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Motion constraint design and implementation for a multi-functional virtual manipulation system

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A R T I C L E I N F O

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A B S T R A C T

Simulation systems nowadays are applied to various tasks, and thus demand a versatile manipulative system for the user to interact with the corresponding simulated environments. To make a single manipulative device applicable to more different kinds of tasks, the concept of virtual mechanisms has been previously proposed, in which virtual motion constraints are constructed via the software to constrain the manipulative device to move within a limited workspace that corresponds to task requirements. Motivated by the idea, in this paper, we propose a systematic approach to design and implement the virtual motion constraints for a multi-functional virtual manipulation system. The motion constraints are generated from sets of virtual walls to deal with the compliance task. And, a pixel-based method is proposed for smooth force rendering between the walls. In experiments, we apply the proposed virtual manipulation system to emulate an omni-directional wrench and a manual gearshift system, based on using a 2-DOF force-reflection joystick. We also evaluate the responses of the users during the manipulation of these two virtual mechanisms, which implicate the proposed system is able to capture the main features of various kinds of manipulative devices.

1. Introduction

Simulation systems have been applied to emulate practical systems, assist in mechanical design, and serve as the interface for teleoperation, among others [1–4]. With the development of virtual reality (VR) and dynamic modeling techniques, today's simulated environments are more realistic, and thus give the user a better feeling of immersion. And, via various communication channels, especially the bilateral manipulative devices, the user may interact with the simulation system in a more natural and efficient manner [4–8]. Due to the great variety of tasks that one may need to simulate, there is a strong demand to have a single manipulative device applicable for various tasks, which poses severe challenges.

In this paper, we intend to design a virtual manipulation system that can be applied to a wider range of simulation systems, but not for exact replication of the real manipulative devices. Because our focus is on the compliance task, which requires both position and force management, we concentrate on the haptic device. Among various kinds of haptic devices, the force-reflection joystick, which has merit in its simplicity and generality, is chosen for our proposed system [9,10]. Our design adopts the concept of virtual mechanisms and virtual fixtures previously proposed [3,11–13]. The basic idea is to generate virtual motion constraints via the software, so that the joystick is constrained to move within a limited workspace that corresponds to task requirements. In other words, the virtual constraints are designed to make the joystick behave similar to the manipulative device it emulates, e.g., a steering wheel, wrench, or gearshift lever. Consequently, the users may feel as though they are operating a manipulative device that is specifically designed for the given task, thus achieving fast and effective manipulation.

We propose a systematic approach to design and implement the virtual motion constraints to tackle various kinds of compliance tasks. First, sets of virtual walls are developed to serve as the building blocks. Motion constraints for complex tasks can then be constructed via proper assembly of these basic building blocks. As different motion constraints may be required in different stages of compliance task execution, the virtual walls may be made of different shapes, placed in different orientations, and with different levels of hardness and stickiness. Furthermore, their shapes, orientations, and physical properties may vary along with the execution of the task. For instance, in a screw-driving task, the screw is tightened to the fixture gradually, with an increasing effect on friction during the process. We also propose a pixel-based method to achieve smooth force rendering between the connected walls. To evaluate whether the proposed virtual manipulation system can capture the main features of various manipulative devices, at the expense of exact replication, we apply it to emulate an omni-directional wrench and a manual gearshift system based on using a

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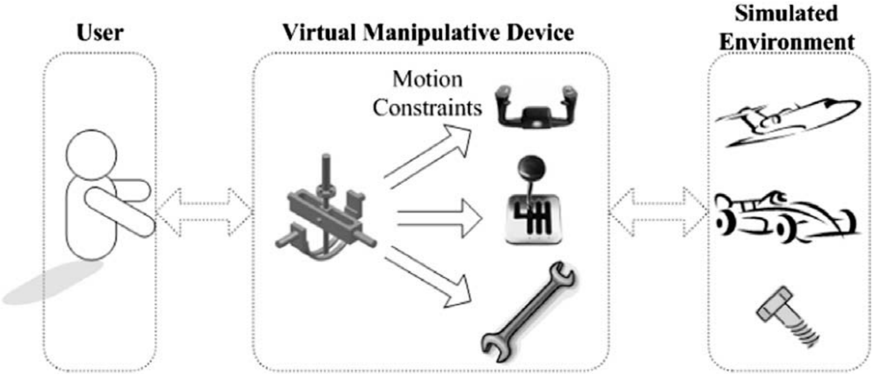


Fig. 1. Conceptual diagram of the proposed multi-functional virtual manipulation system.

2-DOF force-reflection joystick developed in our laboratory [14]. We then analyze the responses of the users during their manipulation. The rest of this paper is organized as: Section 2 describes the proposed virtual manipulation system and how to construct the virtual motion constraints. Experiments for the constructions of both the virtual omni-directional wrench and virtual manual gear-shift system are presented in Section 3. Section 4 provides the discussions on the evaluation of users' responses during the experiments. Finally, conclusions are given in Section 5.

2. Proposed virtual manipulation system

Fig. 1 shows the conceptual diagram of the proposed multi-functional virtual manipulation system. The proposed virtual manipulative device consists of mainly a force-reflection joystick and the motion constraints. With the joystick guided to move within the walls of the motion constraints, the user may gain better manipulability when executing the compliance task. During the manipulation, the user imposes a force on the joystick to move around the motion constraints. In turn, this virtual manipulative device generates the motion command and sends it into the simulated environment. Meanwhile, the force and position feedbacks incurred during the interaction between the virtual manipulative device and the simulated environment are sent back to the user via the joystick and the visual display. With both the reflected haptic feeling and visual feedback, the user can then determine his/her next move.

To let the proposed virtual manipulation system applicable for a wide variety of compliance tasks, the proposed approach must be able to create virtual motion constraints systematically. We list some major considerations in motion constraint design for compliance tasks below:

- For task formulation in the simulated environment, different shapes of motion constraints may be demanded and placed in different orientations. For instance, various virtual scenes may be present during the execution of a peg-in-hole task.
- Objects in various tasks may be made of different materials, and thus exhibit different physical properties.
- Along with the progress of the task execution, the shapes, orientations, and physical properties of the motion constraints may vary, e.g., the friction effect during the tightening of a screw into a fixture.

