

## DESIGN AND DEVELOPMENT OF A NOVEL SINGLE DOF LINEAR HAPTIC SIMULATION DEVICE FOR EDUCATIONAL PURPOSES

Muhammad Shah<sup>\*1</sup>, Hamid Ullah<sup>2</sup>

<sup>\*1,2</sup>Department of Mechanical Engineering, University of Engineering and Technology, Peshawar, Pakistan

<sup>\*1</sup>mshah.mec@uetpeshawar.edu.pk, <sup>2</sup>hamidullah@uetpeshawar.edu.pk

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Corresponding Author: \*

Muhammad Shah

### Abstract

There has been a dire need for students to understand the vast and different concepts of science and technology. An immersive medium is required that aids in teaching these concepts, that is more versatile and easily available than orthodox teaching implements. Educational Haptic interfaces can be used to fulfill this requirement. Widespread educational haptic devices are limited in implementing large-ranging haptic scenarios due to limited force feedback output, workspace, and transparency (when no force feedback is required). The dynamics of the device will either limit the device's force feedback capability or its transparency. Most pedagogical devices work out a compromise between force feedback, transparency, and workspace according to the application of the device. The device that is presented in this research supplements the limitations of implementing both force feedback and transparency with an increased workspace without having to compromise on any one capability. The research began by exploring different applications of haptic devices and identifying different properties and parameters that need to be considered while developing a haptic interface. Different educational haptic devices, their uses, and limitations were reviewed. Techniques from different complex haptic devices are explored to overcome the limitations imposed on them by their physical dynamics. Based on these insights, the requirements were determined for a good educational device that can be used for wide-ranging educational haptic applications. The haptic device was then designed by keeping in mind the limitations imposed on an educational haptic device and incorporating techniques from complex haptic devices to overcome these limitations. The haptic device working was then simulated in Simulink/MATLAB, and the mathematical model and its working were also simulated. The device was fabricated and tested with different haptic scenarios to verify and showcase the advantages and effectiveness of using the haptic device.

### I. INTRODUCTION

The Haptics derived from the Greek word Haptesthai meaning our relation to the sense of touch, is the study of the sense of touch and the science of how humans employ this sense to analyze, manipulate, and interact with their

environment [1]. The haptic sense unlike other senses enables a bidirectional flow of information that enables human's constant interpretation of the environment while actively manipulating it. It is indispensable for any task that involves human

observation and dexterity. Engineers and scientists are using haptic interfaces that can artificially generate a haptic feel for a range of tasks that require human dexterity and a higher level of operational control that can only be provided by human spatial cognition. Progress and development in communication, actuator, computer, and sensor technology lead to haptics being employed in a variety of applications including, remote medical surgeries, medical rehabilitation, industrial design, manufacturing, and everyday use of multimedia equipment like smartphones and gaming controllers [2]. Concepts of sciences taught through only visual and auditory methods give an abstract and passive understanding. These concepts are then supplemented by orthodox lab work by using specialized equipment. Haptic interfaces can be used instead of this specialized equipment in order to teach the same concepts in a more versatile and immersive manner. Haptic interfaces can also be used to teach tasks in which auditory and visual senses are hindered such as manipulating equipment parts behind obstructions. In STEM education, the haptic interface enhances learning of chemistry and physics concepts aiding understanding and visualization, from basic to advanced levels of concepts (such as electromagnetism, network transmission delay, and control systems). The use of haptic feel in teaching students has been shown to aid the learning process and thus is indispensable for this task [3]. Haptic interfaces are being used with AR (Augmented Reality) to overlay a more immersive environment over an existing physical environment like in museums to increase engagement and encourage exploration [4]. They are also used in specialized fields of research, such as teaching medical procedures that require repetitive practice by medical professionals without the use of specialized equipment and cadavers, e.g. dental procedures, neurosurgery, laparoscopy, and in surgical planning. Students who are visually challenged may benefit from using haptic feedback instead of vision. Any haptic device can be broadly categorized into three basic types. The impedance type device, the admittance type device, and the

hybrid type device. The type of device is based on the application of the haptic device. Each of these categories has its own control schemes, physical fabrication, and the ability to render haptics.

