

## **Virtual Walls of the 6-DOF Master Slave System for Miniature Tasks**

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### **Abstract**

This research covers the application of the virtual wall that is implemented on the 6-DOF master-slave system for miniature tasks. A benefit of virtual walls is to increase performance of operating master-slave manipulators. These walls bound the desired working area and allow the manipulator works inside. Moreover the guidance paths can be constructed associated with the desire walls. Consequently, the users are able to control the slave manipulator more accurately. The virtual walls are constructed from the mathematics model in the control unit of this robotic system. Subsequently, the master arm, Phantom Omni<sup>®</sup> Haptic Device, generates the forces interact the users. The direction and magnitude of these forces are associated with the desired virtual wall. In general, virtual walls are modeled as a spring-mass system. This model is able to respond to users' sense of touch effectively. In this research, the method of determining appropriated parameters, such as spring constant. The parameters considered based on the users' feeling of touch and position error of the manipulator. Nevertheless, shape of the virtual walls can be created based on purposes of each task. The strategy and procedure of constructing the walls are also presented in this article.

**Keywords:** Virtual Wall / Master Slave System / Miniature Task Manipulator

### **1. Introduction**

Master-slave robotic systems or teleoperation are used in many applications in order to extend the performance of each operation. Meanwhile the human users command the desired movements; the movements of the slave manipulator can be regulated more precisely and accurately by the robot's AI and controller. Moreover, these robots can operate in

the undesirable environments, such as hazardous wastes and harmful radiation. Nowadays, the medical application, especially MIS (Minimally Invasive Surgery) is currently on focused. The example of the notable MIS robotic system is the daVinci<sup>®</sup> Surgical System [1].

However, the teleoperation cannot be used effectively without the force interaction. Hence, haptic interfaces should be implemented.

With the haptics, the human users 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 users can feel the force when the slave manipulators carry weights or touch the real-world objects. The concept of force interaction is further enhanced to the virtual fixture which can assist the users to control the manipulator more accurately. The haptic device generates the force corresponding to the virtual fixture model in the program. Hence, the movement of the user will be constrained to move only in the desire paths. The experiments and modeling of virtual fixtures are presented in a lot of research e.g. [2-4]. With respect to the mathematics model of the interacting force, the virtual fixture can be categorized into two types: impedance and admittance [2].



Fig. 1 the Phantom Omni Haptic Device

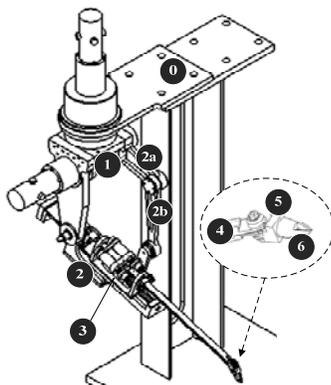


Fig. 2 RCRT-1 Manipulator

(The figures represent the link No.1 - 6)

In this research, the Phantom Omni Haptic device (Fig. 1) is used as the master device. The RCRT-1 Manipulator, a 6-DOF Slave Manipulator for

Miniature Tasks [5] (Fig. 2) is used as the slave manipulator. In addition, impedance type virtual fixture is implemented

## 2. Mathematic model of the virtual fixture

The shape and characteristic of virtual fixture is determined from the mathematics model specified in the program. With respect to the impedance type, the model is equivalent to spring-mass-damper model. The users 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 that normal to the slider [2]. Consequently, the magnitude of force is the function of the deviated distance 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. In the model in Fig. 3,  $m$  is the mass of the Phantom's end-effector and  $F_{user}$  is force applied by the user in order to move the end-effector.

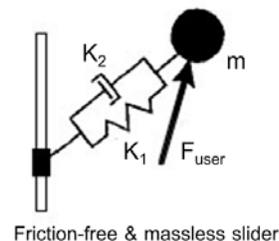


Fig. 3 Spring-mass-damper model

Basically, the magnitude and direction of the force vector is directly relate to the position and speed of the Phantom's end effector, and the spring-constant ( $K_1$ ) and damper-constant ( $K_2$ ), as shown in Eq. (2.1).

$$\mathbf{F} = K_1(\Delta\mathbf{r}) + K_2(\Delta\dot{\mathbf{r}}) \quad \text{Eq. (2.1)}$$

$\Delta \mathbf{r}$  is the displacement between the position of the end-effector and the fixture's boundary, that perpendicular to the fixture's surface.  $\Delta \dot{\mathbf{r}}$  is velocity of the end-effector which is normal to the fixture's surface. The detail of force computation is described as follows.