In responding to the requirements above, the virtual walls, as the building blocks for constructing the motion constraints, should provide varieties in their shape, orientation, and physical property. And, these attributes may be time-invariant or time-varying. The design of these various kinds of virtual walls will be described in Section 2.1. In Section 2.2, we will discuss the connection of walls of various shapes and how smooth manipulation can be achieved when the joystick moves between walls. The procedure on how to construct the virtual motion constraints that correspond to task requirements will also be described.

2.1. Virtual wall design

During the design, we should first make the virtual wall behave like a real one, which implicates a demand of a very high stiffness for the virtual wall itself and an abrupt stiffness change during contact with the wall [15,16]. In addition, digital implementation of the virtual wall may be affected by a fast-moving joystick and low system sampling rate, which would result in deferred force generation [15]. This phenomenon may invoke system instability and cause the human operator to feel unnatural. To provide an instant reflective force, it may demand a sampling rate of up to more than 1 kHz [17]. Another issue in the design is about the pushing force a human operator may impose on the joystick. According to [18], a human hand may generate a pushing force up to above 60 N. If the operator keeps pushing against the joystick with the maximum force, he/she may bend the joystick and make the virtual wall collapse. These requirements have to be well tackled in implementing a realistic virtual wall.

In response to the requirements, we first constructed a 2-DOF force-reflection joystick that achieves the required sampling rate. Meanwhile, we also suggest that the joystick should be constrained to move slowly within the walls to alleviate the risk of a severe collision. The strategy proposed is to pair the virtual walls for forming the virtual aisles, so that the limited space should confine the movement of the joystick. We also assume that the human operator is aware that the virtual motion constraint serves as the guidance and reminder during the manipulation, and is expected not to push hard on the wall intentionally.

Following the concept above, we start with the rectangular and circular aisles as examples, as shown in Fig. 2a. These aisles are designed to generate the reactive force responding to the push of the joystick during its manipulation within the aisle. As the joystick may touch the wall of the aisle in either a perpendicular or slanting direction, the reactive-force generation should depend on both its penetrating direction and depth inside the wall. Two common approaches for this are point-based and ray-based force rendering [19]. The former computes the force based on the stiffness provided by the joystick system and the distance between the collision point inside the wall and the nearest surface point (NSP); the latter uses the distance between the collision point and the surface point along the penetrating ray. We adopt the point-based approach because it yields more smooth force rendering. Force rendering for these two kinds of aisles can be easily extended to other shapes.

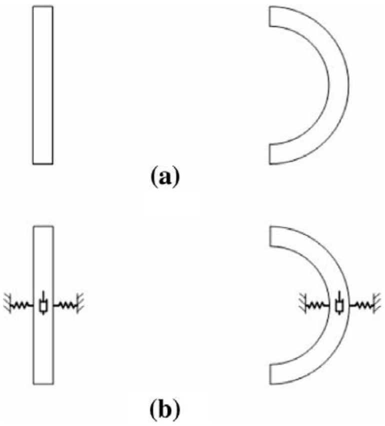


Fig. 2. Virtual aisle design: (a) rectangular and circular aisles and (b) physical property emulation.

Furthermore, to deal with various compliance tasks, physical properties in addition to the stiffness, represented by the spring in Fig. 2b, will also be emulated. For instance, the friction effect for tasks like the tightening of a screw can be realized by installing the damping within the aisle, represented by the damper in Fig. 2b. Damping can also be incorporated into the wall along with the stiffness to alleviate the possible oscillation due to hard hits. The reactive force generated during contact with the wall can thus be formulated as

$$f = K(x_{nsp} - x) - B\dot{x} \quad (1)$$

where K stands for the stiffness, B the damping, and x_{nsp} the NSP corresponding to the current joystick position x.

2.2. Motion constraint construction

In assembling the walls for motion constraint construction, we first deal with the connection between them and the subsequent force rendering. Fig. 3 shows several types of connections between walls of the same or different shapes (again with rectangular and circular types of walls as examples). To smooth out the sharp corners between walls, the spline functions or others may be introduced for wall connection. When the joystick cruises through the vicinity of the connected area, smooth reactive force rendering is much more complicated than that with one single wall. Because a more complex shape is formed, it may not be that straightforward to determine the direction of the reactive force [20]. One resolution for this is to keep tracking previous surface points, like the god-object and proxy algorithms previously proposed [21,22]. Motivated by this idea and to avoid describing connections of walls of various (even irregular) shapes with geometric equations case by case, we propose a pixel-based method for force rendering. In the proposed method, the interaction between the virtual joystick and motion constraints, the recording of the previous surface points, and the force rendering are all executed in the pixel space. Consequently, motion constraints can be easily constructed using the graphics editing software. Detection for contact between objects also becomes very straightforward. In the developed system, the resolution and updating rate for visual rendering are 0.4 mm between two neighboring pixels $(500 \times 500\ \text{pixels}/200 \times 200\ \text{mm}^2)$ and 30 Hz, respectively, and those for haptic rendering are 0.1 mm $(2000 \times 2000\ \text{pixels}/200 \times 200\ \text{mm}^2)$ for each count and above 1 kHz, both satisfying the demand from the operator.

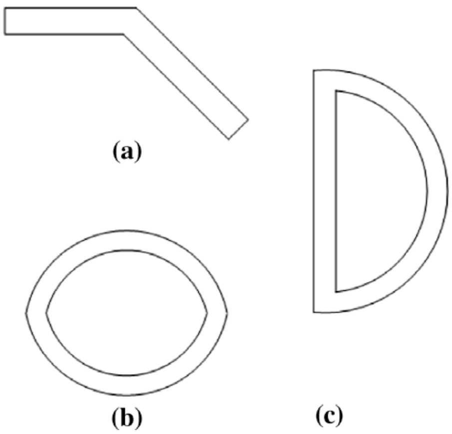


Fig. 3. Connection between walls: (a) line-to-line, (b) curve-to-curve, and (c) line-to-curve.