Impedance-type devices work as a source of force and take the position of the user interacting part as the input for the haptic rendering environment from the user [5]. The property of moving the actuator directly by interacting with the device is known as back drivability. It can render haptics quickly because of low inertial actuators. It is limited in the range of forces it can implement due to these low inertial actuators.

The admittance-type devices work as a position/displacement source moving according to the force implemented by the user [6]. The part with which the user interacts with the device and the actuator generally has a force sensor between them. These devices consist of large inertial actuators that can render a good range of force but have limited free space rendering capabilities [7].

Hybrid-type devices use a combination of the control structure and dynamic properties from both admittance and impedance-type devices in order to compensate for the weaknesses and complement the strengths of both types [8].

This research investigates the development of an innovative educational haptic device to enhance the teaching of complex scientific and technological concepts. The research begins by analyzing existing haptic devices and identifying their functionalities, limitations, and key parameters for effective educational applications. A novel haptic device is designed to address constraints related to force feedback, transparency, and workspace, incorporating advanced techniques from more complex systems. Performance simulations using Simulink/MATLAB validate the mathematical model, followed by the fabrication of a physical prototype. Experiments across various haptic scenarios demonstrate its effectiveness and advantages in educational settings, contributing to the advancement of interactive learning technologies.

Haptic devices are challenging due to varying performance metrics and the interactive nature

between the device and human operators, where measurements taken without human involvement can introduce ambiguity [9]. Key performance aspects include free space rendering, which describes the device's ability to create a contactless environment where users feel no force, also known as transparency. Force rendering refers to the device's accuracy in replicating a range of forces relevant to specific tasks, highlighting its force feedback capability. The physical workspace, or the dimensions within which the device can effectively render haptics, significantly affects the range of feedback. Additionally, fabrication difficulty ensures that the implementation of the device is feasible for users with diverse backgrounds, promoting accessibility while limiting design complexity [10]. Lastly, virtual walls serve as a fundamental technique in haptic rendering, allowing feedback to be conceptualized as combinations of these walls. An ideal device should provide infinite resistance at the point of contact while also simulating low-stiffness scenarios.

#### A. Applications of Haptics in Learning

Haptic simulations have demonstrated enhanced learning results across numerous disciplines and situations, including, but not limited to, science, health, and visual handicap training [11]. Haptics provides an embodied technique for engaging with normally "invisible" subject matter in a tactile way. This type of embodied learning using haptics introduces a new way for learners to engage with biologically secondary information by leveraging biologically primary processes like physical interaction and instinctively understood sensorimotor processing, thereby improving learning outcomes [12].

The hybrid control provides the solution to improve dynamic range for displaying varied virtual environments in a portable device by using a revolutionary particle brake model, partitioning mechanism, and torque feedback, therefore removing frequent artifacts such as the "sticky wall" [13].

In [14] authors, investigate the effect of haptic feedback on skill learning in laparoscopic surgery,

with the hypothesis that it would be more beneficial to orient tasks than cut.

The Hapkit paddle is a popular educational tool, especially when it comes to haptic instruction of control theory and trigonometric functions. Through haptic feedback, it enables students to engage with graphical representations of functions and create virtual mass-spring-damper systems. Additionally, the device is incorporated into virtual laboratories and MOOCs (Massively Open Online Courses) for control system engineering. Hapkit variants are impedance-type devices with a yoke or pulley handle that is coupled to an actuator using a capstan or friction drive. It facilitates linear motion simulation and is simple to install, with a circular workspace (100–160°) and force output up to 5 N. However, the yoke and actuator's inertia limit free-space rendering [15].

