

ISSN 1349-4198

IJICIC

Volume 3, Number 3, June 2007

***International Journal of Innovative
Computing, Information & Control***

Sponsored by National Kaohsiung University of Applied Sciences

Published by ICIC International
<http://www.ijicic.org>

A NOVEL FORCE FEEDBACK-BASED TELEOPERATION SYSTEM FOR MEDICAL APPLICATION

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Received July 2006; revised October 2006

ABSTRACT. *We propose a novel force feedback-based teleoperation system for medical application. Most teleoperation systems are based on the visual feedback from the camera with the occasional use of force feedback. We present the concept and principle of a virtual force feedback in a teleoperation system. The circle tracking experiment was considered using the proposed virtual force feedback. The experimental results showed that the relative tracking error decreased by more than 50% when using the virtual force feedback. We also performed another experiment studying the cutting of a piece of bean curd using the real force feedback. Using real force feedback resulted in a 0.4 N decrease in the contact force of the knife and the object. After further experimentation, the system will be suitable for telesurgical training.*

Keywords: Medical application, Visual feedback, Virtual force feedback, Real force feedback, Telesurgical training

1. Introduction. Robotics has been widely used in many industrial fields. In recent years, it has also been applied in the biomedical field, in which robotic operations have been used for stroke rehabilitation, neurological surgical operation, and a variety of other exciting applications. Of particular relevance to this work are the virtual reality-based surgery simulation systems [1,2]. Given the complexity of realistic environments, full autonomy in robotics has yet to be achieved; hence, semiautonomous robotics systems have been established as a major research line (IEEE Robotics & Automation, 1999). The teleoperation robotic system is a kind of semiautonomous system that has been applied in telerehabilitation [3-5] and telesurgical operations [6-10] in addition to other evolving technologies.

Until now, some surgical operation systems are commercially available. For example, both the ZEUS surgical robotic system from Computer Motion (Goleta, CA) [11,12] and the da Vinci surgical system from Intuitive Surgical, Inc. (Mountain View, CA) [13-17] have been used in cardiac surgery to perform coronary artery bypass grafting and mitral valve repair. Despite these successes, many surgeons claim that further progress in this field is limited by an unresolved problem: the lack of haptic (force and tactile) feedback to the user [18].

Incorporating force feedback into teleoperated systems can reduce the magnitude of contact forces, leading to a reduction in the energy consumption, the task completion time,

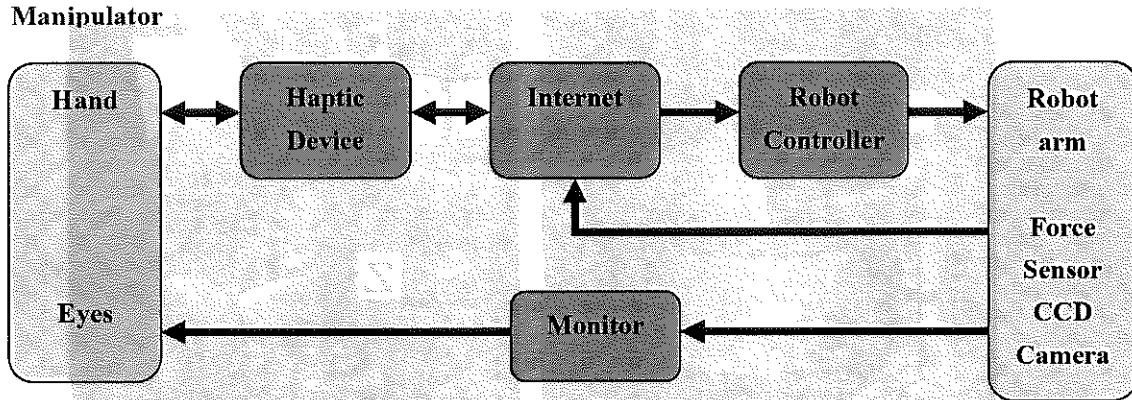


FIGURE 1. Information flow of the system

TABLE 1. Parameters of the haptic device

Force feedback workspace	160 mm × 120 mm × 70 mm
Maximum exertable force at nominal (orthogonal arms) position	3.3 N
Stiffness	x -axis > 1.26 N/mm y -axis > 2.31 N/mm z -axis > 1.02 N/mm
Inertia (apparent mass at tip)	45 g
Force feedback	x, y, z
Position sensing	x, y, z ($\pm 5\%$ linearity potentiometers)