Fig. 4 shows an example of how the proposed method is applied for the case in Fig. 3a, a connection of two rectangular aisles. In Fig. 4, the joystick is moving across the connected area from location J_a to J_b. With the point-based approach, the corresponding NSP for J_a is first identified as C_a. Next, the proposed method will search through a series of circular regions of a small radius to locate the possible NSP for J_b. The process will continue until the desired NSP C_b is found. Details of the searching process for locating C_b are given in Algorithm 1. Due to the small distance between each step resulting from the high sampling rate, the computation load is not demanding. With these NSPs, smooth force rendering with a certain degree of continuity can be achieved. The user may thus experience a smooth maneuvering through the connected portion. In addition, this pixel-space implementation also has merit in direct quantization in the pixel space and extensibility to the 3D cases.

Algorithm 1. Locating NSP C_b by C_a and J_b

```
1: for $C_a$, find all $P_i \in \|P_i - C_a\| < \epsilon, i = 1, 2, \ldots, N$.
2: for $i = 1$ to $N$ do
3:     if $P_i$ is a wall pixel then
4:         go to 2:
5:     end if
6:     if $\|P_i - J_b\| < \|C_a - J_b\|$ then
7:         $C_a \Leftarrow P_i$
8:         go to 1:
9:     end if
10: end for
11: $C_b \Leftarrow C_a$
```

Procedure for motion constraint construction: Construct proper motion constraints corresponding to the requirements of a given compliance task.

Step 1: Perform analysis and specify the requirements for a given compliance task.

Step 2: According to the task requirements, select virtual walls of suitable shapes and physical properties.

Step 3: Assemble the walls into aisles and proceed with the necessary connections between aisles. Perform force rendering for smooth manipulation using the proposed pixel-based method, when the joystick cruises through the connection.

Step 4: Along with the progress of the task execution, update the virtual constraints via proper adjustment of the virtual walls and their physical properties.

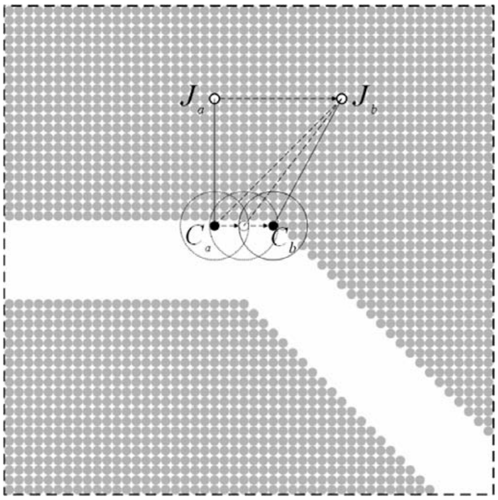
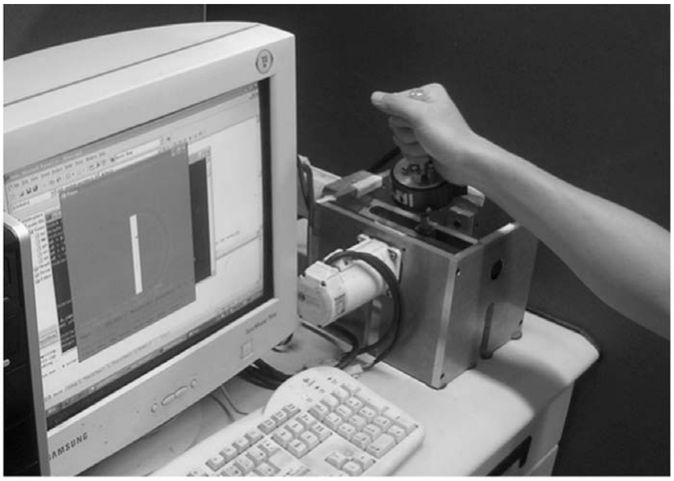


Fig. 4. Applying the proposed pixel-based method for force rendering for wall connection in Fig. 3a.

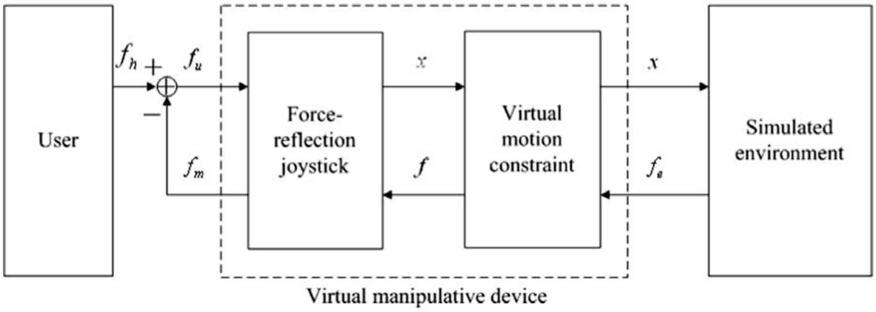
3. Experiments

During the experiments, we apply the developed multi-functional virtual manipulation system to emulate two kinds of manipulative devices, the omni-directional wrench and manual gearshift system. The purpose is to show that this manipulation system is able to capture the main features of several manipulative devices via a systematic approach, while at the expense of exact replication. The emulations of these two manipulative devices pose different requirements in implementation for involving both the circular and rectangular aisles and the physical properties in stiffness and damping.