The Hands-On SEA (Series Elastic Actuation) device is a variation of the Hapkit paddle and is very close in its use. It is intended to teach students about physical human-robot interaction, algorithmic thinking in computer sciences applications by using mass spring systems, and concepts of control system engineering using haptics [16]. By simulating virtual mass-spring systems of different values arranged in a certain order students are taught different sorting algorithms as a part of a computer science course which is a difficult concept to comprehend through orthodox abstract techniques. The students were given a set of similar-looking virtual springs (through a GUI) and were tasked to sort them by stiffness using different algorithms. The difference between the hapkit paddle and the hands-on device is that the Hands-on SEA device is an admittance-type device that uses a series elastic actuation element between the friction drive and user handle/yoke [17]. The use of SEA enables force measurement on the device without using an expensive force sensor at the cost of response time [18]. The use of SEA also enables the user to feel smooth high-fidelity forces.

The I-touch is an impedance-type educational haptic device that is used to teach concepts of control theory, force tele-operability, and natural frequency by using haptics. The concept of control

theory and natural frequency was taught by implementing virtual mass-spring systems and manipulating them through haptics on the device. The device actuator consists of an electrical wire wound around a user-interacting part and is placed between magnets. The haptics are rendered by passing current through the coil according to the virtual environment. In order to reduce interference during free space rendering, it uses a voice coil actuator. It has a circular workspace of  $30^\circ$  and can implement torque up to 0.202 N.m [19].

The Box serves a different function than the I-touch device and is used to teach advanced concepts like network transmission delays, embedded system limitations, and microcontroller programming by the use of haptic. It was used by students to create complex haptic renderings e.g. linking two box devices over a network to create a virtual pong game and to implement virtual mass-spring systems to understand control theory concepts like damping and natural frequency. The box is an impedance-type device that uses a motor and chain transmission system to produce haptics. It has a circular workspace of  $360^\circ$  and can produce forces up to 5.4 N.m. Due to the direct linkage between the interacting part and the actuator, the free space rendering of the device depends upon the inertia of the motor and the transmission system. It could render stiffer environments and greater forces than the I-touch because of this configuration [20].

The Phantom is distinguished by its impedance-based architecture and the capacity to represent forces up to 35 N in the translational and 0.515 N.m in the rotational DOF (Degree of Freedom). It introduced a micro/macro manipulator setup to increase its workspace without losing the representation of the virtual environment. In order to create a system with a longer one-axis workspace and exact force rendering, two small and responsive Phantom devices are mounted on a larger, slower linear track. Along the track's axis, the combined arrangement offers a translational workspace of 697.5 square inches of surface area and a rotating workspace of  $297^\circ$ . Additionally, the translational range is 1.6 m. The Virtual wall

rendering ability is based on the dynamics of the phantom device on two axes and depends upon the combined dynamics of linear track and phantom device on the other axis [21].

The problem of rendering free space while offering a broad range of forces is addressed by the single DOF hybrid control device. It makes use of both passive and active actuators. It has a magnetic brake that serves as a passive actuator and a motor as an active actuator [22]. The magnetic brake offers transitions and the necessary resistance for greater forces, while the active actuator creates a virtual environment. Effective free space rendering is made possible by this design, which reduces the active actuator's dynamics and inertia [23]. When combined with a 1.7 N/mm magnetic brake, the gadget may exert forces of up to 26 N.m. The magnetic brake fully disengages during free space rendering, relying instead on the inertia of the active actuator. It has a  $360^\circ$  circular workspace.

The smooth transition-based encounter-type device offers another way of countering the problem of contradicting requirements for free space rendering and force rendering. It uses a complete disconnect from the user. As the user's finger approaches the periphery of the finger dial, the dial is moved away from the user and only interacts with him to render force feedback in order to implement the virtual scenario. By Doing this, the user feels no force and complete free space rendering until the encounter/transition boundary of the virtual environment is reached. The base device is an impedance type device and can render forces up to 15 N. It has a square, two-dimensional workspace of an area of 157.5 square millimeters. The proximity sensors control, and the impedance device control are two separate control systems switched at the boundary of transition between force and free space rendering governed by the rules of the virtual environment. The virtual wall depends on the maximum force rendering capability of the device and is subjected to the general limitation of impedance-type devices [24].

