Simulation and Control of Sensory-Mode Interaction

Noor Hazrin Hany M Hanif, Irraivan Elamvazuthi, Suziah Sulaiman and Shoon So Oo

***Abstract*— Haptics, the sensation of physical touch to the virtual objects, is the most recent enhancement to virtual environment. With haptic simulation, virtual objects with different properties could be created to touch using haptic device. In current medical practice, haptics technology is being used to aid surgeons to perform surgical procedures such as needle insertion. It is vital that the penetration of the needle does not cause injury to the patients. However, the available technology does not address issues such as tissue texture and the depth of penetration. This project is about the simulation of sensory mode interaction of virtual objects of different stiffness and friction using PHANToM Haptic device. The penetration depth and force exerted into the objects should be within limit to avoid any deformity to the objects. PID controller is incorporated into the system to eliminate steady state errors as well as to ensure better transient response. To conduct the specified work, MATLAB software was used. Experimental results on the sensory mode interaction have proven the ability of the system to touch the objects within specified object limits. Simulated results on the system response have also shown the capability of the controller to provide fast and accurate response of the haptic device.**

***Index Term*— Control, haptic, PHANToM, sensory mode interaction**

I. INTRODUCTION

Haptics, the science of incorporating the sense of touch and control into computer applications through force (kinesthetic) or tactile feedback has become one of the most interesting areas of research [1]. Haptics is widely used for the development of technology and improvement of the future science with applications ranging from educational applications (e.g. surgical simulation) to luxurious gadgets (e.g. haptic phone) [2]. With the help of haptic technology, one can gain the sense of touch to virtual objects. It is believed that being able to touch could lead to better results and great satisfaction. A haptic interface links a human operator with a virtual environment in such way the user feels the scene with the sense of touch. The haptic interface between the haptic programming and physical response is a motorized and instrumented device called haptic device that allows a human user to touch and manipulate objects within a virtual environment [3]. These interfaces devices have the ability to measure forces or pressure applied by the user and also able to provide the feedback force or pressure [4].

Many research and applications widely apply haptic technology nowadays. Several authors have described and compared several different techniques on haptics. For example, Guido B¨ottcher, Dennis Allerkamp and Franz-Erich Wolter from Institute of Man-Machine Communication, Germany, published their work on simulating two finger contacts haptics on fabric [5]. This haptic simulation allows the user to interact with the fabric using two fingers (i.e. Thumb and Index finger). The user can select types of fabric and feel the texture of fabric. The features of simulation allows user to squeeze, stretch, rub and lift. Research performed by Volkov and Vance [6] show the addition of haptic feedback significantly decreases task completion times. They used a PHANToM and a desktop monitor display to evaluate part designs for criteria such as ease of use by human operators.

Lian and Chen from University of Hong Kong worked on the virtual suturing simulation [7] which requires not only graphic modeling but also haptic modeling. The characteristics of tissues needed to model are acquired from MRI (Magnetic Resonance Imaging) or other types of scanned image. With this simulation, user would be able to feel the different types of tissues. Cagatay Basdogan and fellow scientists cooperated to simulate Minimally Invasive Surgical Training program [8]. In minimal invasive surgeries, a camera and long slender tools would be inserted into the abdomen through small skin incisions to explore the internal cavity and manipulate organs from outside the body as they view their actions on a video display. Since the surgeons are operating with minimal opening, it is important rely more on the feeling of net forces resulting from tool-tissue interactions. Therefore, this haptic simulation training would help practice surgeons in such minimal invasive surgeries.

