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A Control Technique for a 6-DOF Master-Slave Robot Manipulator System for Miniature Tasks

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ABSTRACT

This research covers the application of the virtual fixtures that is implemented on the 6-DOF master-slave robot manipulator system for miniature tasks. A benefit of the control technique using virtual fixtures is to increase performance of operating master-slave manipulators. In this paper, we discuss the implementation of two categories of virtual fixtures: guidance virtual fixtures, which assist the operator in moving the manipulator along desired paths or surfaces in the workspace, and virtual wall, which prevent the manipulator from entering into forbidden regions of the workspace. The virtual fixtures are constructed from the mathematics model in the control unit of the developed robotic system. The master arm, Phantom Omni® Haptic Device, generates the forces reflect from the slave arm that interacts with the virtual fixtures. These forces are felt by the operator. The direction and magnitude of these forces are associated with the desired virtual wall. In general, virtual walls are modelled as a spring-mass system. This model is able to respond effectively to sense of touch of an operator. In this research, the method of determining appropriated parameters, such as spring constant and/or damp constant. These parameters based on the operators' feeling-of-touch and position error of the manipulator. Nevertheless, shape of the virtual walls can be created based on a desired task. The strategy and procedure of constructing the walls are also presented in this article.

INTRODUCTION

Master-slave robot manipulator systems or teleoperation have been well known as one of the extension of manipulation capability to a remote location and a person's sensing. They are used in many applications in order to extend the performance of each operation. The movements of the slave manipulator can be commanded more precisely and accurately by the robot's AI and controller than human operator command of the desired movements. In addition, these robots can operate in difficult tasks, such as difficult assembly tasks, inspection and manipulation tasks in dangerous environments, and medical applications. There are many robotic medical applications, especially Minimally Invasive Surgery (MIS). For example, the daVinci® Surgical System [1] is a notable MIS robotic system.

However, the teleoperation cannot be used effectively without the force reaction. Hence, haptic interfaces should be implemented. With the haptics, the human operators can control the slave manipulator more effectively. The feedback force, generated from the haptic device (the master device), represents the force that acts on the slave manipulator. Therefore, the operators can feel the force when the slave manipulators carry weights or touch the real–world objects.

The concept of force reaction is further extended to the virtual fixture which can assist human operators to control the manipulator more accurately. Haptic virtual fixtures are software-generated force and position signals applied to operators via haptic devices. Virtual fixtures help operators perform master-slave manipulation tasks by limiting movement into restricted regions and/or influencing movement along desired paths. The haptic device generates the force corresponding to the virtual fixture math model. The movement of the operators will be constrained to move only in the desired paths. The experiments and math modeling of virtual fixtures are presented in several researches [2-4]. With respect to the math model of the reacting force, the virtual fixture can be categorized into two types: impedance and admittance [2].

In this research, the virtual fixtures are implemented on the 6-DOF master-slave robot manipulator system for miniature tasks. The Phantom Omni Haptic device (Figure 1) is used as the master device. The RCRT-1 Manipulator, a 6-DOF Slave Manipulator for Miniature Tasks

[5] (Figure 2) is used as the slave manipulator with the six links labeled No.1 - 6. In addition, impedance type virtual fixture is implemented.

Figure 1: Phantom Omni Haptic Device

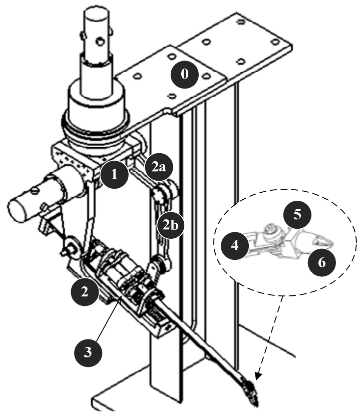

Figure 2: RCRT-1 Manipulator

MATHEMATICAL MODEL OF THE VIRTUAL FIXTURE

The concept of virtual fixtures is to specify the working area of the master device virtually. This will help the operator to work in the specific area more convenience. Human-machine systems with virtual fixtures can achieve safer and faster operation.