6-DOF force sensor (MINI 4/20) is also equipped on the robot's arm to measure the force and torque on the robot's arm in the x -, y -, and z -directions. The profile of the 6-DOF force sensor is shown in Figure 4, and the parameters of the force sensor are shown in Table 2. Additionally, the force components, F_x , F_y and F_z , and the torque components, T_x , T_y and T_z can be calculated using $\mathbf{F} = \mathbf{C}\mathbf{V}$, where \mathbf{C} is the constant matrix of the force. \mathbf{F} is defined in terms of the force and torque components as (1).

$$\mathbf{F} = | F_x \ F_y \ F_z \ T_x \ T_y \ T_z | \tag{1}$$

and

$$\mathbf{V} = | SG.0 \ SG.1 \ SG.2 \ SG.3 \ SG.4 \ SG.5 | \tag{2}$$

where \mathbf{V} is the digital vector sampled with the A/D board of the computer every millisecond.

3. Evaluation Experiments. To establish the advantage of the virtual force feedback and the real force feedback in teleoperating systems, we performed two different experiments. One was the circle tracking experiment, and the other was the bean curd cutting experiment.

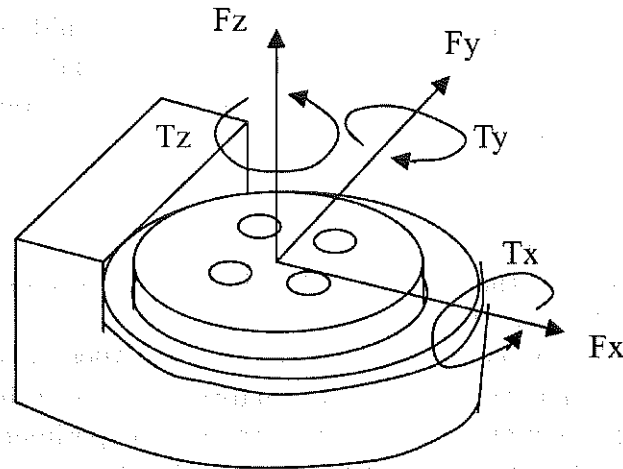


FIGURE 4. Profile of the force sensor

3.1. Circle tracking experiment. In the circle tracking experiment, we designed a virtual environment that comprised a virtual 3-D board in the vertical plane with three circles drawn on the virtual board. Additionally, a virtual 3-D ball was present in the virtual environment and its position represented the haptic device's stylus position in space (see Figure 5). When the virtual ball reached the surface of the virtual board, a force vertical to the monitor would act on the subject's hand through the haptic device's stylus. Furthermore, performing the circle tracking experiment was analogous to a subject tracking a real circle on a real board.

For the slave system, a ballpoint pen was fixed to the bottom of the 6-DOF robot arm, and a piece of paper was fastened to the surface of the experimental desk as in Figure 6. When the subject tracked the circle in the vertical plane of the virtual environment, the robot arm drew a circle with the same radius on the paper in the horizontal plane.