The common parameters of senses of touch include friction, weight, stiffness and so on. In current medical practice, haptics technology is being used to aid surgeons to perform surgical procedures such as needle insertion. It is extremely important that the needle insertion should not be too deep to ensure the surgical procedures could be done without causing permanent injury the patients. However, the available technology does not address issues such as tissue texture and the depth of penetration. Therefore, the primary goal of this study is to provide an individual with capabilities to feel the sense of the touch of virtual objects which eventually could be used in simulation of medical applications. The study is based on the sensory interaction with different objects which has different parameters. Preliminary results of this study were published in IEEE conference proceedings [9]. In this study, virtual objects of different stiffness and friction were simulated and touched via a haptic device called PHANToM Desktop [10] to generate force feedbacks of three different objects which users could physically feel the different stiffness and

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frictions of objects.

II. MATERIALS AND METHODS

A. Design Considerations

There are two classes of control schemes available for force reflection: impedance control and admittance control [11]. Impedance controlled systems detect the motion commanded by the operator and control the force applied by the haptic device. Admittance controlled systems detect the force commanded by the operator and control the velocity or displacement of the haptic device. Sometimes, force is used as an additional input to the impedance controller or displacement is used as an additional input to the admittance controller. However, the type of output (force or position) can ordinarily be used to determine the class of controller being used. In the past, which approach to use often depended on the application being considered. Impedance controllers were generally used when the environment being simulated was highly compliant such as human tissue in surgical simulators. Admittance control was generally used when the environment was unyielding such as flight simulator platforms. However, the use of force and velocity inputs for both classes of control often blurs this distinction. [12]. Several studies have been carried out using impedance control by authors [13-16].

Closed-loop force feedback is a closed-loop system with the feedback that always examines the output. Closed-loop, determine a rule for decision-making at each stage of the planning period which provides the optimal decision for each possible state of the system, could be applied for better performance. In this study, the friction and penetration depth which relates to output feedback force was monitored and examined so that further improvements could be applied easily such as controlling penetration depth relating to the output force.

Stiffness determines the resistances of the object when then the device attempt to penetrate it. Stiffness could be generated using Hooke's Law

$$F = kx \qquad (1)$$

where k is the stiffness coefficient and x is the penetration depth. In simpler term, if we define the stiffness coefficient k, the penetratable depth x will varies (and therefore, stiffness will varies) according to the force F that user manipulate via haptic interface [17].

Friction provides resistance to motion along the surfaces (i.e. surface of object and the PHANToM probe in this case). Static friction, when two solid objects are not moving relative to each other, is considered in rendering haptics. Static friction could be represented by the equation

$$f = \mu_s F_n \qquad (2)$$

where F_n the normal force and μ_s is the friction coefficient. In simpler term, if we define the friction coefficient μ_s the friction force f will vary according to the force that user manipulate via haptic interface [18].

When it comes to the idea of generating different virtual objects, different objects with big differences in stiffness and frictions could be great selection for the study. Therefore, limestone (high stiffness and moderate friction), natural rubber (moderate stiffness with high friction) and cork (low stiffness and low friction) were selected. According to haptic library, the stiffness and friction coefficients could be assigned any value from 0 to 1 where 0 coefficient will exert minimal stiffness and friction and maximum stiffness and friction will be yielded by assigning 1. However, stiffness and friction coefficients could exceed 1 in real life situation. In order to acquire the difference sensations and to be able to differentiate, the coefficients shown in Table I are assigned to virtual materials.

TABLE I
STIFFNESS AND FRICTION COEFFICIENTS

Material	Stiffness Coefficient	Friction Coefficient
Limestone	0.9999	0.6500
Natural Rubber	0.5000	0.8500
Cork	0.1000	0.4500

The coefficients were chosen so that $k_{limestone} > k_{rubber} > k_{cork}$ [19] [20] [21] and $\mu_{rubber} > \mu_{limestone} > \mu_{cork}$ [18] which is close to real conditions.

The ultimate strength of the selected materials are as follows: [13-15] - Rock = 27.6 MPa (e.g. Limestone), Rubber= 15MPa (e.g. Tyre) and Cork = 1 MPa (e.g. Cork Stopper). Based on these values, scaled values for force limit of each materials that PHANToM device can coorperate is calculated and assigned.