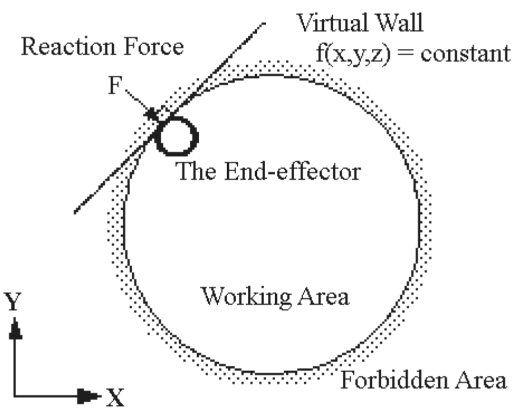

Figure 3: The circular working area

Figure 3 shows the circular working area. The virtual wall is defined by a function, f(x,y,z) = constant. When the operator move the end-effector contact to the virtual wall. The reaction force (F) will be generated to against the operation motion.

The shape and characteristic of virtual fixture is determined from the mathematical model. With respect to the impedance type, the math model is equivalent to spring-mass-damper model. The operator will feel the pushing force that interacts to their hands when the end-effector moves out of the preferred virtual path. Equivalent to the real mechanical spring-mass-damper system that is attached on the friction-free and massless slider, the force is generated only in the direction normal to the slider [2]. Consequently, the magnitude of force is the function of the deviated distance Δr (See Figure 5) and absolute movement speed. The deviated distance, is determined from the distance between the end-effector and the preferred path. On the other hand, the end-effector can be moved freely along the rail slider, representing the preferred path of the virtual fixture. The math model in represented by Figure 4, where, m is the mass of the Phantom's end-effector and F_{user} is force applied by the operator in order to move the end-effector.

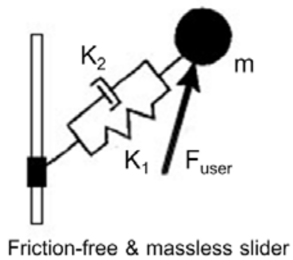

Figure 4: Spring-mass-damper model

Basically, the magnitude and direction of the force vector is directly related to the position, speed (Phantom's end effector), and spring-constant (K_1) and damper-constant (K_2), as shown in Equation (1),

$$\mathbf{F} = K_1(\Delta\mathbf{r}) + K_2(\Delta\dot{\mathbf{r}}) \quad (1)$$

where, $\Delta\mathbf{r}$ is the displacement between the position of the end-effector and the fixture's boundary perpendicular to the fixture's surface. $\Delta\dot{\mathbf{r}}$ is velocity of the end-effector.

COMPUTATION OF THE FORCE VECTOR

Direction of the force vector must be perpendicular to the fixture's surface boundary in order to provide the most appropriate feeling to the operator. These force vectors are determined from the gradient vector field of the scalar function which represents the shape of the virtual fixture. The description of a virtual fixture is shown in Figure 5. $\Delta\delta$ is thickness of soft wall zone specified by math model K-constants.

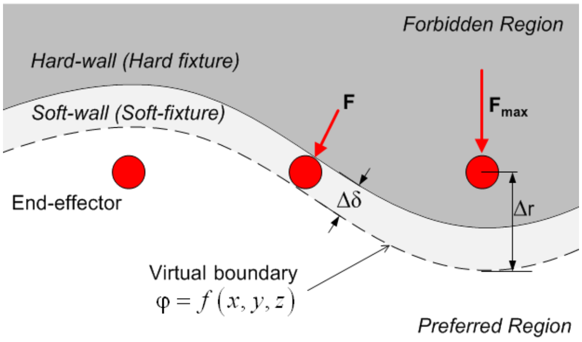

Figure 5: Description of a virtual fixture

Rewrite Equation (1) as a linear combination of a unit vector $\mathbf{n}$, as shown in Equation (2):

$$\mathbf{F} = (K_1 \cdot dr)\mathbf{n} + (K_2 \cdot V)\mathbf{n} \qquad (2)$$

where, $\Delta\mathbf{r} = \mathbf{n}(dr)$, which dr is the corresponding distance. $\Delta\dot{\mathbf{r}} = \mathbf{n}(V)$, V is the speed of the end-effector. The unit vector $\mathbf{n}$ and dr can be determined from Equation (4) – (6). The speed (V) can be obtained directly from the Phantom's API and libraries.