The experiment was performed with and without the virtual force feedback. In the tracking experiment, the ideal result was that the manipulator's hand can track the existing circle completely. In fact, there must be some errors between the existing circle and the trajectory of manipulator's hand. So, we proposed a virtual spring force model to get a compensation force for manipulator's tracking error. If the manipulator's hand deviated from the existed circle more, the compensation force would get bigger. In our way, the tracking error was expected to decrease. In this opinion, we can say that the virtual spring force model is ideal for the system. Figure 7 shows the principle of the virtual force. The virtual force was calculated using (3).

$$F = k * |AB| = k * (|AO| - R) \quad (3)$$

where k is the virtual spring constant and R is the radius of the tracked virtual circle. The value of $|AO|$ was defined by (4).

$$|AO| = \sqrt{(x_a - x_o)^2 + (y_a - y_o)^2} \quad (4)$$

where (x_a, y_a) were the coordinates of point A, and (x_o, y_o) were the coordinates of point O in Figure 7.

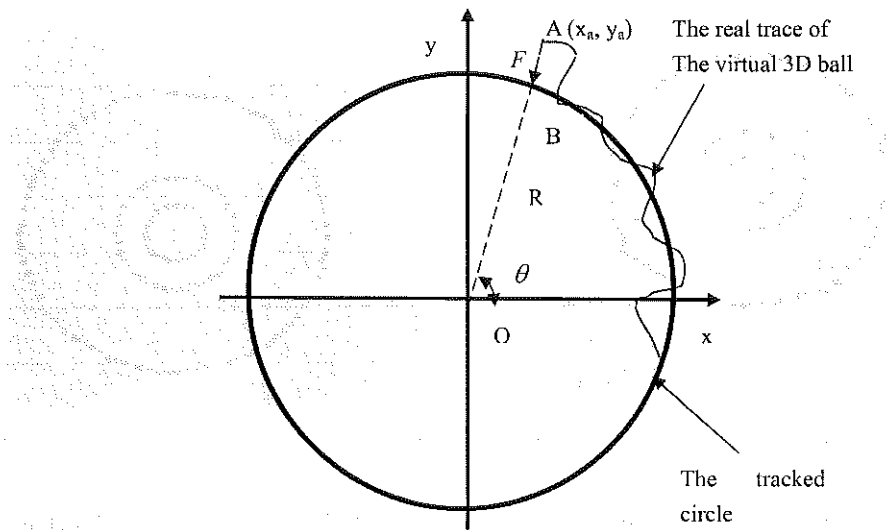


FIGURE 7. The principle of the virtual force

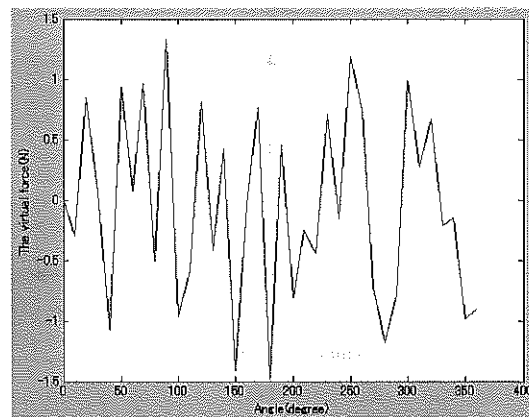


FIGURE 8. The typical virtual force feedback in the tracking experiment for subject A

Figure 9 shows the circle drawn by the robot arm when subject A performed the circle tracking experiment. The figure clearly illustrates that with virtual force feedback, the tracking performance improved significantly over no virtual force feedback. The tracking error is defined as in Figure 10. The absolute tracking error is defined by $E = R_{max} - R_{min}$, where R_{max} and R_{min} are, respectively, the radii of the circumcircle and inscribed circle produced by the 3-D virtual ball's trace in the virtual environment. The relative tracking error $\alpha = E/R$, where E is the absolute tracking error and R is the radius of the tracked virtual circle. Figures 11 and 12 show that the relative tracking error of the circle tracking experiment for subjects A, B, and C decreased to less than 50% with the virtual force feedback. For every subject, the relative error of the tracking experiment decreased with an increase of the circle's radius.