B. Tools

The haptic interaction may include a haptic device, mechanical components (e.g. a robot arm), electrical components (e.g. actuators, sensors and signal conditioning circuits), computer part, software for the virtual environment simulation and control part (e.g. control algorithm). This is illustrated in Fig. 1[22].

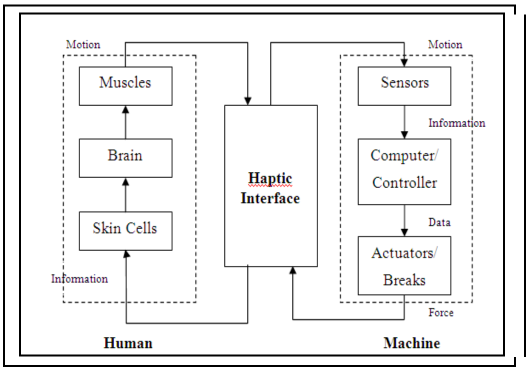


Fig. 1. Haptic Operation

Haptic technology assist users in interacting with sensor based interactions. As the interaction in the sensory mode, users not only can provide haptic input in to the program (e.g. computer) but also can receive the output sense that is generated by the program (i.e. information flows in two direction). The range of materials that could be simulated to touch varies in term of hardness, friction, size and so on.

There were two Haptic devices available for us in the Laboratory, namely, PHANToM Desktop and Omni. However, for this study, PHANToM Desktop device was used because it was able to handle stronger forces compared to PHANToM Omni. The OpenHaptics toolkit, provided by

SensAble Technologies, includes two options of Application Programming Interface to render haptic simulations, namely Haptic Library Application Programming Interface (HLAPI) and Haptic Device Application Programming Interface (HDAPI). These API assist developer in rendering haptics simulations for better pace and quality [17]. In this study, HLAPI was chosen due to abundant resource libraries and pre-built functions.

The model of the object is chosen as the spherical with the radius of 80 mm, however, any shapes with acceptable size could be chosen. In this study, the skeleton of the sphere (without any force and friction effect) is acquired from example provided by SensAble Technologies. The scene of touching the virtual object is shown in Fig. 2.

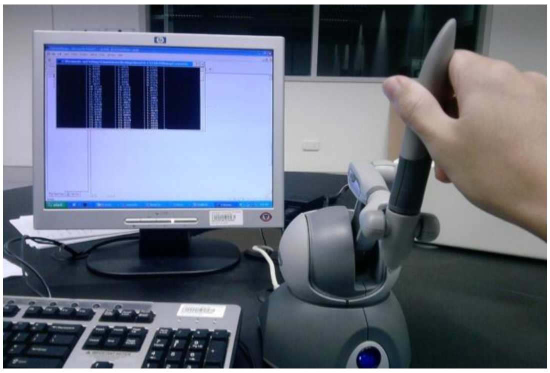


Fig. 2. Touching the virtual object by using PHANToM Desktop

C. Simulation

The flow of the program from how haptic program is started till it terminates is shown in Fig. 3.

Fig. 3 shows that upon starting the program, haptic will be initiated, objects will then be created, and the haptic feedbacks will be predefined. Users are then allowed to make a choice on the three selections of the haptic objects i.e. simulation of the limestone, rubber, and cork. Once a selection has been made, the output sense and input force value applied will be displayed. The program will do a checking on whether the input force applied by the users exceeds its limits or not. If it does, a warning message will displayed, operation will be halted, and users are prompted back to the haptic object selection. However, if the force does not exceed its limit, the haptic data simulation will be displayed. Should a user decide to end the program; haptic frame and feedback will be cleaned up, ending the haptic loop.