Assume a scalar function as virtual boundary (Figure 5), continuous function,

$$\varphi = f(x, y, z) \qquad (3)$$

The, compute F as follows:

$$dr = \frac{d\varphi|\nabla\varphi|}{\nabla\varphi \cdot \nabla\varphi} \qquad (4)$$

$$\mathbf{n} = \pm\frac{\nabla\varphi}{|\nabla\varphi|} \qquad (5)$$

$$\nabla\varphi = \mathbf{i}\frac{\partial\varphi}{\partial x} + \mathbf{j}\frac{\partial\varphi}{\partial y} + \mathbf{k}\frac{\partial\varphi}{\partial z} \qquad (6)$$

Substitute Equations (4) – (5) into Equation (2), the force vector is:

$$\mathbf{F} = \frac{K_1 d\varphi}{|\nabla\varphi|^2} + K_2 V\frac{\nabla\varphi}{|\nabla\varphi|} \qquad (7)$$

where $d\varphi = f_{boundary}(x_i, y_i, z_i) - \varphi_{boundary}$ (8)

$$\varphi_{boundary} = f_{boundary}(x_i, y_i, z_i)\big|_{i=boundary} \qquad (9)$$

Note that $\varphi_{boundary}$ = constant since φ is a continuous function. This scalar function φ , represents the shape of virtual fixtures described in Section 3.

In general, the characterization of virtual fixtures is based on the basic geometry or primitive volumes (i.e. straight line, sphere, cylinder, cone, and rectangular cube). This is a good approach for several reasons. First of all, this design enforces well-defined boundaries on the forbidden region, which makes the usage and graphic display of the fixtures comprehensible. Secondly, a volumetric representation of virtual fixtures facilitates their integration with the simulator or master-slave robotic systems. Thirdly, a set of basic volumetric forbidden region would make a flexible virtual fixture library for operators to assemble forbidden region of more geometrical complexity.

SPECIFY THE K-CONSTANT

Physically, the K-constant represents how hard is the constrain boundary. In case of the hard-fixture or hard-wall (large K-constant), the interacting force effectively regulate the movement within the preferred path or boundary with no or little deviation from this constraint is allowed during the operation. On the other hand, in case of the soft-fixture or soft-wall (small K-constant), the operator can move more freely in the non-preferred directions. Theoretically, the K-constant should be as large as possible in order to completely control the end-effector to move within the preferred path. However, the maximum force is limited by the limitation of the master device (the Phantom's maximum force is 3.3 N). Nevertheless, too large K-constant leads to large feedback force. It leads to overshoot when the end-effector had been pushed back into the preferred paths or boundary. In practice, the appropriate value of K_1 and K_2 must be adjusted in order to improve the operators' interaction. The value of K_1 should be increased as large as possible until the response becomes underdamp. While, the value of K_2 is adjusted to eliminate the overshoot. In this research, the preferred values are: $K_1 = 1$ and $K_2 = 0.01$.

FORBIDDEN REGION

The force is computed from Equation (2) – (6) are in the forbidden region. As the force magnitude is typically related to the distance dr, the force is continuously changing along the non-preferred direction. The force that determines the boundary hardness is as shown in Figure 6.

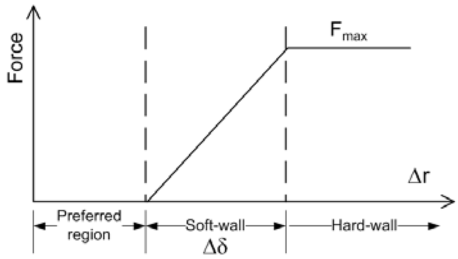

Figure 6: The interacting force in each region

The soft-wall thickness $\Delta\delta$ can be computed from the maximum force produced by the Phantom and K_1 not dependent on the function of K_2, as shown in Equation (10):

$$\Delta\delta = F_{\max} / K_1 \qquad (10)$$

SHAPE OF THE VIRTUAL FIXTURE

Virtual fixture can be categorized according to its boundary. Two types of the fixture presented are 1) guidance virtual fixture and 2) virtual wall. A major difference between these two fixtures is the region that the end-effector can move without constrained force. The details are described as follows.

