Effects of Haptic Feedback on Telepresence and Navigational Performance

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Abstract

We address the problem of teleoperating a mobile robot using shared autonomy: an on-board controller performs obstacle avoidance while the operator uses the manipulandum of a haptic probe to designate the desired speed and rate of turn. Sensors on the robot are used to measure obstacle range information. We describe a strategy to convert such range information into forces, which are reflected to the operator's hand, via the haptic probe. This haptic information provides feedback to the operator in addition to imagery from a front-facing camera mounted on the mobile robot. Extensive experiments in a real test environment with a user population show that the added haptic feedback significantly improves not only operator performance but also subjective presence.

Key words: Haptics, Teleoperation, Presence, Mobile Robot

1. Introduction

Teleoperation is often employed in controlling mobile robots navigating in unknown and unstructured environments. This is largely because teleoperation makes use of the sophisticated cognitive capabilities of the human operator [1, 2].

However, for navigation in dynamic environments or at high-speeds, it is often desirable to provide a sensor-based collision avoidance scheme on-board the robot to guarantee safe navigation. Without such a collision avoidance scheme, it would be difficult for the (remote) operator to prevent the robot from colliding with obstacles. This is primarily due to (1) limited information from the robot's sensors, such as images within a restricted viewing angle without depth information, which is insufficient for the users' full perception of the environment in which the robot moves [3], and (2) significant delay in the communication channel between the operator and the robot.

On the other hand, the implementation of a collision avoidance scheme on-board the robot can cause conflict between the user's actions and the movement of the robot. For example, consider a situation where the operator directly controls the movement of a mobile robot with a joystick and the robot is supposed to move forward when the user pushes the stick forward. Imagine that the robot is also programmed with a simple collision avoidance algorithm to avoid obstacles. If an obstacle exists in front of the robot, the robot may stop or turn in order to avoid collision, although the operator is clearly commanding it to move ahead. In this example, the conflict may not be a problem if the user can easily see the obstacles. If however, the obstacles are invisible due to a restricted viewing angle, the user might be confused since the robot does not move nor act according to the teleoperation commands. Such a conflict can have a negative influence upon subjective presence of the operator. We hypothesize that the conflict can be naturally resolved by exploiting another modality, e.g. such as haptic information, providing the operator with force feedback.

In [4], we have proposed a haptic teleoperation scheme and have shown the effectiveness of the haptic feedback on navigational performance through an experiment in a virtual test environment. In this paper, we verify the effectiveness by conducting an experiment in a real test environment, and show the effectiveness on subjective (tele)presence.

This paper is structured as follows. In Section 2, we describe related work in the area of using haptic information for navigation. In Section 3, we give a review of our force rendering algorithm and the implemented system. In Sections 4 and 5, we describe our experiment (in the real environment) and the results, respectively. Finally, we conclude with a summary in Section 6.

2. Related Work

Force feedback has long been used for precise remote control in the teleoperation of manipulators [5, 6]. Recently, with the spread of commercial haptic devices such as the PHANToM [7, 8], the CyberGrasp [9], and various force-feedback joysticks [10, 11], haptic information is being used in many areas of virtual reality, robotics, training and entertainment. Haptic feedback is usually used as a supplementary cue to help the user understand the virtual environment [12, 13, 14, 15, 16].

For mobile robot navigation, Elhajj et al. [14, 17] proposed an event-based direct control with force feedback. This approach reflected the difference between the actual velocity and the desired velocity of the mobile robot to the operator as force feedback. It was difficult to perform precise navigation in a cluttered environment with their method, as the turn rate was not considered for force rendering and collision avoidance was automatically performed, which compelled the robot to stop at the distance of 0.5 m (too far) from the obstacles.

A full range of advanced interfaces for vehicle control was investigated by Fong, Thorpe, and Bauer [18]. In particular, the HapticDriver [3, 18] had the same aims as ours. They used the force cube primitives modeled from the range information obtained by infrared sensors attached to the vehicle in order to compute the force fed back to operators. It was informally shown that the HapticDriver had improved obstacle detection and collision avoidance in vehicle teleoperation.