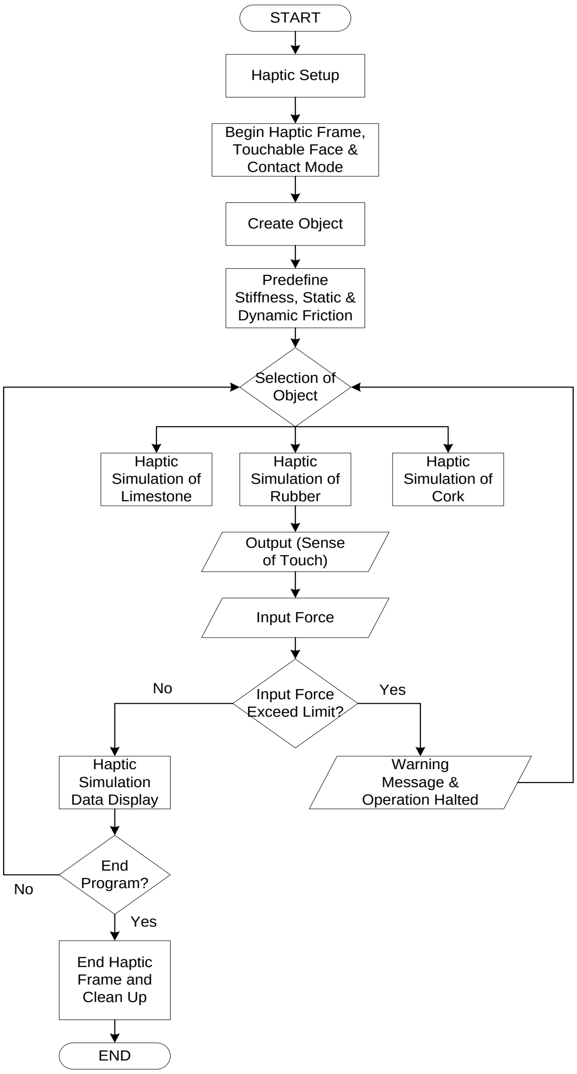
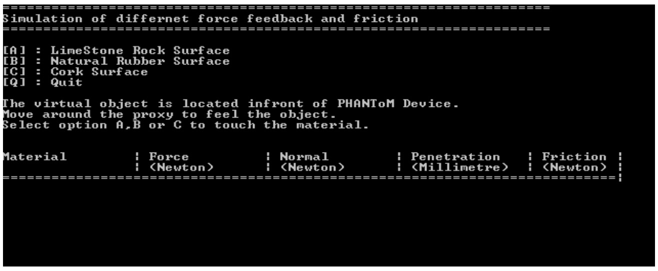


Fig. 3. The flow of the simulation program

The simulation is programmed with the references from OpenHaptics Toolkit and library provided by SensAble Technologies, Inc. [17]. Simulation provides a virtual spherical object which represents three different materials by providing different stiffness and frictions.

III. RESULTS

Once the program has started, the virtual spherical object is created with minimal amount of stiffness and friction. A message from the console requests the user to choose the materials to simulate. According to user’s selection, the different stiffness and frictions will be assigned to the virtual object created until the user chooses to end the selection. The user display screen for input and output is shown in Fig. 4 and Fig.5 respectively.



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=================================================================
Simulation of differnet force feedback and friction
=================================================================

[A] : LimeStone Rock Surface
[B] : Natural Rubber Surface
[C] : Cork Surface
[Q] : Quit

The virtual object is located infront of PHANToM Device.
Move around the proxy to feel the object.
Select option A,B or C to touch the material.

Material         ¦ Force           ¦ Normal          ¦ Penetration   ¦ Friction ¦
                 ¦ (Newton)        ¦ (Newton)        ¦ (Millimetre)  ¦ (Newton) ¦
=================================================================================¦
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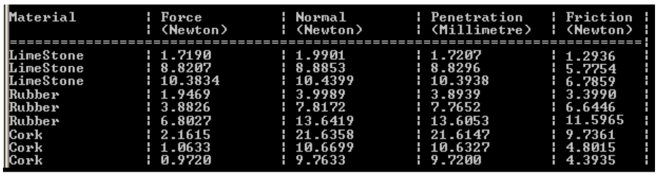
Fig. 4. The user display for the input