Six male and two female graduate students from our institute, between 23 and 28 years old, were invited by our laboratory to perform the experiments. All of them had experience in manipulating the wrench and manual gearshift system. We developed a 2-DOF force-reflection joystick as the manipulative device, as shown in Fig. 5a. This joystick is basically modified from our previous one [14] by using a peripheral with a higher sampling rate, whose specifications are listed in Table 1. The AC servo motor is used as the actuator to move the joystick directly. The motor (type MSMA041A1E, Panasonic, Japan) weighs 1.6 kg with a maximum speed of 4500 rpm and maximum output torque of 3.8 Nm. An encoder is installed within the motor to achieve closed-loop servo control with a resolution of 10,000 pulses per revolution. The encoder is used to measure the position of the joystick. The resolution of the encoder and the quality of the actuator's servo control together determine the resolution of the joystick. For force control, the motor driver is set at torque control mode. And, system identification has been performed via the frequency-response analysis. Fig. 5b shows the system block diagram when the user operates the joystick, as a virtual manipulative device, to interact with the environment. In Fig. 5b, the user sends in the commanded force f_h and receives the reflection force f_m from the joystick. f_h and f_m, combined to be f_u, are sent to the joystick, which in turn generates the command x. Via the virtual motion constraint, x is forwarded to



(a)



(b)

Fig. 5. (a) System view of the 2-DOF force-reflection joystick system developed in our laboratory. (b) System block diagram with the operator interacting with the simulated environment using the force-reflection joystick.

Table 1
Specifications of the developed 2-DOF force-reflection joystick.

Item	Specification
X axis	70–80 deg
Y axis	80–90 deg
Stick length	22 cm
Maximum output force	32.5 N
Precision	0.1 mm/count (28 counts/deg)
Interface	PCI
Sampling rate	Above 1 kHz
Bandwidth	100 Hz

the simulated environment, which responds with an interactive force f_e. This f_e becomes f and then f_m through the virtual manipulative device.

3.1. Virtual omni-directional wrench

We first apply the proposed manipulation system to construct a virtual omni-directional wrench. Fig. 6 shows how to construct the motion constraints for the virtual omni-directional wrench based on manipulating a real wrench for a screw-tightening task. In Fig. 6a, the user turns the wrench every one-half circle clockwise to tighten the screw, and then moves it back to the original location via a linear path. In response to these two motions, one semi-circular and one rectangular virtual aisle are generated, as shown in Fig. 6b. Both of them are equipped with the springs on the two sides of the aisle to provide the resistive force, but only the semi-circular one is equipped with the damper inside of it to emulate the tightening effect. Note that the vertical movement of the screw during wrench turning is neglected due to its smallness. To make the virtual wrench approximate the real one more closely, we actually manipulated the real wrench to tighten a screw. Fig. 7 shows the force response measured by the JR3 force sensor (UFS-3012A-25, NITTA, Japan) mounted on the real wrench shown in Fig. 6a. The measured forces, ranging between 0 and 16 N, increased gradually along with the turning of the wrench, as indicated by the four peaks in Fig. 7. Based on the observation, the damping coefficient B_w, used for exhibiting the increasing friction effect, is thus formulated to be proportional to the screw turning angle α:

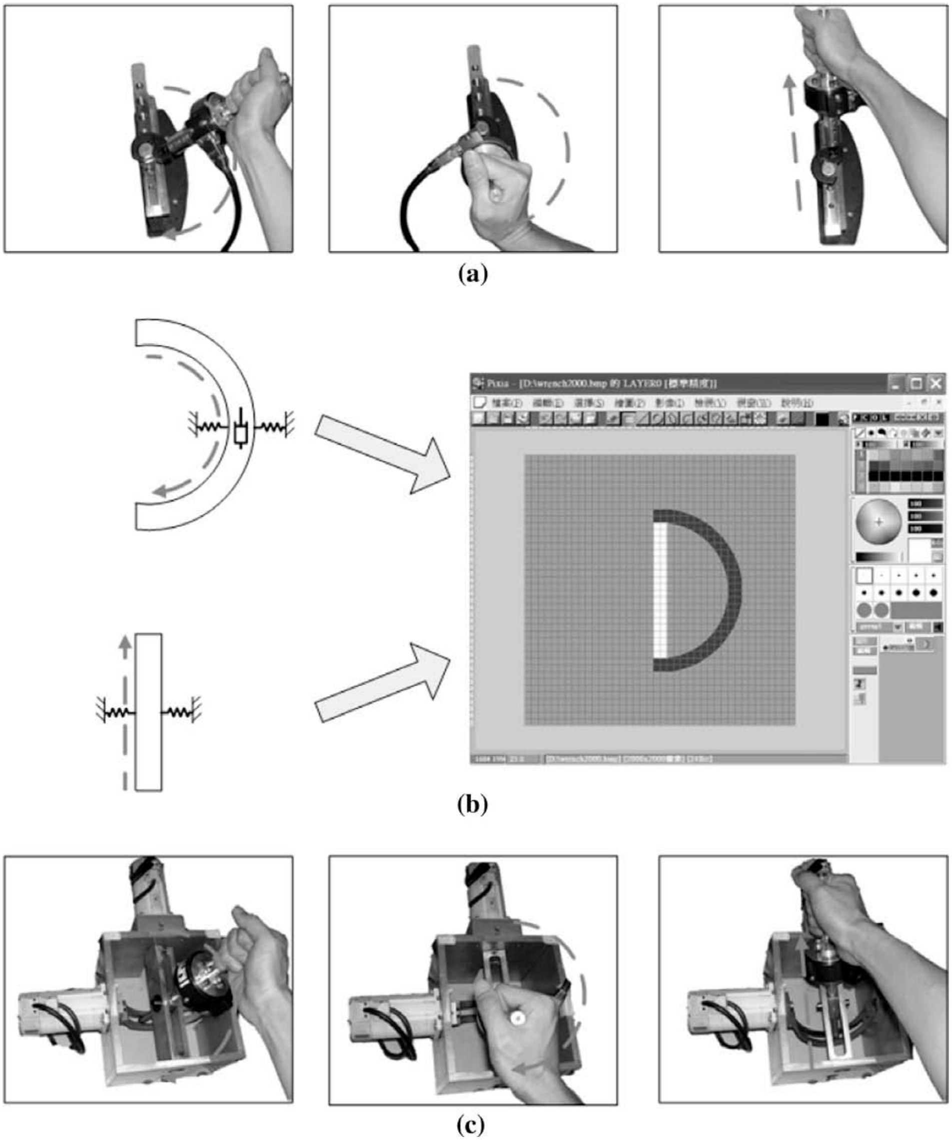


Fig. 6. Motion constraint construction for the virtual omni-directional wrench: (a) manipulation of the real omni-directional wrench, (b) virtual motion constraint generation, and (c) manipulation of the virtual omni-directional wrench.