## 2.1 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 users. These force vectors are determined from the gradient vector field of the scalar function which represents the shape of the virtual fixture. According to the Cartesian coordinated, let scalar function  $\varphi = f(x, y, z)$ . Consequently, the computation is explained in Eq. (2.2) – (2.5). The description of a virtual fixture is demonstrated in Fig. 4.  $\Delta \delta$  is thickness of soft wall zone which is specified from the K-constant.

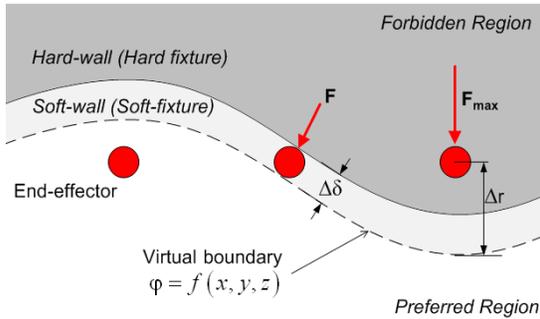


Fig. 4 Description of a virtual fixture

Rewrite Eq. (2.1) as a linear combination of a unit vector  $\mathbf{n}$ . Hence, it is shown in Eq. (2.2)

$$\mathbf{F} = (K_1 \cdot dr) \mathbf{n} + (K_2 \cdot V) \mathbf{n} \quad \text{Eq. (2.2)}$$

Where  $\Delta \mathbf{r} = \mathbf{n}(dr)$ , which  $dr$  is the corresponding distance.  $\Delta \dot{\mathbf{r}} = \mathbf{n}(V)$ , which  $V$  is the speed. The unit vector  $\mathbf{n}$  and  $dr$  can be determined from Eq. (2.3) – (2.5). As regard to the speed ( $V$ ), this information can be obtained directly from the Phantom's API and libraries.

$$dr = \frac{d\varphi |\nabla \varphi|}{\nabla \varphi \cdot \nabla \varphi} \quad \text{Eq. (2.3)}$$

$$\mathbf{n} = \pm \frac{\nabla \varphi}{|\nabla \varphi|} \quad \text{Eq. (2.4)}$$

$$\nabla \varphi = \mathbf{i} \frac{\partial \varphi}{\partial x} + \mathbf{j} \frac{\partial \varphi}{\partial y} + \mathbf{k} \frac{\partial \varphi}{\partial z} \quad \text{Eq. (2.5)}$$

Substitute Eq. (2.2) by Eq. (2.3) – (2.4), the force vector is:

$$\mathbf{F} = \frac{K_1 d\varphi}{|\nabla \varphi|^2} + K_2 V \frac{\nabla \varphi}{|\nabla \varphi|} \quad \text{Eq. (2.6)}$$

Where  $d\varphi = f_{boundary}(x_i, y_i, z_i) - \varphi_{boundary}$  Eq. (2.7)

$$\varphi_{boundary} = f_{boundary}(x_i, y_i, z_i) \Big|_{i=boundary} \quad \text{Eq. (2.8)}$$

Note that  $\varphi_{boundary} = \text{constant}$  in case of the function is continuous. This scalar function represents the shape of virtual fixtures which is clearly described in Topics 3-5.

In general, the virtual fixture can be constructed in any shapes. However, the basic geometry - e.g. line, sphere, cylinder, and cube - is generally concerned because the function can be obtained straightforwardly.

## 2.2 Specify the K-constant

Physically, the K-constant represents how hard of the constrained boundary. In case of the hard-fixture or hard-wall (large K-constant), the interacting force will effectively regulate most of the movement within the preferred path or boundary. 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 user 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 some 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 finely adjusted in order to improve the users' interaction. The value of  $K_1$  should be increased as high as possible until the response becomes underdamp. Subsequently, the value of  $K_2$  should be adjusted in order to eliminate the overshoot. However, the suitable parameters subject to be adjusted according to the requirements of each task. In this research, the preferred values are:  $K_1 = 1$  and  $K_2 = 0.01$ .

### 2.3 Forbidden region

Forbidden region is the area covered with the force field. These force vectors are computed from Eq. (2.2) – (2.5). As the force magnitude is typically related to the distance  $dr$ , the force is continuously changed along the non-preferred direction.. The force that determines the boundary hardness is clearly demonstrated in Fig. 5.