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Material          ¦ Force         ¦ Normal        ¦ Penetration   ¦ Friction ¦
                  ¦ (Newton)      ¦ (Newton)      ¦ (Millimetre)  ¦ (Newton) ¦
=============================================================================¦
LimeStone         ¦ 1.7190        ¦ 1.9901        ¦ 1.7207        ¦ 1.2936   ¦
LimeStone         ¦ 8.8207        ¦ 8.8853        ¦ 8.8296        ¦ 5.7754   ¦
LimeStone         ¦ 10.3834       ¦ 10.4399       ¦ 10.3938       ¦ 6.7859   ¦
Rubber            ¦ 1.9469        ¦ 3.9989        ¦ 3.8939        ¦ 3.3990   ¦
Rubber            ¦ 3.8826        ¦ 7.8172        ¦ 7.7652        ¦ 6.6446   ¦
Rubber            ¦ 6.8027        ¦ 13.6419       ¦ 13.6053       ¦ 11.5965  ¦
Cork              ¦ 2.1615        ¦ 21.6358       ¦ 21.6147       ¦ 9.7361   ¦
Cork              ¦ 1.0633        ¦ 10.6699       ¦ 10.6327       ¦ 4.8015   ¦
Cork              ¦ 0.9720        ¦ 9.7633        ¦ 9.7200        ¦ 4.3935   ¦
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Fig. 5. The user display for the output

From Fig. 5, it can be seen that the results are captured while the user is exerting the force along the object. The columns in the user display screen represent as follows:

Material – According to user's selection (either limetstone, rubber or cork)

Input Force (N) – The measured value of user input force that is reacting to the surface of virtual object.

Normal Force (N) – The measured value that relates with input force and object's surface.

Penetration (mm) – The calculated value from input force and stiffness coefficient and

Friction (N) – The calculated value from user input normal force and friction coefficient.

The penetration depth and friction force are calculated using tested values instead of being measured during the simulation due to the limitation of measuring capability of PHANToM Desktop.

Using the preset coefficients in Table I, the penetration depth of the probe inserted in to the object is calculated by using Hooke's law. With constant stiffness coefficient, the penetration depth will vary according to the amount of force user exerted onto the object and using the PHANToM desktop, the user could feel the difference in penetration depth according to the force exerted. The static friction force is also calculated by applying preset coefficients shown in Table I and normal force measured in static friction equation (2).

For instance, as shown in Fig. 5, once the user exerted force on the selected object, the program measured 1.7190 N force and 1.9901N normal with respect to the user's input and object's surface. With respective coefficients of Limestone, as in Table I, the program calculated how much user has penetrated, 1.7207mm, through the object as well as the friction force, 1.2936N, while moving along the surface.

The data acquired from the haptic simulation is used to perform empirical modeling of the system via Matlab. The obtained empirical model (also known as transfer function) will be useful in understanding the behavior of the haptic device in terms of its stability and transients. In order to get the empirical model of the system, the responses of the system of different materials are selected for duration of 10 seconds. The gathered data and the system response curve are shown in Table II and Fig. 6 respectively.