$$B_w = \begin{cases} c\alpha & if\,\alpha \geqslant 0 \\ 0 & if\,\alpha < 0 \end{cases} \tag{2}$$

where c is a ratio. This process can be viewed as that for friction model identification. With these motion constraints, the joystick, confined to move within the aisles, behaves like a wrench, as shown in Fig. 6c.

The virtual wrench was applied to execute the screw-tightening task in Fig. 6. During the first experiment, the user turned the wrench clockwise four times in tightening the screw. To maintain a constant speed in turning, a guiding ball (designed to be small for less distraction) was presented to visually lead the user to pass through the semi-circular and rectangular aisles in 6 s. This slow, constant movement is intended for the purpose of better observation and performance comparison. And, the ratio c for damping was set to be 5 N s/m rad. The JR3 force sensor was mounted on the handle of the joystick to measure the force reflected on the operator's hand. The resultant torque can be derived by taking the stick as the lever, with an effective length of 15 cm, as listed in Table 1. Fig. 8a shows the screw-tightening process, in which the wrench went through four turns of tightening, Fig. 8b the trajectory of the wrench (in angle), and Fig. 8c the measured force re-

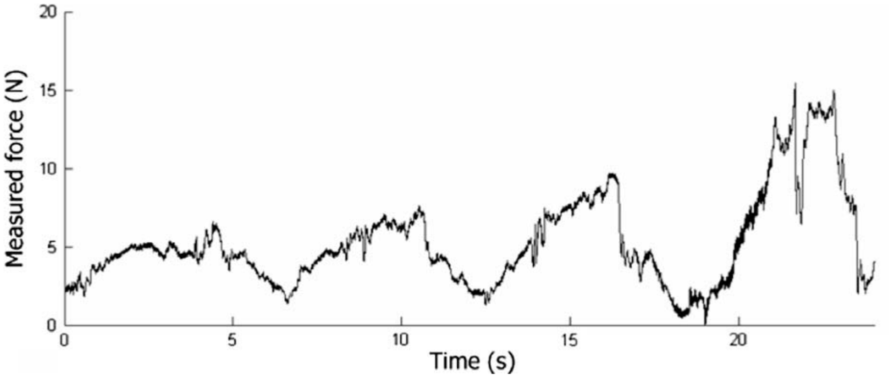
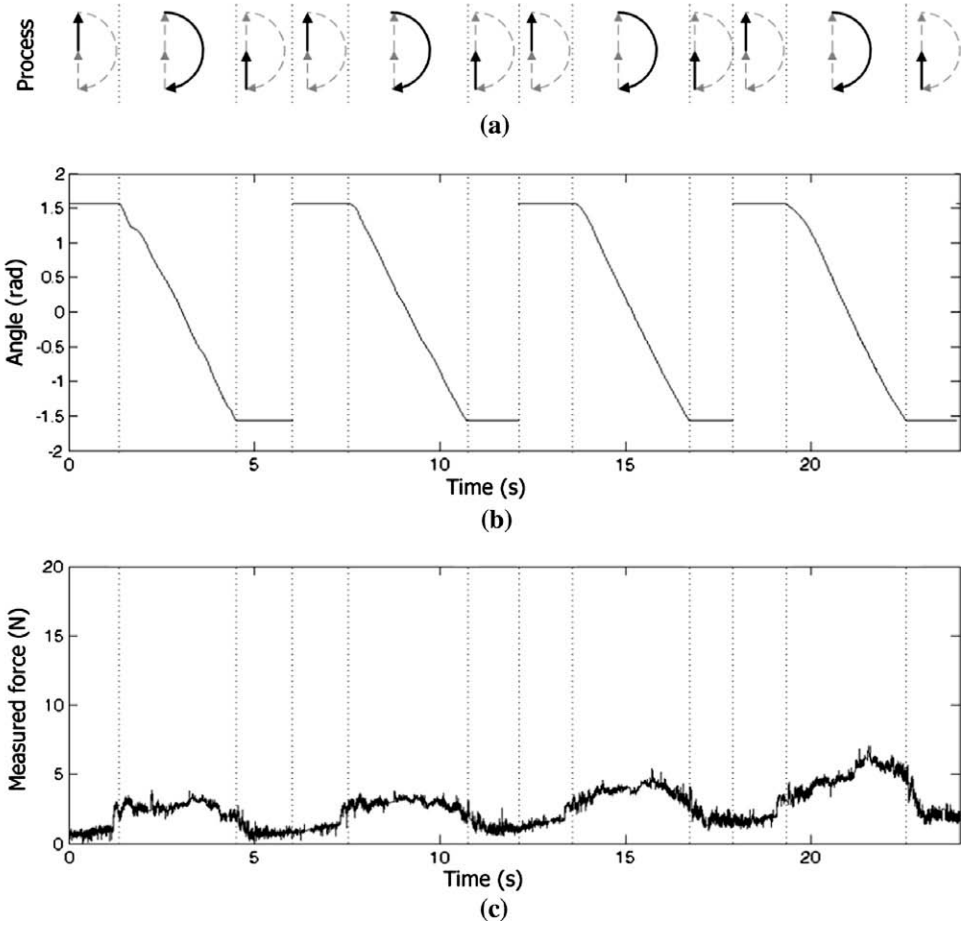


Fig. 7. Measured force response for screw tightening using a real wrench.