Rösch, Schilling, and Roth [19] implemented a haptic interface using a force feedback joystick for the remote control of mobile robots. They used force sensors attached in the front of the robot in order to determine the magnitude of the force that would be fed back to the operator. In terms of the sense of presence, their approach was interesting in that the degree of how strongly the robot pushed obstacles was directly given to the operator in the form of force. Nevertheless, their approach was somewhat unreasonable to be used for safe navigation since the operator could feel the force only after the robot collided with the obstacles.

A haptic teleoperation system was proposed by Diolaiti and Melchiorri [20]. In their approach, when the operator determined the direction and magnitude of the desired "velocity" of the robot with the haptic device, the force, computed from the obstacle map and the displacement of the haptic device, guided the operator to a safe trajectory. In terms of safe navigation, it was a good approach. In terms of precise control, however, it did not consider ways to turn in place. While many researchers proposed and implemented different approaches for haptic teleoperation of mobile robots, most of them have not shown the effectiveness of the respective approaches in formal experiments.

3. Overview of the Haptic Teleoperation System for a Mobile Robot

3.1 Force Rendering

In the direct control mode, the user's action is used to determine the speed and turning rate of the robot. A logical position (x, z) of the haptic probe designated by the user's action is mapped to speed and turning rate as follows:

$$\text{speed } v = k_1 \cdot h(-z, b) \tag{1}$$

$$\text{turning rate } \omega = \begin{cases} k_2 \cdot h(x,b), & \text{if } z \le b \\ k_2 \cdot h(-x,b), & \text{if } z > b \end{cases} \tag{2}$$

$$\text{where } \; h(a,b) = \begin{cases} a-b, & \text{if } a > b \\ a+b, & \text{if } a < -b \\ 0, & \text{if } |a| \le b \end{cases}$$

Note that the speed v is equal to 0 when the logical point is in the area where $|z| \le b$, and the turning rate ω is equal to 0 when the logical position is in the area where $|x| \le b$. This "deadzone" prevents movements of the robot due to small unintended user actions and tremors. k_1 and k_2 are proportionality constants.

When the user determines the logical position, the force that the user should feel at that position is computed from the position information of the obstacles surrounding the robot. Range finding sensors attached to the robot obtains the position information of the obstacles represented as a list of distance values between the robot and the obstacles.

We consider two kinds of forces (on the navigation plane): an "environmental" force and a "collision-preventing" force. Let the environmental force and the collision-preventing force be represented by ($F_{e,x}$, $F_{e,z}$) and ($F_{c,x}$, $F_{c,z}$), respectively. The final rendered force (F_x, F_z) is given by:

$$(F_x, F_z) = (\max\{F_{e,x}, F_{c,x}\}, \max\{F_{e,z}, F_{c,z}\}) \tag{3}$$

The environmental force prevents the robot from moving and turning towards obstacles by giving the user the distance information between the robot and the obstacles in a form of force. When the logical position of the interface is represented by (x, z), the environmental force $\mathbf{F_e} = (F_{e,x}, F_{e,z})$ is given by:

$$F_{e,x} = \begin{cases} k_3 f_{-x}(D)x & \text{if } x \ge 0 \\ -k_3 f_{+x}(D)x & \text{if } x \ge 0 \end{cases} \tag{4}$$

$$F_{e,z} = \begin{cases} k_4 f_{-z}(D)z & \text{if z} \ge 0 \\ -k_4 f_{+z}(D)z & \text{if z} \ge 0 \end{cases} \tag{5}$$

where

$$f_{-x}(D) = \max_{i=1}^{n}[\phi_{-x}(d_i,\theta_i)\frac{d_i - r_{\max}}{r_{\max}}\cos\theta_i]$$

$$f_{+x}(D) = \max_{i=1}^{n}[\phi_{+x}(d_i,\theta_i)\frac{d_i - r_{\max}}{r_{\max}}\cos\theta_i]$$

$$f_{-z}(D) = \max_{i=1}^{n}[\phi_{-z}(d_i,\theta_i)\frac{d_i - r_{\max}}{r_{\max}}\sin\theta_i]$$

$$f_{+z}(D) = \max_{i=1}^{n}[\phi_{+z}(d_i,\theta_i)\frac{d_i - r_{\max}}{r_{\max}}\sin\theta_i]$$