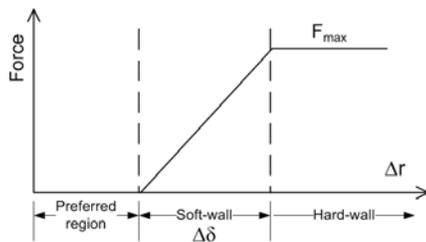


Fig. 5 The interacting force in each region

The soft-wall thickness  $\Delta\delta$  can be simply computed from the maximum force produced by the Phantom and  $K_1$ . It is not the function of  $K_2$ . The computation is shown in Eq. (2.9).

$$\Delta\delta = F_{\max} / K_1 \quad \text{Eq. (2.9)}$$

### 3. Shape of the virtual fixture

Virtual fixture can be categorized according to its boundary. Two types of the fixture are presented, which are guidance virtual fixture and virtual wall. A major difference between these two fixtures is the region that the end-effector can

be moved without constrained force. The details are described as follows.

### 3.1 Guidance Virtual Fixtures (GVFs)

Guidance Virtual Fixtures are constructed as path lines. The users can move the end-effector freely in the preferred-direction along the desired path lines. The force vector is simply computed from Eq. (2.6). Therefore, the pushing force pointing to the path is generated in the forbidden regions around the desired path. An example of the GVF illustrated is shown in Fig. 6.

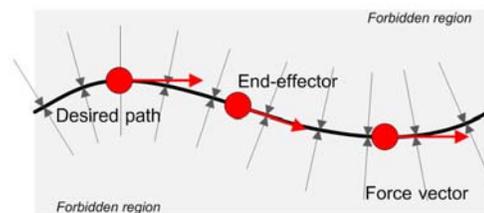


Fig. 6 Guidance Virtual Fixture

Many applications of GVFs are presented, for example in cardiac surgery [6], the virtual fixture is constructed from the image data which provides the exact location of the artery and other organs. Hence, the motion of medical devices will be constrained by the virtual fixture to move in the most appropriated and preferred path.

### 3.2 Virtual wall

The preferred-region is bounded by the virtual fixtures. Consequently, these fixtures act like the walls that prevent the users to move the end-effector outside. On the other hand, it can be moved freely inside this region. An example of virtual wall is illustrated in Fig. 7.

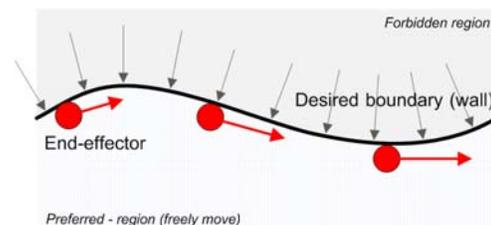


Fig. 7 Virtual wall

The desired boundary can be specified as the scalar function in Eq. (2.6). However, the additional boundary conditions have to be supplied in order to determine which region is preferred or non-preferred. For example, in Eq. (3.1), the force vector is immediately generated 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. On the contrary, the force is not generated in the preferred-region.

$$\mathbf{F} = \begin{cases} K_1 \frac{d\varphi}{|\nabla\varphi|^2} + K_2 V \frac{\nabla\varphi}{|\nabla\varphi|} & ; \varphi(x_i, y_i, z_i) \geq \varphi_{boundary} \\ 0 & ; \varphi(x_i, y_i, z_i) < \varphi_{boundary} \end{cases} \quad \text{Eq. (3.1)}$$

The major benefit of virtual walls is to limit the device to move only in the desired area. The walls assist the users 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 users can feel the walls and operate the tasks through the haptic device.

#### 4 Construct virtual fixtures using the Phantom

Shape of the virtual fixtures is defined from their boundary. For both GVF's of 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.