(a)

(b)

(c)

Fig. 8. Experimental results for applying the virtual omni-directional wrench for screw tightening (c = 5 N s/m rad): (a) the screw-tightening process, (b) the trajectory of the wrench (in angle), and (c) the measured force response.

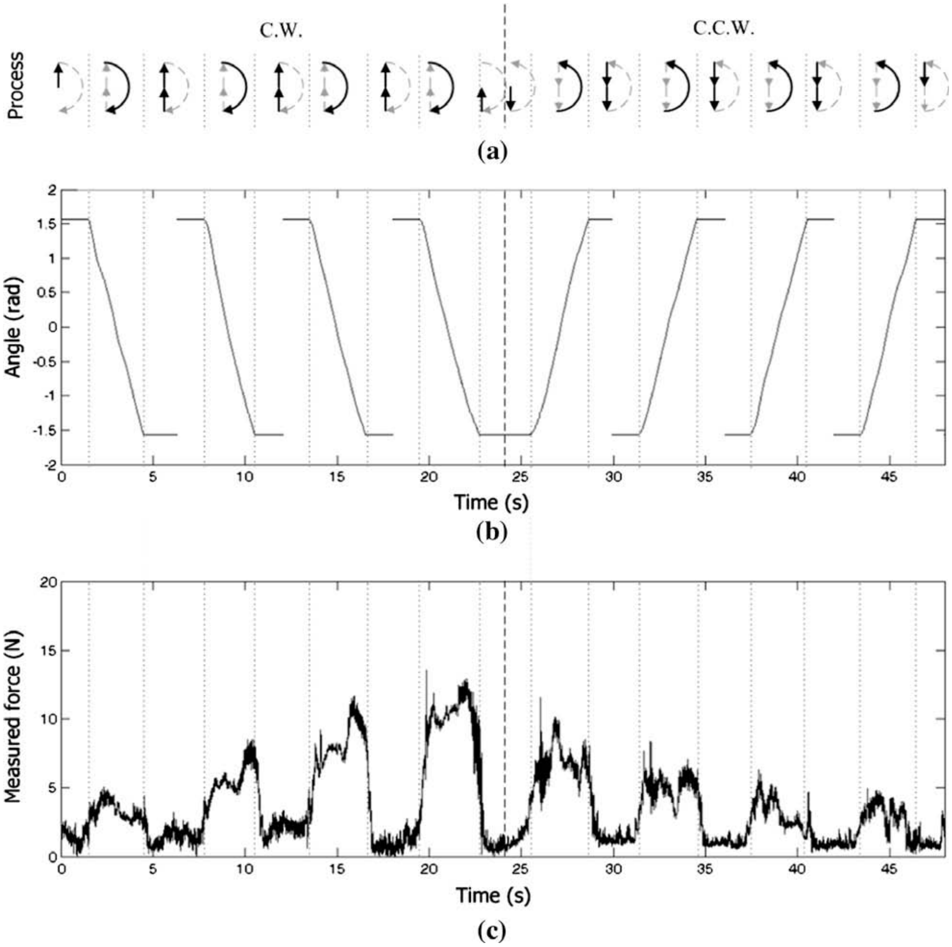


Fig. 9. Experimental results for applying the virtual omni-directional wrench for both screw tightening and loosening (c = 15 N s/m rad): (a) the screw-tightening (clockwise) and loosening (counterclockwise) processes, (b) the trajectory of the wrench (in angle), and (c) the measured force response.

sponse, which increased gradually along with a steady turning wrench. In the second experiment, the user first tightened the screw and then loosened it by turning the wrench clockwise four times, followed by four counterclockwise turns. We also increased the ratio c up to 15 N s/m rad to check on the effect of the damping. Fig. 9a shows both the tightening and loosening processes, Fig. 9b the trajectory of the wrench, and Fig. 9c the measured force response, which increased gradually during the tightening process, and decreased gradually during that of loosening. Compared with that in Fig. 8c, a more evident force variation was observed during the process.

3.2. Virtual manual gearshift system

As another demonstration, we applied the proposed system to construct a virtual manual gearshift system, and let the 2-DOF force-reflection joystick emulate a gearshift lever. Fig. 10a shows the developed virtual manual 5-speed gearshift system, which consists of one horizontal and three vertical aisles. The five speed gear positions and that for the reverse gear are located at the two ends (semi-circular walls) of the three vertical aisles, marked by 1–5 and R, respectively. Our design also includes a locking function when the joystick rests in the six gear positions, and an automatic return to the neutral position, located at the center of the horizontal aisle, when the joystick is away from the gear positions. Fig. 10b shows one demonstrated position trajectory of the virtual gearshift lever, in which the lever started from the neutral position, moved to the five speed gear positions and the reverse gear position, and finally returned to the neutral position. Fig. 10c shows the corresponding position responses along the X and Y axes, respectively, and Fig. 10d the measured force response, which reflected how the joystick hit the wall during the movement (a larger force indicated a harder hit to the wall). During the manipulation, the lever was confined to move within the aisles via the guidance provided by the virtual constraints.