GUIDANCE VIRTUAL FIXTURES (GVFS)

Guidance Virtual Fixtures are constructed as path lines. The operators can move the end-effector freely in the preferred-direction along the desired path lines. The force vector is computed from Equation (7). Therefore, the pushing force pointing to the path is generated in the forbidden regions around the desired path. An example of the GVF is shown in Figure. 7.

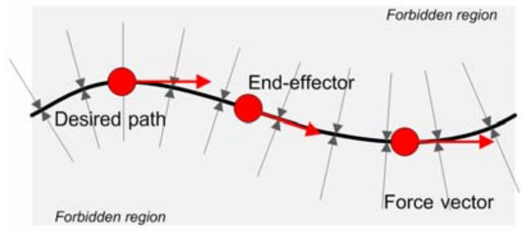

Figure 7: Guidance Virtual Fixture

There are many applications of GVFs, for example in cardiac surgery [6], the virtual fixture is constructed from the image data that provides the exact location of the artery and other organs.

VIRTUAL WALL

The preferred-region is bounded by the virtual fixtures. These fixtures act like the walls that prevent the operators moving the end-effector outside, while can moves freely inside this region. An example of virtual wall is shown in Figure 8.

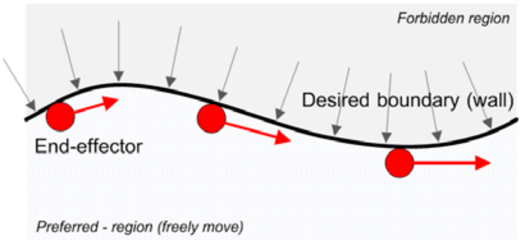

Figure 8: Virtual wall

The desired boundary can be specified as the scalar function in Equation (3). However, the additional boundary conditions must be provided to determine which region is preferred or non-preferred. For example, in Equation (11), the force vector is computed if the end-effector is in the position (x_i, y_i, z_i) that corresponds to the condition $\varphi(x_i, y_i, z_i) \geq \varphi_{boundary}$. Apparently, this means the end-effector is in the forbidden-region and there is no force generated in the preferred-region.

$$\mathbf{F} = \begin{cases} \dfrac{K_1 d\varphi}{|\nabla\varphi|^2} + K_2 V \dfrac{\nabla\varphi}{|\nabla\varphi|} & ;\varphi(x_i, y_i, z_i) \geq \varphi_{boundary} \\ 0 & ;\varphi(x_i, y_i, z_i) < \varphi_{boundary} \end{cases} \qquad (11)$$

The major benefit of virtual walls is to limit the device to move only in the desired area. The walls assist the operators to control the movement easily and effectively in order to avoid prohibited area. Moreover, the virtual environment can be created from virtual walls. For example [2], many walls are constructed and arranged in proper location. The operators can feel the walls and operate the tasks through the haptic device.

CONSTRUCT VIRTUAL FIXTURES USING THE PHANTOM

Shape of the virtual fixtures is defined from their boundary. For both GVFs and virtual walls, the boundary can be specified from the scalar function $\varphi_{boundary}$. In this research, the Phantom was used to define the desired location of the virtual fixtures in 3D coordinate.

BASIC GEOMETRY VIRTUAL FIXTURES

The location of virtual fixtures can be defined from one point if other features of the geometry (e.g. radius, height, length, orientation etc) are specified or pre-defined. This point can be set at the center point of a virtual sphere, or a point on the center line of a cylinder, or the center of a cube. For example, motions of the end-effector are bounded inside these geometries. The scalar functions of cylindrical and sphere are Equations (12) and (13), respectively. As examples, movement path of the end-effectors of the Phantom and the RCRT-1 Manipulator in Cartesian space are shown in Figures 9 and 10.

$$\varphi_{cylinder} = x^2 + y^2 - R^2 \quad (12)$$

$$\varphi_{spherical} = x^2 + y^2 + z^2 - R^2 \quad (13)$$

SHAPE-DEFINABLE VIRTUAL FIXTURES

Since the shape of objects in real world application is various and complex, e.g. human's organs, blood vessels, and etc, virtual fixtures constructed based on basic geometries are not capable to represent those objects effectively. Therefore, "shape-definable virtual fixture", which is a virtual fixture that its shape can be manually defined by the operators, is proposed in this research.