The device used as the base of this research is an admittance type device hence it has very limited ability to render free space [25]. The research shows that by using SEA (Series Elastic Actuation), one

can improve the response and hence free space rendering ability of an admittance-type device while also omitting the use of expensive force sensors. The ability, although increased the free space rendering capability, was still largely dependent on the response of the actuator. It also limited the stiffness of the virtual wall by making it dependent on the spring constant of the elastic element being used. The end result is an admittance-type device capable of rendering better free space rendering than a general admittance-type device just using a force sensor. The force rendering depends on the type of actuator and its precision of movement due to it being an admittance-type device [26].

As a result of the literature review, it is found that the available haptic devices have a number of limitations including limited ability to render a complete haptic scenario, because of their structure and actuator dynamics. They have very limited workspace and a limited range of forces. Due to these limitations, they have a limited range of

pedagogical haptic uses and are only designed to teach specific concepts. The device presented in this research has a workaround for these limitations that will be suitable for wide-ranging pedagogical purposes.

## II. METHODS

This section covers the research methodology and outlines the methods and approaches used to conduct the research and the necessary requirements for an optimum haptic device.

### A. Single DOF Linear Haptic Simulation Device

The design of the single DOF haptic device uses the closed loop and grounded admittance type, which gets around the drawbacks of the current educational tools. A sturdy ball screw actuator, which is perfect for applying a variety of forces, is used in this design to provide precise position control as shown in Figure 1.

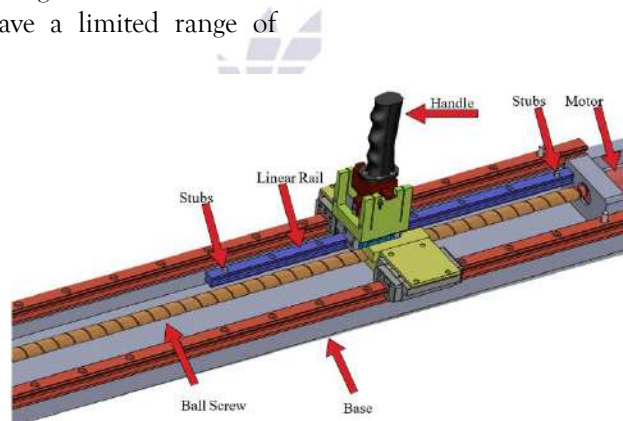


Figure 1: Single DOF Linear Haptic Simulation Device (Isometric View)

### B. Key Features and Working Mechanism

1) User Handle/End Effector Assembly: Series Elastic Actuation (SEA) is used to measure force through the handle assembly, which is fixed on the linear rail. By converting force control into

a position control task, SEA creates a compliant element between the user and the actuator. In order to simplify and guarantee ease of installation, metallic strips are used in place of traditional springs as shown in Figure 2.

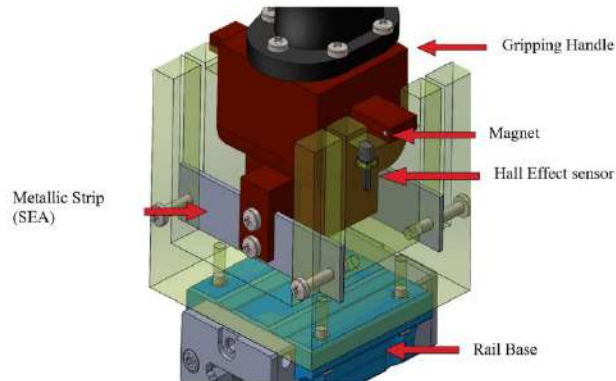


Figure 2: Enlarged View of Handle Components of the Haptic Device

2) Force and Free Space Rendering: In order to minimize resistance during operation, the device uses a linear rail mounted on the ball screw actuator to enable a mechanical disconnect for free space simulation as shown in Figure 3. In free

space mode, smooth operation is ensured by stubs at the ends of the rail. The stubs engage with the user handle for force rendering, dynamically shifting their location in response to the simulated haptic scenario and user-applied forces.