##### 4.1 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 in the program. This point can be set at the center point of a virtual sphere, a point on the centerline 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 Eq. (4.1) and (4.2), respectively. Furthermore, the examples of movement path of the end-effectors of the Phantom and the RCRT-1 Manipulator in Cartesian space are shown in Figs. 8,9.

$$\varphi_{cylinder} = x^2 + y^2 - R^2 \quad \text{Eq. (4.1)}$$

$$\varphi_{spherical} = x^2 + y^2 + z^2 - R^2 \quad \text{Eq. (4.2)}$$

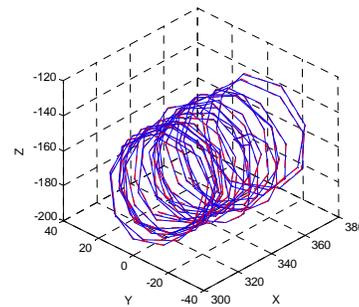


Fig. 8 A cylinder virtual fixture

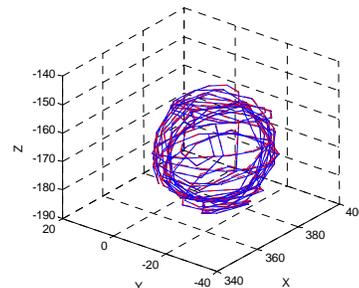


Fig. 9 A sphere virtual fixture

##### 4.2 Shape-definable virtual fixtures

As the preferred region of each task is totally different, basic geometry virtual walls are not capable to serve all requirements effectively. Thereby, the shape-definable virtual wall has been introduced in this research. Basically, the walls are considered only in 2D (XY-plane) so that plains are concerned as straight lines. Physically, the whole virtual wall boundary or preferred path is constructed from the connecting plain (connecting lines in 2D) virtual wall. Shape of the virtual boundary is defined from the sample points which specified by the users.

As regard to the master-slave system for miniature tasks in [5], the user can monitor the position and movement of the slave's end-effector through the digital microscope. The master-slave system test bed is configured as shown in Fig. 10.

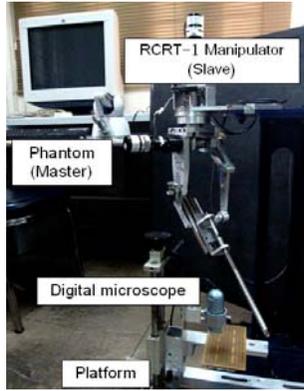


Fig. 10 the master-slave system test bed

Consequently, the desired sample points will be collected manually by the user's decision when the end-effector reaches those points. These collected sample points are stored in the software memory in order to construct the virtual boundary or preferred paths. In general, each connecting straight line is totally reconstructed from the coordinate of 2 points. Eventually, the linear equation and interacting force equation are used only in the range between these two points. Eventually, the connecting lines and their corresponding equations are constructed repeatedly for the whole virtual boundary's range. Description of the shape-definable virtual fixture is shown in Fig. 11.

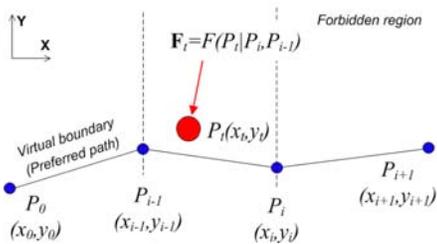


Fig. 11 The shape-definable virtual fixture

$P_i$  is the position of the end-effector at time  $t$ .  $P_i$  is the desired sampling point.  $F_i$  is the interacting

force that act on the end-effector when it is moving in the range between  $x_i$  and  $x_{i-1}$ . This force vector is typically computed from Eq. (2.6) and the equation of the connecting line is assigned to the scalar function. Hence, this function is derived from  $x_i$ ,  $y_i$ ,  $x_{i-1}$  and  $y_{i-1}$ .

$$\varphi_{line}(x_i, y_i) = y_i - m_i x_i - (y_{i-1} - m_i x_{i-1}) ; x_{i-1} < x_i \leq x_i$$

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

Eq. (4.3)

Hence, force vector in this range can be simply defined as Eq. (4.4).

$$F_i = F(x_i, y_i | x_i, y_i, x_{i-1}, y_{i-1}, K_1, K_2) \quad \text{Eq. (4.4)}$$

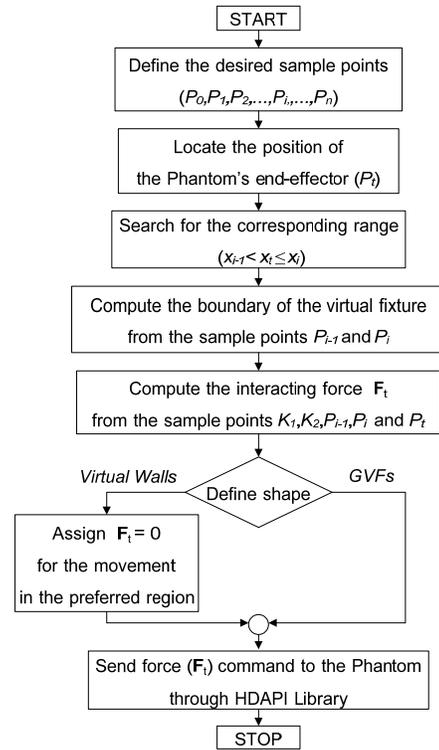


Fig. 12 Process flowchart of constructing the shape-definable shape virtual fixtures