$$\phi_{-x}(d_i,\theta_i) = \begin{cases} 1 \;\; \text{if } d_i < r_{\max} \text{ and } \cos\theta_i > 0 \\ 0 \;\; \text{otherwise} \end{cases}$$

$$\phi_{+x}(d_i,\theta_i)=\begin{cases}1 & \text{if } d_i<r_{\max} \text{ and } \cos\theta_i<0\\ 0 & \text{otherwise}\end{cases}$$

$$\phi_{-z}(d_i,\theta_i)=\begin{cases}1 & \text{if } d_i<r_{\max} \text{ and } \sin\theta_i>0\\ 0 & \text{otherwise}\end{cases}$$

$$\phi_{+z}(d_i,\theta_i)=\begin{cases}1 & \text{if } d_i<r_{\max} \text{ and } \sin\theta_i<0\\ 0 & \text{otherwise}\end{cases}$$

$$D=\{(d_1,\theta_1),\ (d_2,\theta_2),\ \cdots,\ (d_n,\theta_n)\}$$

$$d_i : \text{the distance value of the } i\text{th scanned obstacle point}$$

$$\theta_i : \text{the angle of the } i\text{th scanned obstacle point}$$

The absolute value of the force due to an obstacle is inversely proportional to the distance d_i between the robot and the obstacle, and does not affect the robot when the distance is equal to or more than $r_{\max}$. k_3 and k_4 are the constants to adjust the magnitude of the force. We use $k_3 = k_4 = 0.1$, which are determined empirically.

Although the environmental force prevents the robot from moving and turning towards obstacles to some degree, it does not guarantee that the robot will not collide with any obstacles. This is because the robot is modeled as a point, while, in actuality, the robot can have any shape and an obstacle is modeled as a polygon whose vertices are the scanned points obtained by the range sensors. To guarantee collision-free navigation, we introduce the collision-preventing force.

The collision-preventing force is computed from possible-turning angles and the distances between the robot and the obstacles in the front and rear direction of the robot. The possible-turning angles are the maximum angles by which the robot can turn without any collision. These angles have two types: the left (or counterclockwise) angle (δ_{ccw}) and the right (or clockwise) angle (δ_{cw}) since the robot can turn both left and right. The distances between the robot and the obstacle in the front and rear direction of the robot are the maximum distances (d_{front} and d_{rear}) by which the robot can move forward and backward without any collision.

When the logical position of the interface is represented by (x, z), the collision-preventing force $\mathbf{F_c} = (F_{c,x}, F_{c,z})$ is given by:

$$F_{c,x}=\begin{cases}k_5\dfrac{\delta_{avg}-\delta_{ccw}}{\delta_{avg}}x & \text{if } x\geq 0 \text{ and } \delta_{avg}-\delta_{cw}>0\\[2ex] k_5\dfrac{\delta_{avg}-\delta_{cw}}{\delta_{avg}}x & \text{if } x<0 \text{ and } \delta_{avg}-\delta_{ccw}>0\end{cases} \tag{6}$$

$$F_{c,z}=\begin{cases}k_6\dfrac{d_{front}-d_{\max}}{d_{\max}}z & \text{if } z\leq 0 \text{ and } d_{front}<d_{\max}\\[2ex] -k_6\dfrac{d_{rear}-d_{\max}}{d_{\max}}z & \text{if } z>0 \text{ and } d_{rear}<d_{\max}\\[2ex] 0 & \text{otherwise}\end{cases} \tag{7}$$

$$\text{where}\quad \delta_{avg}=\frac{\delta_{ccw}+\delta_{cw}}{2}$$

The constant values k_5 and k_6 play the similar role to k_3 and k_4 in Equations (4) and (5), respectively. A proper value for both of k_5 and k_6 is 0.3, which was determined empirically.

Note that it is impractical to use the collision-preventing force alone since it may change suddenly when the robot moves and turns simultaneously. The collision-preventing force should be used together with the environmental force, which plays a role to buffer sudden increase in force feedback.