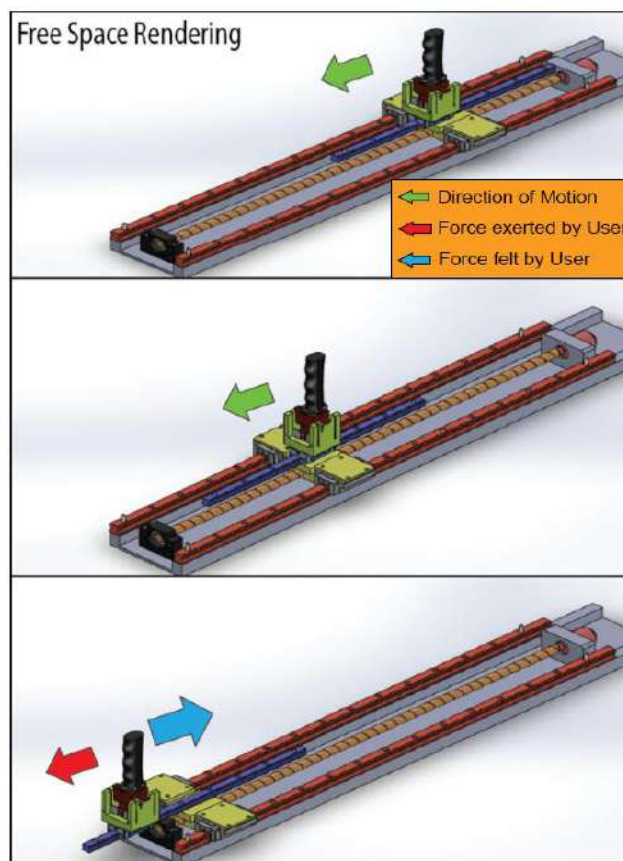


Figure 3: Free Space Rendering

### 3) Transition/Encounter Type Rendering:

Due to the actuator disconnect there is a transition before and during the force rendering phase in which it switches between force and free space rendering according to the physics of the haptic virtual environment as shown in Figure 4. This transition also occurs in real-world environments and thus is desirable for the device to render a more immersive virtual environment.

### C. Control Design

Due to the introduced physical disconnect, the haptic rendering is based on alternatively switching between free space and force rendering control schemes according to the virtual environment. By using this disconnect the device becomes a hybrid encounter-type haptic device. In free space

rendering the device takes the position and according to the virtual environment renders an obstacle-less environment (free space), this is the impedance type operation of the device. The only time the user will feel this force is at the physical limits of the device in this mode. When force rendering is implemented, the device switches to take the force as input from the SEA element and implement the force feedback. This is the admittance-type operation. The switch-based control law is governed by the logic and the design of the virtual environment. By using this physical disconnect and decoupling the user dynamics from the machine dynamics we can implement the full haptic rendering scenario and increase the workspace.