Here, the fixtures are considered only in 2D (XY-plane) in order to reduce degree of complexity. Hence, planes are defined as straight lines. Physically, the whole virtual wall boundary or preferred path is constructed from the set of 2D-connecting lines. These connecting lines are defined from the set of defined points (Blue points in Figure 11) which located by the operators.

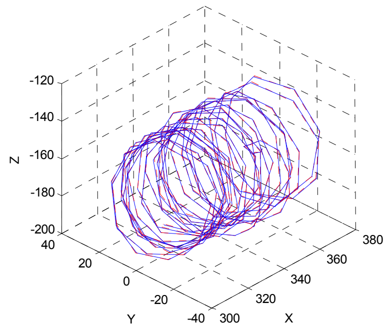

Figure 9: A cylinder virtual fixture

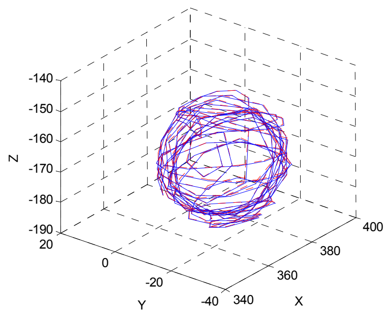

Figure 10: A sphere virtual fixture

Typically, the operation can be divided into 2 key stages. In the first stage, the operator needs to specify the number of defined point and define location of each one. The operator needs to move the end-effector to the desired location of the defined point. Then, the desired points will be collected when the operator send a command to the program. Coordinate (x, y) of the location corresponding to each defined point will be stored in the program memory. This process needs to be done repeatedly until every defined point is defined. Afterwards, in the second stage, the virtual boundary (or preferred path) corresponding to the defined points will be automatically constructed by the program. Force interaction will be generated along the boundaries.

As regard to the connecting straight lines. Each line is reconstructed from a pair of defined points. The linear equation and interacting force equation are used only between these two points. The connecting lines and their corresponding equations are constructed repeatedly for the whole virtual boundary's range of operation. The description of the shape-definable virtual fixture is shown in Figure 11, where, P_t is the position of the end-effector at time t, P_i is the desired point and $\mathbf{F}_t$ is the interacting force that act on the end-effector when it is moving in the corresponding range $(x_{i-1}, x_i]$.

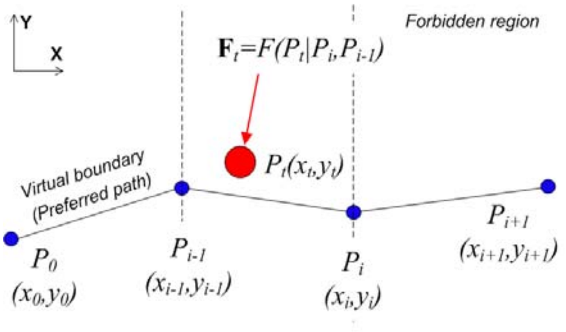

Figure 11: The shape-definable virtual fixture

As shown previously this force is computed from Equation (7) using scalar continuous function, φ, as the equation of the connecting line. Hence, this function is derived from x_i, y_i, x_{i-1} and y_{i-1}:

$$\varphi_{line}(x_t, y_t) = y_t - m_i x_t - (y_{i-1} - m_i x_{i-1}) \quad ; \quad x_{i-1} < x_t \le x_i \tag{14}$$

where

$$m_i = (y_{i-1} - y_i)/(x_{i-1} - x_i) \quad ; \quad i = 0, 1, 2, \ldots, n$$

Similarly, force vector in this range can be defined by Equation (15), below:

$$\mathbf{F}_t = F\left(x_t, y_t \mid x_i, y_i, x_{i-1}, y_{i-1}, K_1, K_2\right) \tag{15}$$

From the process flowchart in Figure 12, the virtual fixture is constructed after the entire defined points are defined by the operators. As the end-effector is moved within the workspace, the appropriate function corresponding to each position is assigned and the interacting force vector $\mathbf{F}_t$ is generated.