From the process flowchart in Fig. 12, the virtual fixture is simultaneously constructed after the entire sample points are defined by the users. As the end-effector is moved within the workspace, the appropriate function relating to each position is assigned and the interacting force vector  $F_i$  is generated. The corresponding

range is determined by searching algorithm which the iteration is started from  $i=0$ . The searching will be stopped when the condition  $x_i \geq x_r$  is not satisfied. This force command will be sent to the Phantom through HDAPI (function  $hdset()$ )

## 5. Performance of the master-slave system

### 5.1 The Phantom Omni Haptic Device

This haptic device has 6-DOF which the nominal resolution = 0.055 mm. 3-direction force feedback can be produced. The maximum force is 3.3 N and the continuous force is 0.88 N. [7].

### 5.2 The RCRT-1 Manipulator

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

## 6. Experiment and result

### 6.1 Experiment method

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 procedure started with the user manually defined the sample points corresponding to the preferred-boundary or the desired path (see Fig.13).

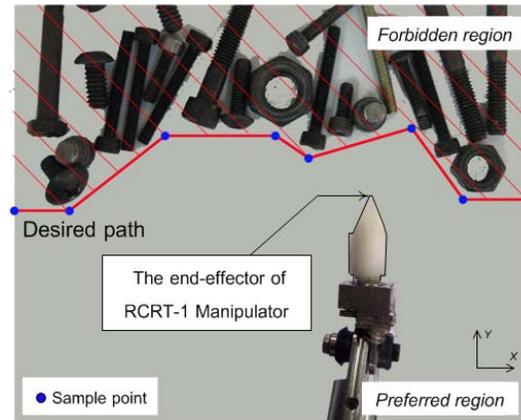


Fig. 13 A virtual fixture in the experiment

The desired boundary supposed to prevent the testing objects which lied in the forbidden area from the end-effector. This path would be used for both GVFs and virtual walls testing. The parameters  $K_1 = 1$  and  $K_2 = 0.01$  were set so that  $\Delta\delta = 3.3$  mm. Afterwards, the user control the RCRT-1 to move freely within the preferred path or region. In this step, the user was no longer allowed to see the movements from the camera. Hence, the force interaction was only information and constraint that the user was able to sense.

### 6.2 Results

Finally, data of the movement in both tests were captured and illustrated in Figs. 14,15. Furthermore, some undesirable movements that penetrated into the forbidden region were occurred similarly in both tests. This deviation is concerned as an error, which is determined from the location of "desired path" and "RCRT-1's end-effector". The RMS error = 1.646 mm for virtual wall and 1.552 mm for GVF.

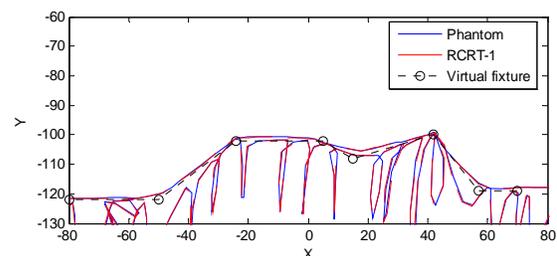


Fig.14 Movement in the virtual wall test

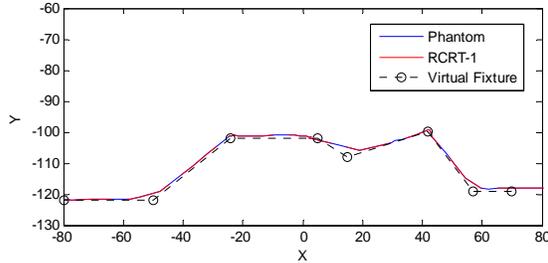


Fig.15 Movement in the GVF test

## 7. Conclusion

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

In conclusion, the virtual fixture can be applied to a number of applications. However, performance of the virtual fixture, such as precision and user's sensing, can be further improved by finely adjusting the virtual fixture gain. In addition, improvement of the motion control of the RCRT-1 is necessary.

## 8. Future works

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

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