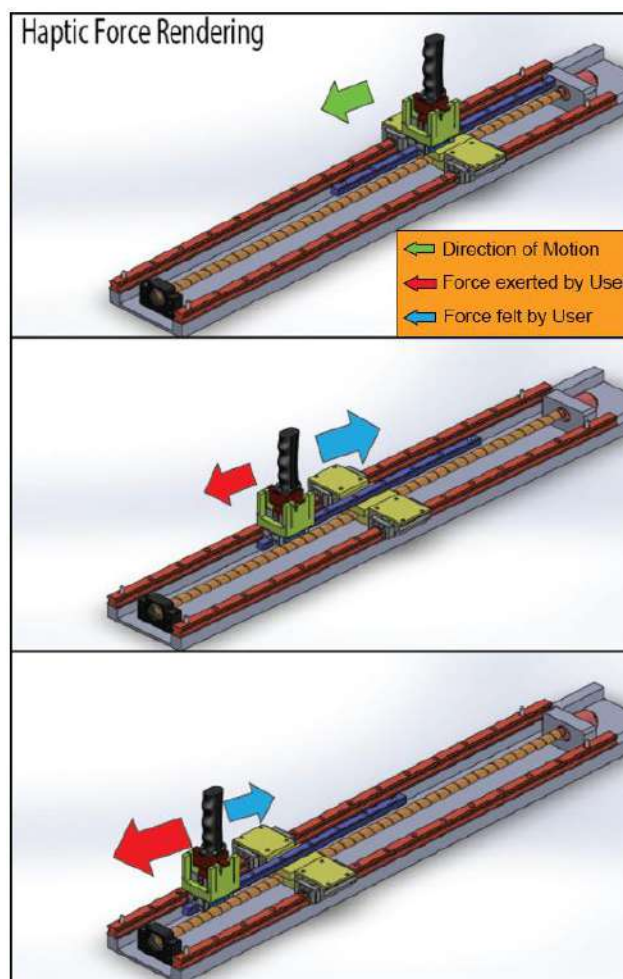


Figure 4: Force-Haptic Rendering Working

1) **Dynamic Device Simulation with MATLAB:** The device is simulated in MATLAB in order to confirm the working of the device and the implementation of the control schemes. To confirm the working of free space and force rendering of the device sim-multibody and sim-mechanics are used. We can clearly determine during free space rendering the user handle never interacts with the stubs and thus user feels no force in free space mode until the physical limits of the device are reached. In the force rendering mode, the user interacts with the stubs of the linear rail and feels force feedback. The complete device simulated in MATLAB is shown in Figure 5.

2) **Modeling:** The device can be modeled as a single linked manipulator actuated by a DC motor with a gearbox in between. It is assumed, the fixture between the motor and ball screw actuator is solid and fixed. The inertia of the motor shaft is calculated which is magnitudes less than that of the ball screw actuator and thus it is ignored. The weight of the traveler/table of the ball screw is greater than the weight of the handle assembly and it is also ignored. All un-modeled dynamics are considered as disturbances and compensated by robust control.

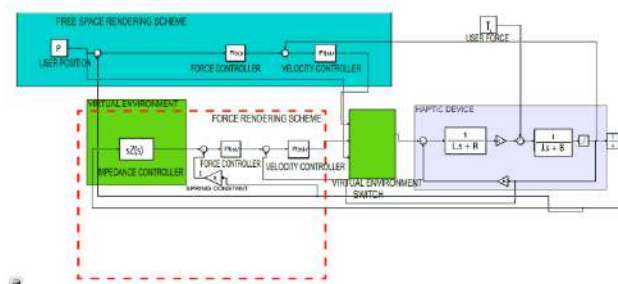


Figure 5: Full Device Simulated in SIMULINK

The device parameters are shown in Table 1 are used to model the proposed system and the equations used are as below:

Table 1: Device Parameters

Parameters	Symbol	Values
Motor Resistance	R	2.25 Ohm
Motor Inductance	L	2.35 mH
Weight of Ball Screw	$W_s$	6.5 N
Weight of Traveler	$W_T$	10.5 N
Inertia of Ball Screw	$J_s$	0.07653 kgm <sup>2</sup>
Inertia of Traveler/Table	$J_T$	0.025803 kgm <sup>2</sup>
Total Inertia	$J_{Total}$	0.10233 kgm <sup>2</sup>
Nominal Diameter of ball screw	$D_s$	0.02 m
Lead of Ball screw	$l_s$	0.02 m
Gear ratio	n	60:1
Motor Torque Constant	K	0.375 Nm/A
Efficiency of Ball-Screw	$\eta_s$	85 %
Force user	$F_{user}$	1 - 45 N
Viscous Damping	C	0.01 N.m/s

Starting the system with the electrical dynamics of the motor where current is given by:

$$I(s) = \frac{V(s) - E_b(s)}{R + sL} \quad (1)$$

Relating the motor torque with motor speed

$$w(s) = \frac{T_{(\text{motor})}}{R + sL} \quad (2)$$

Through a proportional gain, the current produces the motor torque.

$$T_{(\text{motor})} = K \cdot I(s) \quad (3)$$

Using equations (1) to (3) to model the plant with added load torque  $T_L$ . Using standard feedback equation (4) to model the transfer function (7).

$$T.F = \frac{G(s)}{1 + G(s)H(s)} \quad (4)$$

The transfer function is used to express the system dynamics in order to account for the load torque.