The corresponding range (xi-1, xi] of end-effector position Pt is determined by searching algorithm. The searching procedure start with assigning i=1. Then repeatedly increase i by 1 if (xt ≥ xi-1) and (i < number of defined point – 1) are satisfied. Eventually, this loop will be terminated if the corresponding range is found (xi-1 < xt ≤ xi) or xt is out of the range (xt ≥ xi). Afterwards, this force command Ft (magnitude and direction) will be sent to the Phantom through HDAPI (function hdset(…))

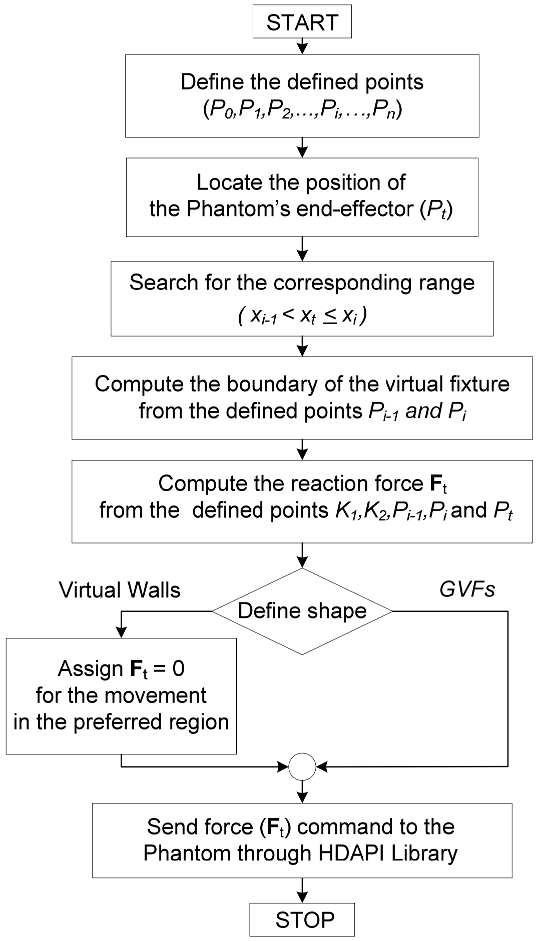

Figure 12: Process flowchart of constructing the shape-definable shape virtual fixtures

PERFORMANCE OF THE MASTER-SLAVE SYSTEM

THE PHANTOM OMNI HAPTIC DEVICE

This haptic device has 6-DOF having nominal resolution of 0.055 mm, producing 3-direction force feedbacks. The maximum force is 3.3 N and the continuous force is 0.88 N [7].

THE RCRT-1 MANIPULATOR

This 6-DOF slave manipulator with the PID-gravity compensation is normally used as a motion controller (at 1,000 Hz). When used in independent operation (without a master device), it has 0.514 mm precision with 0.005 mm repeatability. For master-slave operation, its overall capability is marginally reduced due to the unpredictable movements of human's control. Overall, the RMS (Root Mean Square) maximum position error is 0.791 mm, average position error is 0.293 mm and maximum orientation error is 0.832 degree (fine motion mode) [8].

EXPERIMENT AND RESULT

In the case of the master-slave system for miniature tasks, the operator can monitor the position and movement of the slave's end-effector through the digital microscope [5]. The master-slave system test bed is configured as shown in Figure 13.

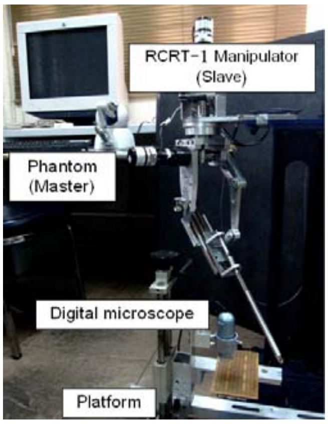

Figure 13: The master-slave system test bed

EXPERIMENT METHODE

The performance of a shape-definable virtual fixture was emphasized in this experiment; both GVFs and virtual walls were tested. On the test bed, a digital microscope was equipped on the slave-side in order to monitor the movement of the RCRT-1's end-effector. The test operation was conducted according to 2 stages described in section 4.2. First, the operator defined location of every defined points corresponding to the preferred boundary or desired path. Afterwards, the operator controlled the movement of the end-effector via the master-slave system. In general, the movement should be occurred only in the preferred-region or the desired path. (see Figure 14).

