks; for example, removing an explosive, repairing something, or collecting a radioactive substance. After finishing the manipulation task, the navigation mode is resumed to allow the robot to safely come home and complete the mission.

During a mission, the navigation task seems routine and insignificant, but actually, spends a great amount of time. For navigation purposes, a common joystick is adequate to control the mobile base; therefore, a six DOF device is inefficient rather than useful for force-feedback. However, a six DOF master is essential for easier operation during the manipulation mode. The haptic master developed in this study offers a unified and efficient input for both tasks. Designed with a joystick, the lower mechanism provides an easy and comfortable way to control the mobile base, and the upper mechanism is stretched to control manipulation. Consequently, the operator can handle two mechanisms simultaneously so that all six DOFs can be intuitively used. These features were evaluated using the following experiments.

6.1. Teleoperation of a mobile manipulator in a virtual environment

The proposed system was tested in the virtual environment shown in Fig. 10. A virtual field was constructed with computer graphics, and virtual models of trees, stones, and a monument were built on the field. A mobile manipulator that can be controlled by the developed haptic master was also simulated. At the start of the mission, the operator controlled the mobile

Fig. 11. Experimental results. (a) Motion of handle to control mobile manipulator during operation. (b) Reference forces for haptic sensation during interaction with virtual environment. (c) Generated torques at joints of upper mechanism with respect to reference forces. (d) Generated torques at joints of lower mechanism with respect to reference forces.
manipulator to move from spot A to spot B, as shown in Fig. 10. The white line in Fig. 10 shows the trajectory of the movement. When the robot approached stones or trees, feedback force was provided to avoid collision with the obstacles in regions $S_1$, $S_2$, $S_3$ and $S_4$ shown in Fig. 10a. After the mobile manipulator reached spot B and the operator finished exploring, the operator began to control the manipulator. In this scenario, the operator tried to place a fire extinguisher at one corner under the monument, as shown in Fig. 10c. If the extinguisher came in contact with the wall, a reaction force would have been provided to the operator in proportion to the depth of penetration. In the real field, this would protect the manipulator from damage due to an unexpected collision. A rate control was used in the navigation mode so that the position of the lower mechanism was translated to a velocity command for the mobile base. On the other hand, a position control was adopted for the manipulation mode. In using a position control scheme, the motion was limited because the workspace of the developed device was much smaller than the workspace of the manipulator. To overcome this limitation, indexing and scaling techniques were adopted [26].

Experimental results are shown in Fig. 11. The position of the haptic handle and the force-feedback command are shown in Fig. 11a and b, respectively. The fluctuations of actual torques of the lower and upper mechanism are illustrated in Fig. 11c and d.

![Haptic Interface](image1)

![Visual Interface](image2)

![Speech & auditory Interface](image3)

![Remote control station for teleoperation of field mobile manipulator](image4)

![Navigating over rugged road](image5)

![Approaching target and unfolding manipulator](image6)

![Manipulating imitation bomb](image7)

![Successfully finishing mission and returns](image8)

**Fig. 12.** EOD demonstration with actual robot system operated by developed haptic master. (a) Remote control station for teleoperation of field mobile manipulator. Developed haptic master provided a unified interface for both navigation and manipulation. (b) Navigating over rugged road. (c) Approaching target and unfolding manipulator. (d) Manipulating imitation bomb. (e) Successfully finishing mission and returns.
It took $t_{\text{navigation}}$ during travel from spot A to spot B. The robot approached obstacles four times in regions $S_1$, $S_2$, $S_3$, and $S_4$ (Fig. 10a), and feedback force was exerted at the times of approach, as shown in Fig. 11b. When the robot moved near the obstacles, the feedback force guided the handle to avoid them. While force reflection affected the operation, the force adjusted the motion of the handle, as shown in Fig. 11a. Section $S_2$ is a particularly good example of this typical behavior. In this area, the feedback force to the $x$ direction drove the handle to the right because a stone post approached as shown in Fig. 11c and d. The experimental results revealed that all actuators for the upper and lower mechanisms were activated, plane directions were generated due to the contact. When the feedback force in the $z$ direction was exerted on the stone platform, all actuators for the upper and lower mechanisms were activated, as shown in Fig. 11c and d. The experimental results revealed that the activated actuators involved only three motors for the lower mechanism during navigation. However, the manipulation task required all six actuators, consistent with the operation of typical six DOF haptic devices. These results demonstrate that the proposed master is adequate and efficient for the teleoperation of a mobile manipulator.

6.2. Application of field robot system and EOD demonstration

Recently developed field robots have been equipped with articulated manipulators which extend the application range of the robots. However, to control the dexterous motion of a mobile base and installed arm, the operator control unit (OCU) must be equipped with many buttons and paddles in addition to a joystick [5]. These numerous control features add unwanted complexity to the user interface, and make slave robots difficult to use. Furthermore, the added complexity increases the likelihood of an operator error. An easier operation method would help prevent such errors. Therefore, the developed master was applied to an actual field mobile manipulator, and both the navigation and manipulation tasks were controlled by one haptic master. The master unified diverse controllers and provided a simple user interface. A demonstration setup for explosive ordnance disposal (EOD) was artificially constructed [24], as shown in Fig. 12.

An operator controlled the robot from a remote location by means of the haptic device (Fig. 12a) while watching the transmitted images on a head mount display. Fig. 12b shows that the robot accessed the explosive ordnance after traveling over a hazardous field. The robot finished the navigation task in the vicinity of the target, and the manipulation task started, as shown in Fig. 12c. Fig. 12d shows that the operator could approach, grip, and pick up an imitation bomb by using all six DOFs of the haptic master. The mission was successfully completed, and the robot returned to a safe place to dispose of the removed ordnance (Fig. 12e). During the navigation phase of this experiment, the operator handled the lower mechanism of the haptic master in a familiar manner (like a typical joystick), but stretched the upper mechanism and used all six DOFs for manipulation. In this manner, a simple unified interface for both navigation and manipulation of an actual robot system was achieved.

7. Conclusion

This paper discussed the development of a new haptic master for the teleoperation of a mobile manipulator. The master adopted a separable structure composed of two parallel mechanisms: one mechanism had three planar DOFs adequate for navigation, and the other used the remaining three DOFs for manipulation. As a result, the proposed master achieved efficient actuation and reduced computational burden by using only three actuators in planar tasks during navigation. All actuators were installed on the base frame; thus, power transmission, which was designed to use the structural characteristics of the master, was employed. Finally, backdrivability and transparency were improved due to the low inertia.

In this research, the kinematics for the proposed master was analyzed and the dexterous workspace was examined. The proper values for the link parameters and the initial pose were determined based on the kinematic analysis, and an actual system was implemented. Experiments in both virtual and real environments were performed to evaluate the developed master, and the results proved that the master was efficient for the teleoperation of a mobile manipulator. The proposed haptic master was adequate for haptic tasks consisting mainly of planar motion as well as tasks consisting of six DOF motion.

References