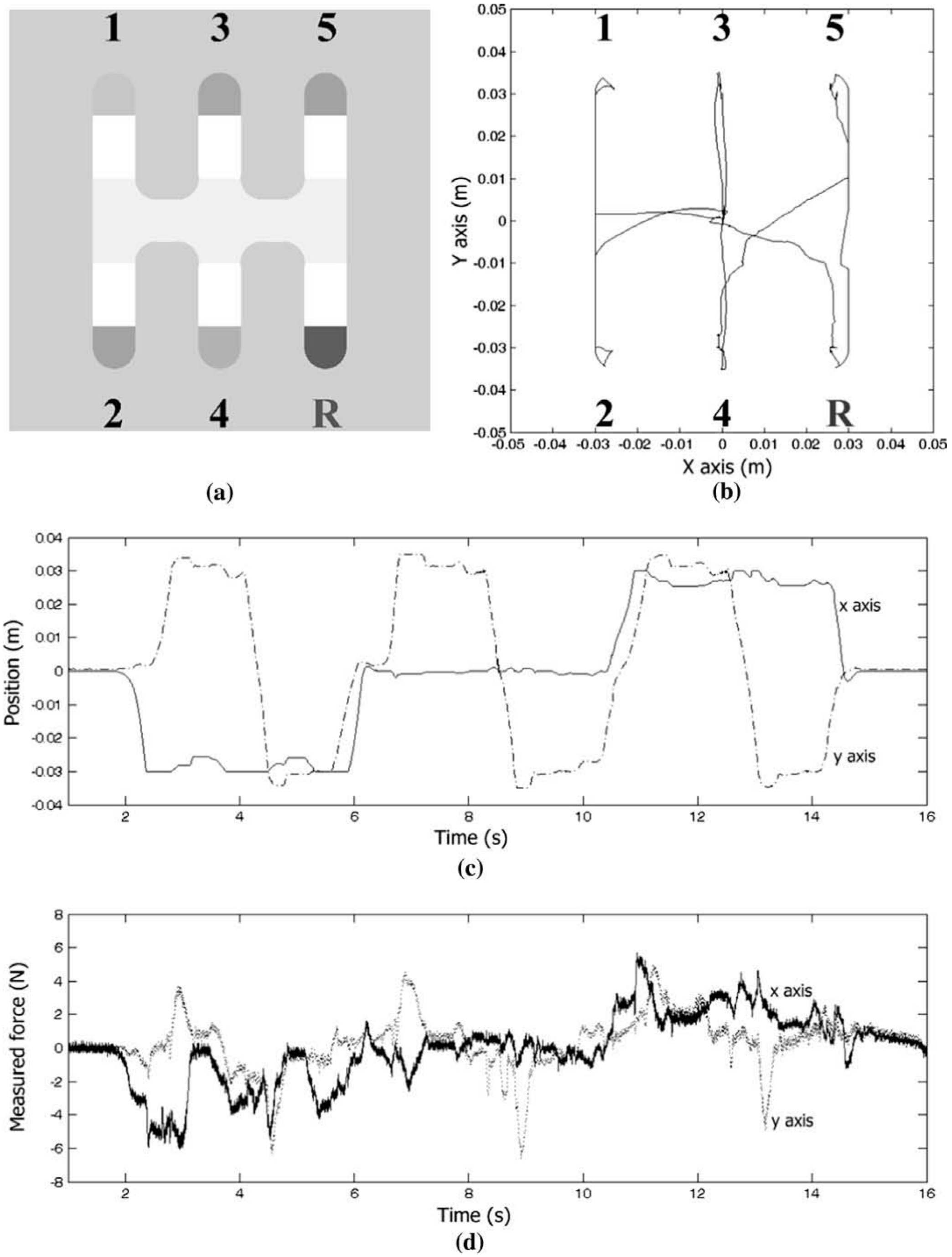
4. User response evaluation

To evaluate the responses of the eight users, they were asked to score the degree (from 1 (lowest) to 5 (highest)) with which he/she agrees with some statements related to the manipulation during the experiments.

For the omni-directional wrench emulation, the statements are

- I experience a realistic feeling as that of manipulating a real omni-directional wrench (Resemblance).
- I feel that the virtual constraints do provide the guidance (Guidance).
- I experience a realistic feeling of a screw-tightening process (Tightening effect).

  For the manual gearshift system emulation, we asked the first two statements above, along with a third statement:
- I feel the visual information from the virtual environment is helpful during the manipulation (Visual effect).



(a) (b)

(c)

(d)

Fig. 10. Experimental results for the emulation of a virtual manual 5-speed gearshift system: (a) the virtual manual 5-speed gearshift system, (b) the position trajectory of the virtual gearshift lever, (c) the position responses along the *X* and *Y* axes, and (d) the measured force response.

Fig. 11a shows the scores for the omni-directional wrench, represented in box plots, and Fig. 11b those for the manual gearshift system. In Fig. 11a, the box plot shows the maximum at 5, minimum 3, average 3.8, and median 4 for the resemblance statement, and higher scores for the guidance statement (average at 4.6 and median 5) and tightening effect statement (average and median both at 4.5). In Fig. 11b, it shows the maximum at 4, minimum 3, and both average and median at 3.5 for the resemblance statement, and also higher scores for the guidance statement (average and median both at 4.5) and visual effect statement (average at 4.6 and median 5). From the scores, almost all the users felt that the virtual constraints did provide them the guidance during the manipulation for both emulations. Most users experienced a realistic feeling of a screw-tightening process, and considered the visual information was helpful for the gearshift system emulation. Meanwhile, several users considered the proposed manipulation system did exhibit certain degree of resemblance between the virtual and real manipulative devices in both emulations, although some differences were noticed. Judging from the evaluation results, we considered that the proposed manipulation system did capture the main features of these two manipulative devices, and yielded the realistic feeling to a certain extent.

The users also gave several comments that deserved attention. For both emulations, many of them mentioned that the spring

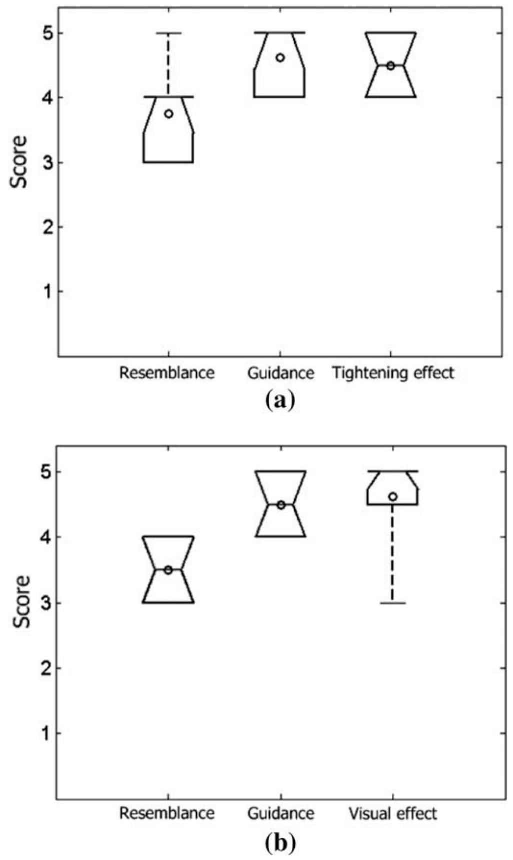


Fig. 11. Evaluation of the users' responses: (a) the omni-directional wrench and (b) the manual gearshift system.