3.2 Implementation

We implemented a direct control system for the Activmedia Pioneer 2-DX [21] mobile robots equipped with one SICK LMS-200 laser scanner for front coverage, eight Polaroid 600 series ultrasonic transducers for rear coverage and the Sony EVID-30 camera. The laser scanner provides a scan resolution of 1 degree, a coverage of 180 degrees, and a distance range of approximately 8m at a scan rate of approximately 10Hz. We used the SensAble PHANToM as the force-feedback device.

The system used 2 PCs and an embedded PC in the Pioneer 2-DX. The control PC with the PHANToM was indirectly connected to the Pioneer 2-DX via the intermediate PC since the control PC did not support a wireless network connection in our setup. The network connections of the control PC to the intermediate PC and the intermediate PC to Pioneer 2-DX had 100Mbps and 1Mbps bandwidths, respectively.

In addition to force feedback, the system provided visual feedback of the image sequence captured by the camera attached to Pioneer 2-DX. The image update rate on the control PC was about 8Hz where the resolution of an image was 160 × 48 and each pixel was represented by 256 gray levels.

A physical position of the PHANToM was converted to a logical position (x, z), which was mapped to the motion parameters (speed rate v, turning rate ω) of the mobile robot. Although the PHANToM provided 3DOF position information, we ignored one DOF. In our implementation, a logical position was same as a physical position in the unit of millimeter but the y value was not used. The system uses $b = 30.0$, $k_1 = 20.0$, and $k_2 = 1.0$ in Equations (1) and (2), and limits the working area of the PHANToM to 180 mm × 200 mm, so that the speed rate and the turning rate of the robot are at most 1.4 m/s and 60 °/sec respectively.

4. Experiment

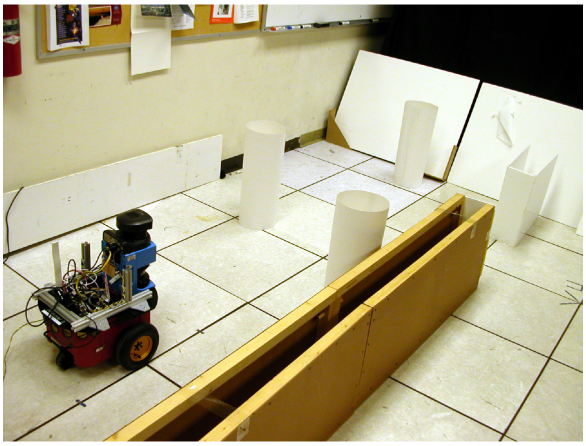
Three different methods of force rendering (independent variable) were tested and compared with one another in terms of users' performance and their sense of presence in the actual remote world:

- NF: No force feedback ($k_3 = k_4 = k_5 = k_6 = 0.0$).
- EF-only: Using environmental force only ($k_3 = k_4 = 0.1$, $k_5 = k_6 = 0.0$).
- EF & CF: Using both environmental and collision-preventing force ($k_3 = k_4 = 0.1$, $k_5 = k_6 = 0.3$).

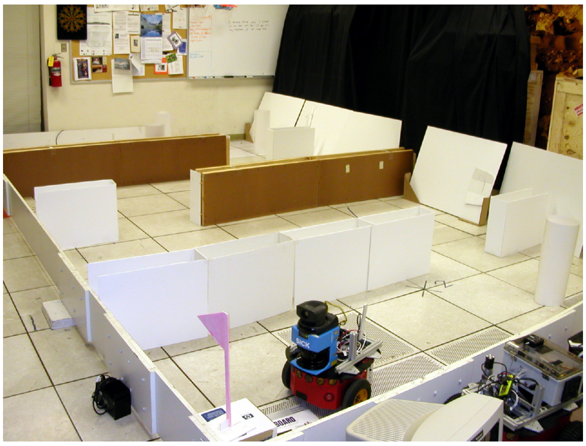
4.1 Real Test Environment

A subject was required to remotely control a mobile robot navigate a real environment whose size was 3.65 m × 6.86 m. Two snapshots of the real test environment are shown in Figure 1.