TABLE II
DATA FOR EMPIRICAL MODEL

Rubber	4.1343	8.3287	8.2687	6.2465
Rubber	4.1215	8.3033	8.2431	6.2275
Rubber	4.0830	8.2269	8.1661	6.1701
Rubber	4.0830	8.2269	8.1661	6.1701
Rubber	4.0937	8.2481	8.1874	6.1861
Rubber	4.0938	8.2482	8.1876	6.1862
Rubber	4.0938	8.2482	8.1876	6.1862
Rubber	4.0612	8.1835	8.1224	6.1376
Rubber	4.0508	8.1628	8.1016	6.1221
Rubber	4.0080	8.0779	8.0160	6.0584
Rubber	3.9867	8.0356	7.9733	6.0267
Rubber	3.9654	7.9934	7.9308	5.9951
Rubber	3.9331	7.9293	7.8662	5.9470
Rubber	3.9224	7.9081	7.8448	5.9311
Rubber	3.8600	7.743	7.7200	5.8382
Rubber	3.8600	7.7843	7.7200	5.8382
Rubber	3.8600	7.7843	7.7200	5.8382
Rubber	3.8391	7.7428	7.6782	5.8071
LimeStone	3.8006	3.9295	3.8006	0.3930
LimeStone	7.4795	7.5457	7.4795	0.7546
LimeStone	7.3828	7.4499	7.3828	0.7450
LimeStone	7.3560	7.4233	7.3560	0.7423
LimeStone	7.2684	7.3366	7.2684	0.7337
LimeStone	6.3794	6.4570	6.3794	0.6457
LimeStone	6.0530	6.1347	6.0530	0.6135
LimeStone	6.0519	6.1335	6.0519	0.6134
LimeStone	6.0404	6.1221	6.0404	0.6122
LimeStone	6.0520	6.1336	6.0520	0.6134
LimeStone	6.0415	6.1232	6.0415	0.6123
LimeStone	6.0407	6.1224	6.0407	0.6122
LimeStone	6.0407	6.1224	6.0407	0.6122
LimeStone	6.0298	6.1116	6.0298	0.6112
LimeStone	6.0407	6.1224	6.0407	0.6122
LimeStone	6.0407	6.1224	6.0407	0.6122
LimeStone	6.0407	6.1224	6.0407	0.6122
LimeStone	6.0522	6.1337	6.0522	0.6134

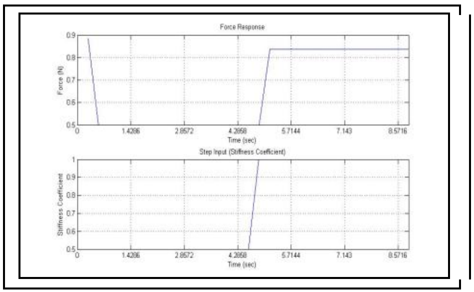

Fig. 6. The system response curve

The response curve shown in fig. 6 is a first order system with dead time. The necessary parameters such as maximum slope (S), input change (δ), step output (Δ), gain constant (K_p), dead time (θ) as well as time constant (τ) were calculated to obtain the empirical model of the system. The overall transfer function of this haptic device is hence derived as follows:

$$G(s)=\frac{0.673e^{-0.08395s}}{(0.01935s+1)} \tag{3}$$

To investigate the behavior of this system, a force of 0.9N was provided as a set point to the system. However, without any controller in the system, the system seemed not to be able to achieve the desired set point as shown in fig. 7. The maximum output response was barely 0.6N before settling at about 0.35N. The steady state error is 61.1%, which is considerably very high. The system however has a very fast response, which is highly required in manipulating the haptic device.

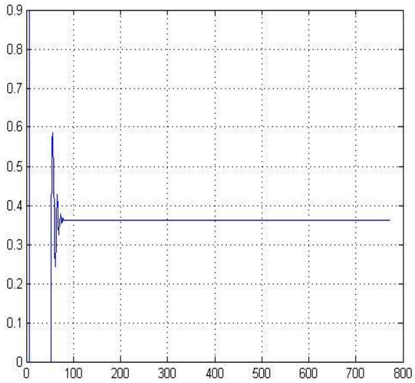

Fig. 7. The system response (without controller)

To ensure the steady state error is reduced (or eliminated) while maintaining a fast response, a PID controller is integrated into the system. The calculations were done using the Ziegler-Nichols open loop tuning, and the resulted PID formula is as follows:

$$MV(s) = 0.410985\left[E(t) + \frac{1}{0.1679}\int_0^t E(t')dt' - 0.6875\frac{dCV(t)}{dt}\right] \quad (4)$$

where E(t) is error and CV(t) is controlled variable (i.e.: the force exerted to the system). When this controller is included into the system, the desired set point of 0.9N is achieved as shown in fig. 8.