effect appeared to be more impressive, when compared with that of the damping, which was not very realistic. Suggestions for improvement include the handle of the joystick should be modified to be more like that of the real gearshift lever, and the visual presentation of the interacting wrench and screw be provided. For the gearshift system emulation, the design of the attractive force for locking the lever into the gear position was appreciated.

5. Conclusion

In this paper, we have proposed a systematic approach to design and implement the virtual motion constraints for a multi-functional virtual manipulation system based on a 2-DOF force-reflection joystick. Virtual walls of various shapes and physical properties are employed for motion constraint construction. And, a pixel-based method for force rendering is proposed to achieve smooth manipulation between walls, which well tackles walls of various shapes. The proposed system has been applied to emulate an omni-directional wrench and a manual gearshift system. And, the responses of the users during the manipulation have been analyzed. Although the proposed system is designed to be versatile, but not for exactly replication of the real mechanism, both emulations exhibit certain degree of resemblance and reality. For its extension to 3D applications, the virtual walls will need to be assembled in the 3D space. It thus induces higher complexity for motion constraint construction. Meanwhile, the proposed pixel-based method is ready for 3D force rendering as its implementation is in the pixel space and can be easily extended to 3D cases. In future works, we will apply the proposed system for various kinds of compliance tasks, tasks with multiple users, and tasks with 3D motion constraints.

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References

[1] Frisoli A, Avizzano CA, Bergamasco M. Simulation of a manual gearshift with a 2 DOF force-feedback joystick. In: IEEE international conference on robotics and automation; 2001. p. 1364–9.
[2] Gasparetto A, Vidoni R, Zanotto V. Dforce: delayed force reference control for master–slave robotic systems. Mechatronics 2009;19(5):639–46.
[3] Joly L, Andriot C. Imposing motion constraints to a force reflecting telerobot through real-time simulation of virtual mechanisms. In: IEEE international conference on robotics and automation; 1995. p. 357–62.
[4] Nahvi A, Nelson DD, Hollerbach JM, Johnson DE. Haptic manipulation of virtual mechanisms from mechanical CAD designs. In: IEEE international conference on robotics and automation; 1998. p. 375–80.
[5] Chu C-CP, Dani TH, Gadh R. Multimodal interface for a virtual reality based computer aided designed system. In: IEEE international conference on robotics and automation; 1997. p. 1329–34.
[6] Clover CL, Luecke GR, Troy JJ, McNeely WA. Dynamic simulation of virtual mechanisms with haptic feedback using industrial robotics equipment. In: IEEE international conference on robotics and automation; 1997. p. 724–30.
[7] Kuan CP, Young KY. VR-based teleoperation for robot compliance control. J Intell Robot Syst 2001;30(4):377–98.
[8] Ohtsuka H, Shibasato K, Kawaji S. Experimental study of collaborator in human–machine system. Mechatronics 2009;19(4):450–6.
[9] Burdea G. Force and touch feedback for virtual reality. New York: John Wiley & Sons; 1996.
[10] Ouh-young M, Tsai W-N, Tsai M-C, Wu J-R, Huang C-H, Yang T-J. Low-cost force feedback joystick and its use in PC video games. IEEE Trans Consum Elect 1995;41(3):787–94.
[11] Peshkin MA, Colgate JE, Wannasuphoprasit W, Moore CA, Gillespie RB, Akella P. Cobot architecture. IEEE Trans Robot Autom 2001;17(4):377–90.
[12] Prada R, Payandeh S. A study on design and analysis of virtual fixtures for cutting in training environments. In: IEEE joint Eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems; 2005. p. 375–80.
[13] Rosenberg LB. Virtual fixtures: perceptual tools for telerobotic manipulation. In: IEEE virtual reality annual international symposium; 1993. p. 76–82.
[14] Lin WC, Young KY. Design of force-reflection joystick system for VR-based simulation. J Inform Sci Eng 2007;23(5):1421–36.
[15] Colgate JE, Grafing PE, Stanley MC, Schenkel G. Implementation of stiff virtual walls in force-reflecting interfaces. In: IEEE virtual reality annual international symposium; 1993. p. 202–8.
[16] Minsky M, Ouh-young M, Steele O, Brooks Jr FP, Behensky M. Feeling and seeing: issues in force display. Comput Graph 1990;24(2):235–43.
[17] Adachi Y, Kumano T, Ogino K. Intermediate representation for stiff virtual objects. In: IEEE virtual reality annual international symposium; 1995. p. 203–11.
[18] Tilley AR. The measure of man and woman — human factors in design. New York: John Wiley & Sons; 2002.
[19] Srinivasan MA, Basdogan C. Haptics in virtual environments: taxonomy, research status, and challenges. Comput Graph 1997;21(4):393–404.
[20] Salisbury K, Conti F, Barbagli F. Haptic rendering: introductory concepts. IEEE Comput Graph Appl 2004;24(2):24–32.
[21] Ruspini DC, Kolarov K, Khatib O. The haptic display of complex graphical environments. In: ACM international conference on computer graphics and interactive techniques; 1997. p. 345–52.
[22] Zilles CB, Salisbury JK. A constraint-based god-object method for haptic display. In: IEEE international conference on intelligent robots and systems; 1995. p. 146–51.