The real environment had the two types of obstacles: the cylinder and the wall types. The obstacles were arranged in two different ways: scattered cylinders and straight rectangular walls. In the zone of scattered cylinders, the distances between cylinders ranged between 0.7 m and 1.55 m. In the zone of the rectangular walls, the widths of wall openings were 0.65 m and the distance between the walls were 1.5 m.



(a) With the robot on the start position.



(b) With the robot near the goal flag.

Fig. 1. Two views of the real test environment.

Stage I: The subject is briefly introduced to the teleoperation system and about the experiment. Then, the subject is asked to fill out the personal information form (including age, gender, and experiences in car-driving and computer games).

↓

Stage II: The subject receives the training for navigating in the virtual test environment. The environment is designed similarly to the real test environment using the same three interfaces (one trial for each method).

↓

Stage III: The subject carries out actual task making the real robot navigate in the real test environment (one trial for each method). After each trial, the subject is asked to fill out the questionnaire (Table 1).

↓

Stage IV: The subject is debriefed for further comments.

Fig. 2. The experimental procedure.

Table 1. The questionnaire used in the experiment. The category information was not shown to the subjects.

No. (Category)	Question
1* (Force Perception)	Do you think that there was any difference between the interface used in the previous trial and that in this trial ? (Please circle the answer.) Yes / No
2** (Force Perception)	Do you think that there was any difference among the 3 interfaces ? (Please circle the answer.) Yes / No
3 (Perceived Performance)	How good do you think the interface for this trial was in terms of achieving the required task ? (Please rate with a score, in the scale from 0 to 100, where 0 represents “Never” and 100 represents “Very much”)
4 (Presence Question 1)	When you were performing this trial, how much did you feel as if you were in the environment ? (Please rate with a score, in the scale from 0 to 100, where 0 represents “Never” and 100 represents “Completely”)
5 (Presence Question 2)	When you think back about your experience in this trial, do you think of the environment more as images that you saw, or more as somewhere that you visited ? (Please rate with a score, in the scale from 0 to 100, where 0 represents “Images that I saw” and 100 represents “Somewhere that I visited”)
6 (Presence Question 3)	During the course of the experience in this trial, which was stronger on the whole, your sense of being in the remote environment, or of being in the laboratory ? (Please rate with a score, in the scale from 0 to 100, where 0 represents “In the laboratory” and 100 represents “In the remote environment”)

*No. 1 was filled out after the 2nd and 3rd trials only. **No. 2 was filled out after the 3rd trial only.

4.2 Experimental Design

A subject was required to control the robot navigate the real environment from a start position to a goal position as *safely* as possible. The maximum speed and turning rate was limited to 0.14 m/s and 15 °/s, respectively, in order to reduce damage to the robot in case of a collision at the full speed.

The experimental procedure is shown in Figure 2. A repeated-measure design was applied to the experiment. A subject made one trial of the task with each force rendering method, so that each subject made a total of three trials of the task. There was no break time between the trials. The methods were ordered differently for each subject in order to reduce the carry-over effect, and subjects were not notified of which method they were using. After finishing a trial, each subject filled out the questionnaire shown in Table 1. The set of the presence questions in the questionnaire was a modified version of that proposed in [22].

Each subject had a training session before the experimental session in order to learn how to use interfaces and to understand the task. In the training session, a subject made one trial of the task with each method. A virtual environment was used for the training. The virtual training environment was designed very close (i.e. with same types of walls and obstacles) to the real environment in order to make the subject waste less time in the navigation time in the actual experimental session. Figure 3 shows a view of the virtual environment used for training.

In the virtual environment, a virtual robot was represented as a cube (like the bounding box of the real robot), and had a top-center-positioned virtual camera with the resolution of 640 × 480 and the field of view of 45°, a front-facing virtual laser scanner, and a rear-facing sonar array including 8 individual virtual sonars. The virtual range sensors were positioned at the same place as those of the real robot, and simulated with a ray casting method. Given the position, direction, speed and turning rate of the robot at time t, as $\mathbf{P}(t) = [P_x(t)\ P_z(t)]^T$, $\mathbf{D}(t) = [D_x(t)\ D_z(t)]^T$, $v(t)$ and, $\omega(t)$ respectively, the motion of the robot was modeled as follows:

$$\mathbf{P}(t) = \mathbf{P}(t - \Delta t) + v(t - \Delta t)\mathbf{D}(t - \Delta t)\Delta t$$
$$\mathbf{D}(t) = \mathbf{R}(\omega(t - \Delta t)\Delta t)\mathbf{D}(t - \Delta t)$$
$$\mathbf{P}(0): \text{initial position}$$
$$\mathbf{D}(0): \text{initial direction}$$
$$\mathbf{R}(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}: \text{rotation matrix}$$

Δt denotes the time interval between the previous frame and the current frame.