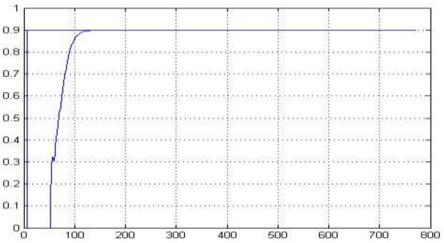

Fig. 8. The system response (with PID controller)

IV. DISCUSSION

Various methods could be utilized in obtaining a system model (or transfer function) that provides the dynamic relationship between selected input and output variables. In this research, empirical modeling was selected to derive the model of the haptic system. This method was opted because sufficient and relevant data could easily be obtained by performing a simple experiment to the haptic system. The experiment was done by making small changes in the input variable about a nominal operating condition. Based from the process curve shown in fig. 8, the following parameters were obtained, tabulated in Table III.

TABLE III
EMPIRICAL MODELING PARAMETERS

Parameters	Values
Output change (Δ)	0.3365 N
Input change (δ)	0.5 N
Gain constant (K_p)	0.673
Time at which output reaches 63% of its final value ($t_{63\%}$)	0.1033 s
Time at which output reaches 28% of its final value ($t_{28\%}$)	0.0904 s
Time constant (τ)	0.01935 s
Dead time (θ)	0.08395 s

The following values were then plugged in into the first order with dead time formula as follows:

$$G(s) = \frac{K_p e^{-\theta s}}{(\tau s + 1)} \quad (5)$$

The overall transfer function of the haptic device is hence obtained as shown in equation (1).

For the simplicity of this work, only Ziegler-Nichols open loop method was considered as the tuning method for the controller. According to [23], this tuning method ensures a 25% decay ratio of the controlled variable. This capability is very useful as it has been observed the system was quite oscillatory without the PID controller (as shown in fig. 8 previously). By implementing the controller via this method, the amplitude of oscillation could be reduced at least to 25% of the overshoot value at every deviation. The tuning constants of the PID controller were calculated and tabulated in Table IV.

TABLE IV
PID CONTROLLER TUNING PARAMETERS USING
ZIEGLER-NICHOLS OPEN-LOOP METHOD

Parameters	Values
Proportional Gain (Kp)	0.410985
Integral Time (TI)	0.1679 s
Derivative Time (Td)	0.6875 s

The following values were then plugged in into the general PID controller formula,

$$MV(s) = K_c\left[E(t) + \frac{1}{T_I}\int_0^t E(t')dt' - T_d\frac{dCV(t)}{dt}\right] \quad (6)$$

The performance of this controller was then simulated in MATLAB and the output response was obtained as shown in fig. 8.

The ultimate strength (force per area) of the materials are in MPa, however, haptic device can only provide one point touch which makes the contact area very small and difficult to measure. In order to settle the situation, the assumptions of the area of contact point between haptic device and virtual object is considered as $1\text{x}10^{-6}$ mm^2 which finally yields the maximum forces that virtual can take as 27.1 Newton for

Limestone, 15 Newton for Rubber and 1 Newton for cork stopper. By this scaling, the application has relation to real life values as well as it is able to simulate through PHANToM device.

V. CONCLUSION

This paper has discussed the sensory-mode interaction using haptic closed-looped force control feedback which is interesting yet challenging. It was found that the algorithm is adequate since it is fast enough to provide a sense of touching for different objects through different stiffness and friction using the PHANToM haptic device. However, the quality and usability of sensory-mode interaction can be substantially improved by the integration of online testing. In relation to this, it is hoped that continuing research will provide much value to the sensory-mode interaction in the near future.

ACKNOWLEDGEMENT

The authors would like to thank the Dept. of Computer and Information Sciences and Dept. of Electrical and Electronic Engineering of Universiti Teknologi PETRONAS for supporting this work.

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