3.2. The bean curd cutting experiment. The second experiment required cutting through a bean curd using teleoperation. In the bean curd, two plastic vessels were

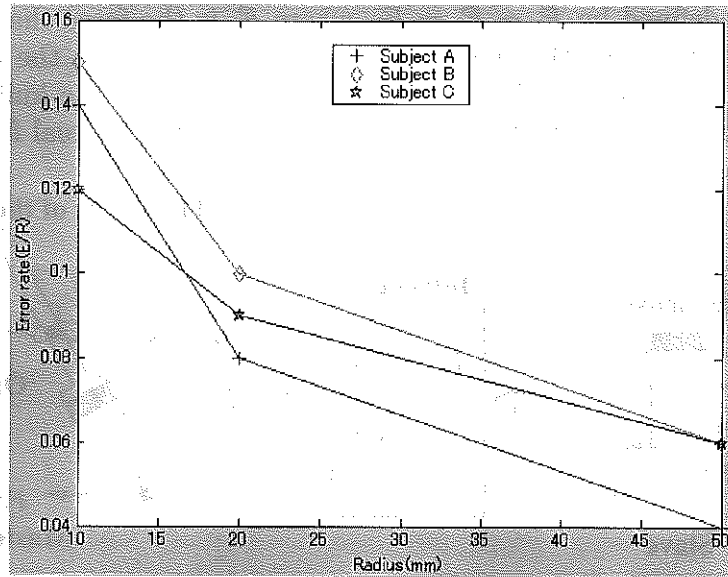


FIGURE 11. The maximum relative error without virtual force feedback

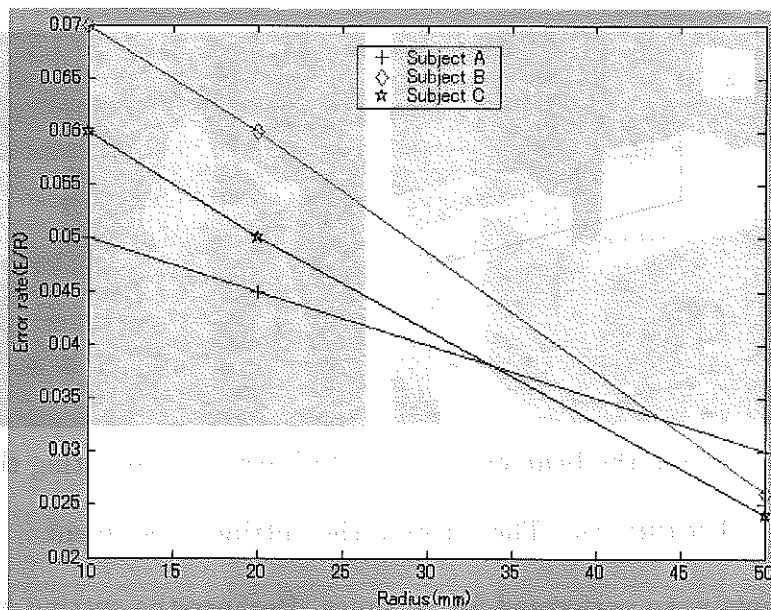


FIGURE 12. The maximum relative error with virtual force feedback

The other occasion was when both the real-time 2-D visual feedback of the CCD camera and the real-time force feedback on the stylus were applied. Figure 13 shows the principle of the force transmission. When the knife contacted the plastic vessel in the bean curd, a force would act on the knife that could be measured with the force sensor on the robot arm. Through the network connection, an equal force on the haptic device was exerted so that the subject could feel the force caused by the knife contacting the plastic vessel. The real-time force feedback and the real-time visual feedback were expected to cause a decrease in the contact force on the robot arm. The relationship of the forces is shown