Twelve subjects participated in the experiment. The ages of the subjects were between 23 and 37, and all of the subjects except two were male.

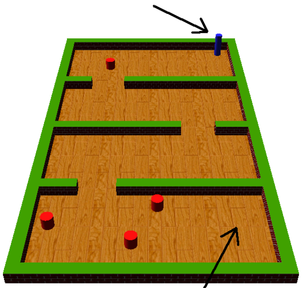


Fig. 3. The virtual environment used for training.

5. Experimental Results

5.1 Analysis on Navigational Performance

The following two dependent variables were measured.

- The number of collisions between the robot and the environment (total, while moving forward, while moving backward, and while turning)
- Navigation time from the start to the goal

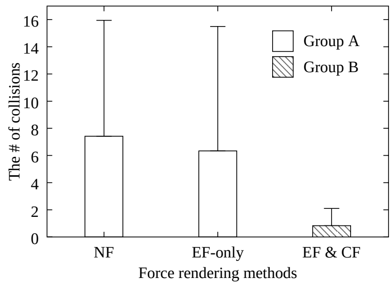
The results of the dependent variables are summarized in Figure 4 and Table 2. The within-subject ANOVA on the results revealed statistically significant differences among the methods on the total number of collisions ($F_{2,22}$ = 5.49, p < 0.015). However, there was no significant difference on the navigation time ($F_{2,22}$ = 0.02, p > 0.98).

For post hoc comparison, the SNK (Student-Newman-Keuls) grouping test was performed for the total number of collisions. Figure 4 shows the results of the test (α = 0.05). According to the test, NF and EF-only were not significantly different from each other, but EF & CF was significantly different from NF and EF-only. EF-only showed just a marginally greater reduction in the number of collisions than NF. It was because the subjects did not learn how to use EF-only sufficiently to make the robot avoid the collisions. We believe that EF-only should have shown a significantly greater reduction than NF provided that the subjects sufficiently understood how to use the EF-only or were trained more with EF-only. The collision-preventing force did not completely prevent the collisions. This was because the PHANToM generated forces that were too small to prevent user actions. Nevertheless, seven subjects were able to navigate the robot without any collision.

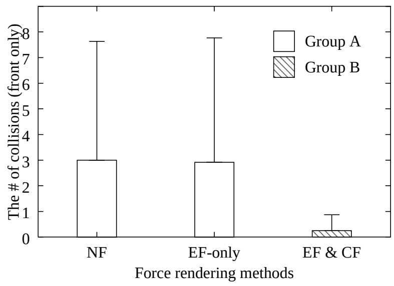
As for the number of collisions in each motion, the results were similar to those on the total number of collisions except while moving backward. According to our observation in the experiment, the subjects tended to make the robot move backward only rarely and did so at a low speed after securing a sufficient room (by making the robot move forward). This and the relatively small number of collisions while moving backward explain why there was no significant difference.

5.2 Analysis on Perceived Performance and Telepresence

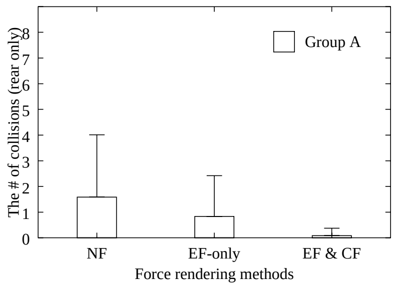
Two subjects answered ‘no’ for the 1st and 2nd questions of the questionnaire. For the rest of the ten subjects who answered ‘yes’, results for questions 3 through 6 are shown in Figure 5 and Table 3. For all of the questions, the within-subject ANOVA revealed that there were significant differences among the methods ($F_{2,18}$ > 4.10, p < 0.05). According to the SNK grouping tests, EF-only and EF & CF were significantly different from NF, but were not significantly different from



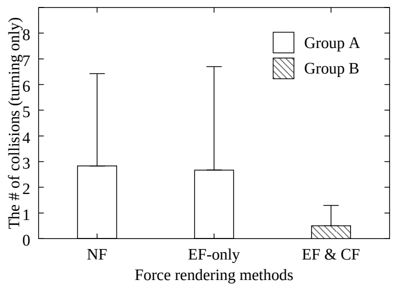
(a) The number of collisions (total).