The following is the open loop transfer function:

$$G(s) = \frac{n \cdot K - T_L(R + sL)}{(R + sL)(Js + C)} \quad (5)$$

$$H(s) = K \quad (6)$$

By putting the equations (5) and (6) in equation (4).

$$\frac{\theta(s)}{V(s)} = \frac{(-LT_L)s + nK - (T_L R)}{s[(L) s^2 + (A)s + B]} \quad (7)$$

Where:

$$A = RJ + LC - (nLK T_L)$$

$$B = CR - (nK T_L R) + nK^2$$

The moments of inertia for a system with a moving traveler and a ball screw are as follows:

$$J_{\text{ballscrew}} = \frac{W_s}{2g} \left( \frac{D_s N}{2} \right)^2 (n)^2 \quad (8)$$

$$J_{\text{Traveller}} = \frac{W_T}{g} \left( \frac{l_s}{2\pi} \right)^2 (n)^2 \quad (9)$$

The torque of the external load is determined by:

$$T_L = \frac{F_{\text{user}} l_s}{2\pi \eta_s} \quad (10)$$

3) **Control Scheme:** The control of the device is divided into two parts. In free space implementation, a closed-loop position controller is used as a way to implement free space in which a cascaded PI velocity controller nested in a proportional position control. In force or haptic rendering mode a cascaded control scheme is used, an inner loop velocity controller, an

intermediate force controller, and the outer impedance controller. The inner velocity controller ensures robustness to disturbances caused by friction, stiction, and slip. The intermediate control loop implements force control with good force tracking and the impedance control is used to implement haptics as shown in Figure 6.

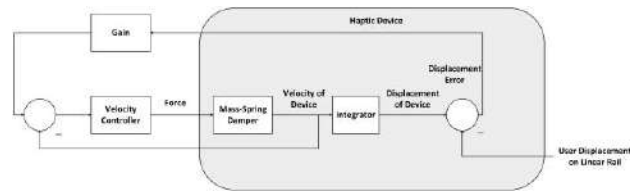


Figure 6: Free Space Control Scheme of the Device

In force or haptic rendering mode, a cascaded control scheme, an inner loop velocity controller, an intermediate force controller, and the outer impedance controller are used as shown in Figure 7.

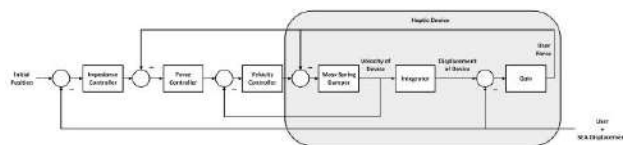


Figure 7: Force-Haptic Rendering Block Diagram [27]

The inner velocity controller ensures robustness to disturbances caused by friction, stiction, and slip. The intermediate control loop implements force control with good force tracking and impedance control is used to implement haptics.

#### D. Hardware Implementation

The base device is a closed loop grounded admittance type device that consists of a linear ball screw actuator having a pitch of 2 cm actuated by a Pololu 12 V 200 rpm 5 A DC gear motor with an attached 64 PPR (pulse per revolution) count. This power train provides a range of forces and a displacement accuracy of 1 mm.

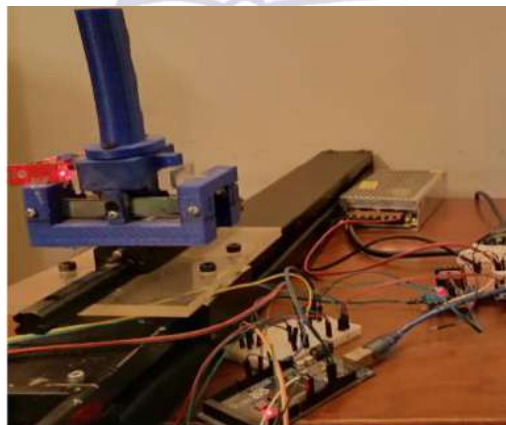


Figure 8: Full Setup of the Device

It has a linear workspace of 1 m and is capable of delivering forces up to 45 N. The interacting part consists of a 3-D printed base and handle connected by a SEA (series elastic actuation) element whose deflection is measured by a KY-024 hall effect sensor gives us the amount of force exerted by the user. The handle assembly is