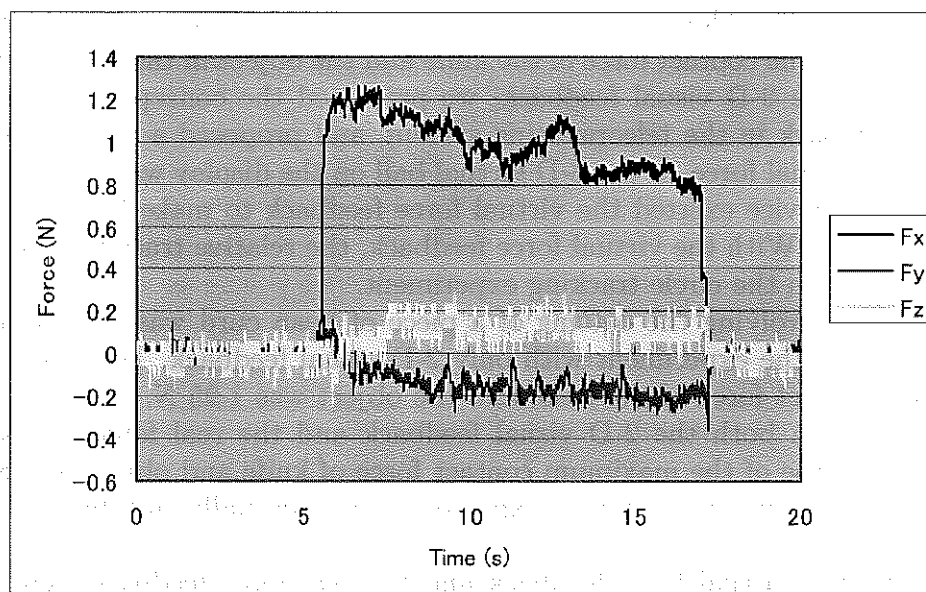


FIGURE 15. The contact force of the knife and the object with only visual feedback

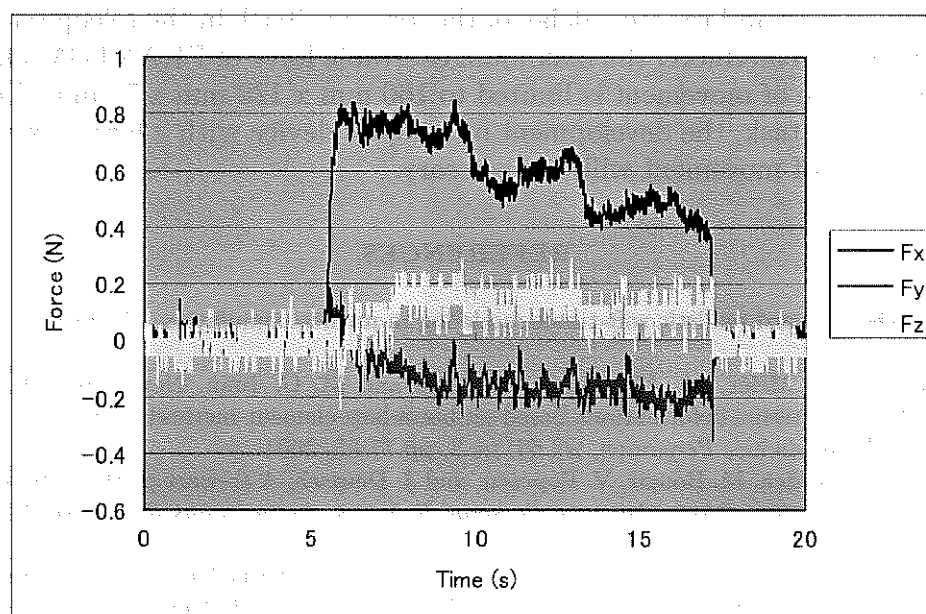


FIGURE 16. The contact force of the knife and the object with visual and force feedback

the maximum of the x -component is about 0.8 N. So, there was a 0.4 N decrease of the x -component of the contact force because of the force feedback.

4. Conclusions and Future Work. We have proposed a novel force feedback-based teleoperation system, which mainly consists of a haptic device (PHANTOM Omni) and a 6-DOF robot's arm. A high-speed CCD camera was equipped on the robot's arm to obtain

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