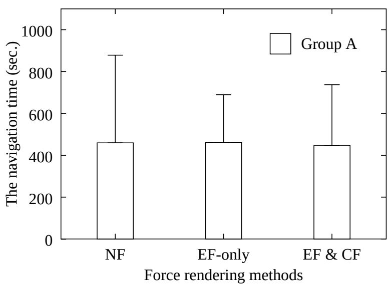
(b) The number of collisions (while moving forward).



(c) The number of collisions (while moving backward).



(d) The number of collisions (while turning).



(e) The navigation time.

Fig. 4. The results on the objective task performance.

Table 2. The mean and standard deviation of the results on the objective task performance, and their within-subject ANOVA results.

(a) The number of collisions (total):
$F_{2,22} = 5.49$, $p < 0.015$

NF	7.42 (8.53)
EF-only	6.33 (9.16)
EF & CF	0.83 (1.27)

(b) The number of collisions (while moving forward):
$F_{2,22} = 4.25$, $p < 0.03$

NF	7.42 (8.53)
EF-only	6.33 (9.16)
EF & CF	0.83 (1.27)

(c) The number of collisions (while moving backward):
$F_{2,22} = 2.47$, $p > 0.1$

NF	7.42 (8.53)
EF-only	6.33 (9.16)
EF & CF	0.83 (1.27)

(d) The number of collisions (while turning):
$F_{2,22} = 3.97$, $p < 0.04$

NF	7.42 (8.53)
EF-only	6.33 (9.16)
EF & CF	0.83 (1.27)

(e) The navigation time (sec.):
$F_{2,22} = 0.02$, $p > 0.98$

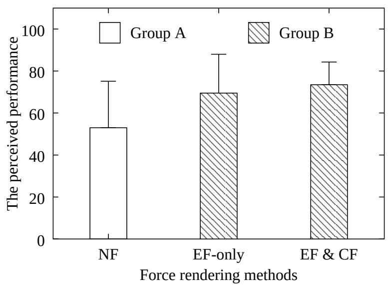
NF	7.42 (8.53)
EF-only	6.33 (9.16)
EF & CF	0.83 (1.27)

each other. This means that the subjects felt that the force feedback methods had been better than no force feedback method in terms of the task performance and presence. Particularly, it is an interesting fact that the subjects felt significantly more present with the force feedback methods than with no force feedback method, although the force feedback methods *indirectly*[1] gave the environmental information to the subjects. While there have been reports that direct or passive haptics improved the subjective presence [23, 24], this is one of the first results showing that the indirect haptics also enhanced presence.

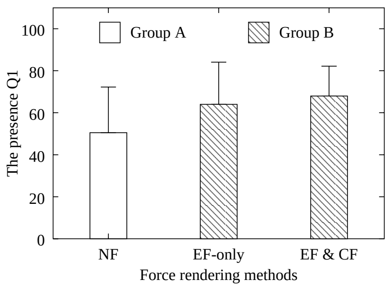
5.3 Correlation Analysis between Navigational Performance and Telepresence

Figure 6 shows the result of the Pearson correlation analysis among the number of collisions (OP), the

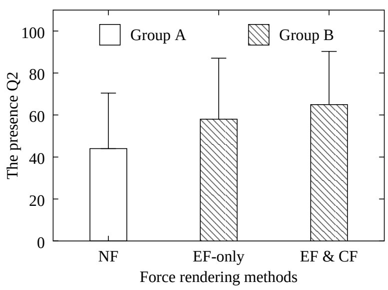
[1] "indirectly" means "without a touch with the environment or the geometric models reproduced from the environment."