This desired boundary path were used for both GVFs and virtual walls testing. The parameters K_1 = 1 and K_2 = 0.01 were specified. Hence, soft-wall thickness is $\Delta\delta$ = 3.3 mm. Afterwards, the operator controlled the RCRT-1 to move freely within the preferred path or region.

In practice, the operator may intentionally avoid penetrating the end-effector into the forbidden region. This factor leads to the bias in measurement of the performance of the GVFs and the virtual wall. In order to avoid this bias, the operator's visual sensing was eliminated by shutting down the camera which is used to monitor movement of the end-effector. Therefore, only one perception of the operator was force interaction corresponding to the virtual boundary and the preferred path. This force regulated the hand movement to move only in the proper area.

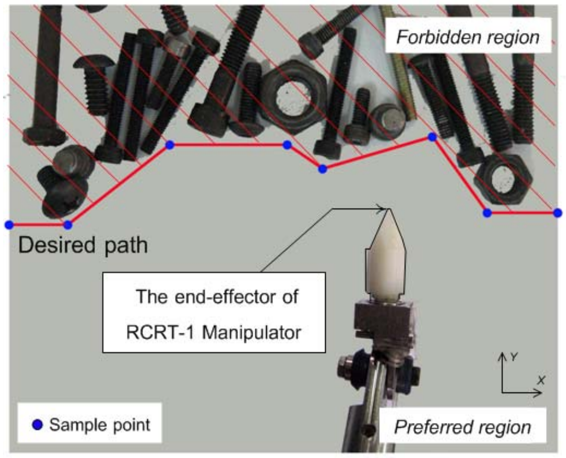

Figure 14: A virtual fixture in the experiment

RESULTS

Data of the movement in both tests were captured as illustrated in Figures 14 and 15. Some undesirable movements that penetrated into the forbidden region were observed in both tests. Each deviation is as an error determinable from the location of "desired path" and "RCRT-1's end-effector". These RMS errors are 1.646 mm and 1.552 mm for virtual wall and GVF respectively.

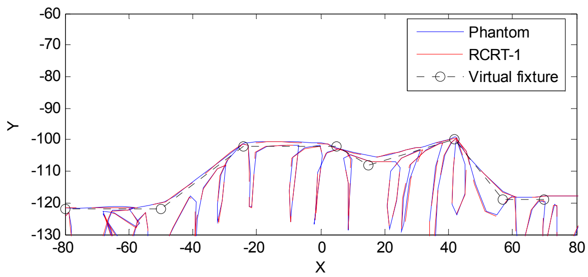

Figure 15: Movement in the virtual wall test

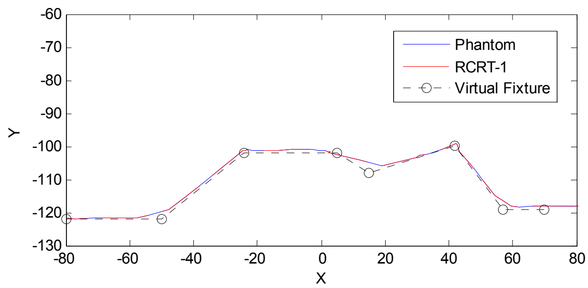

Figure 16: A Movement in the GVF test

CONCLUSIONS

The impedance type virtual fixtures were able to regulate the movements of the operator effectively. The end-effector moved within the preferred bounded region but approximately 1.6 mm deviation occurred in both virtual walls and GVFs testing. However, with regard to the 3.3 mm thickness (soft-wall), the movements were still constrained within this zone and did not penetrate the hard-wall zone. Moreover, the performance of the RCRT-1 partly affected these overall errors.

In conclusion, the virtual fixture is expected to be applied to a number of applications. For example, regarding MIS, the surgeon can manually define forbidden regions containing parts of important tissue that is severely sensitive. Consequently, the surgeon can sense this boundary via the interacting force and avoid collisions. Moreover, GVF is possibly used as a guide path in order to increase precision in sutures. The performance of the virtual fixture, such as precision and operator's sensing, can be further improved by fine adjustment of the virtual fixture gain. In addition, improvement of the motion control of the RCRT-1 is necessary.

FUTURE WORKS

The vision system and image processing can be used to automatically define the boundary of forbidden region. Moreover, the reconstruction and more complicated 3D boundary should be investigated.

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