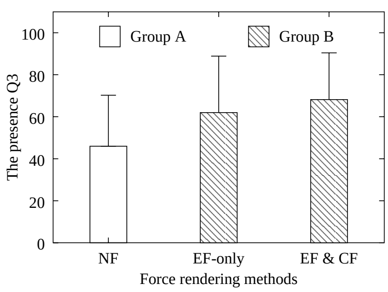
(a) The perceived performance.



(b) The presence question 1.



(c) The presence question 2.



(d) The presence question 3.

Fig. 5. The results of the questionnaire.

perceived performance (PP), and the presence scores (PQ1, PQ2, and PQ3). There were high correlations between OP and PP, and between PP and PQs. However, there was no correlation between OP and PQs. This is an interesting result because it is generally believed that whether high presence correlates to high user performance is task-dependent. However in this case, it was the difference in the haptic feedback that contributed more effectively on the user performance than on the user-felt presence. The provision of or different styles of haptic feedback is usually treated as a

Table 3. The mean and standard deviation of the results of the questionnaire, and their within-subject ANOVA results.

(a) The perceived performance: $F_{2,18} = 4.11$, $p < 0.035$

NF	53.0 (22.1)
EF-only	69.5 (18.5)
EF & CF	73.5 (10.8)

(b) The presence question 1: $F_{2,18} = 4.11$, $p < 0.035$

NF	50.5 (21.8)
EF-only	64.0 (20.1)
EF & CF	68.0 (14.2)

(c) The presence question 2: $F_{2,18} = 9.66$, $p < 0.01$

NF	44.0 (26.4)
EF-only	58.0 (29.1)
EF & CF	65.0 (25.3)

(d) The presence question 3: $F_{2,18} = 9.40$, $p < 0.01$

NF	46.0 (24.2)
EF-only	62.0 (26.9)
EF & CF	68.2 (22.2)

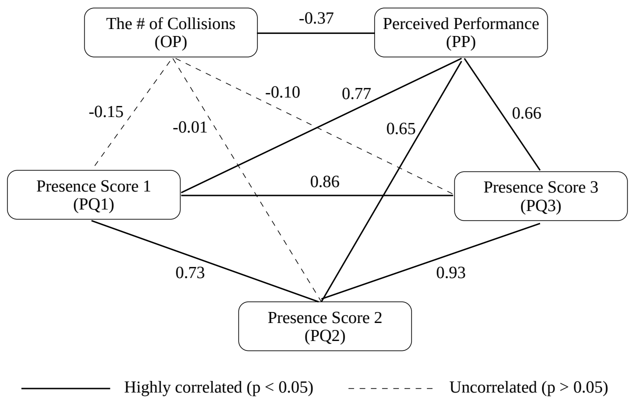


Fig. 6. The result of Pearson correlation analysis (N = 30) among the navigational performance (OP and PP) and the presence scores (PQ1, PQ2, and PQ3).

presence cue and not as a differential in the task itself. We project that the provision of indirect haptics only marginally (even though statistically significant) improved presence because it acted as a local spatial cue (i.e. indirect detection of the wall in front of the robot) with respect to the perception of the whole space. In fact, this result is consistent with that of Marsh and Shamus who reported no differences in spatial perception when collision detection and response was used or not in a virtual navigational task [25]. It was also observed that with indirect haptic feedback, the users were somewhat more concentrated on using it effectively to avoid the walls (even though they were all told to avoid colliding with the walls). Such mental concentration could have the user perceive less of the surrounding physical environment, and hence result in less user-felt presence (although only marginal in this case).

6. Conclusions

In this paper, the effectiveness of the haptic feedback proposed previously in [4] was verified through an experiment in a real test environment. It is stipulated that the provision of forces (in one way or another) seems to promote the user's sense of presence in the remote environment and helped the user navigate more safely with better cognition of the remote environment, especially with impoverished sensory feedback in other modalities (e.g. limited field of view, low resolution of camera image, and no sound). Contrary to our expectation, the task performance and user-felt presence were uncorrelated despite the task being spatial in nature due to its relatively marginal effect toward perception of the whole space, acting as a restricted local cue.

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