mounted on a linear rail that gives us the disconnect from the linear ball screw actuator used for the purpose of free space rendering. The displacement of the handle along the linear rail is measured by a CALT CESI 2000mm draw wire encoder. An Atmega 2560 Arduino microcontroller along with an LM298 motor

driver is used to control the device and implement haptics. A surplus ball screw actuator of pitch 2 cm and length 1 m has been used along with a low-speed 200 rpm motor. The encoder gives a movement resolution of 0.0625 mm. The minimum force that can be stably delivered is 1 N and the maximum force is 45 N. This force is further limited by JND at 38 N (maximum at 15%

of 45 N for JND of successive haptic stimuli) when successive force rendering needs to be implemented. The reason for the use of a low-speed actuator is to limit the response of the device in order to ensure the safety of the user without limiting the force rendering range or using complex damping techniques. The handle and full view of the device are shown in Figures 8 and 9.

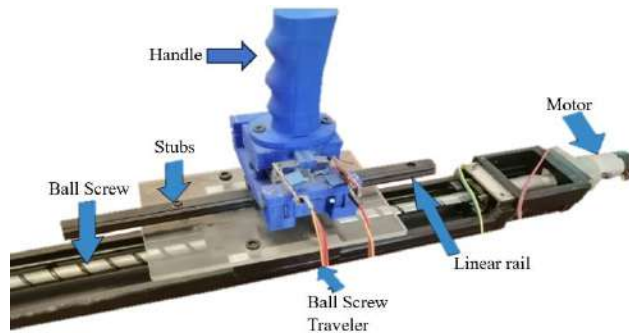


Figure 9: Full View of the Device Setup

**E. Force Bandwidth of the Haptic Device**

In the following plots, the response of the device to different forces has been characterized. As expected from the simulations the device has a greater

bandwidth for generated forces of smaller magnitude than those with higher magnitude as shown in Figures 10, 11, and 12.

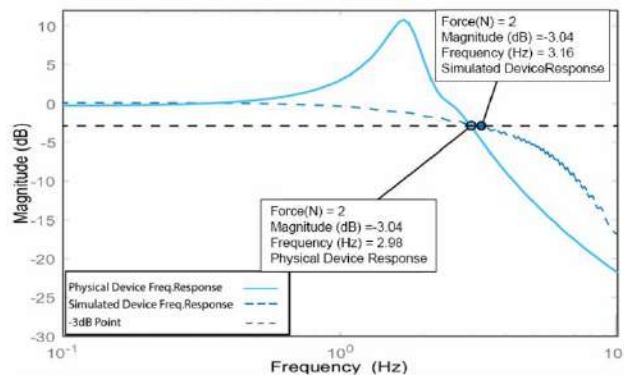


Figure 10: Frequency Response of 2-N Force Bode Diagram

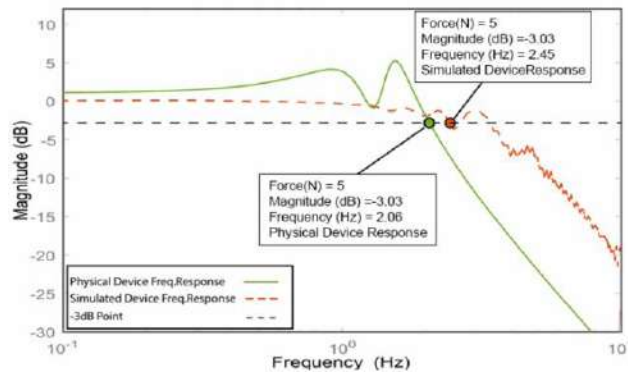


Figure 11: Frequency Response of 5-N Force Bode Diagram

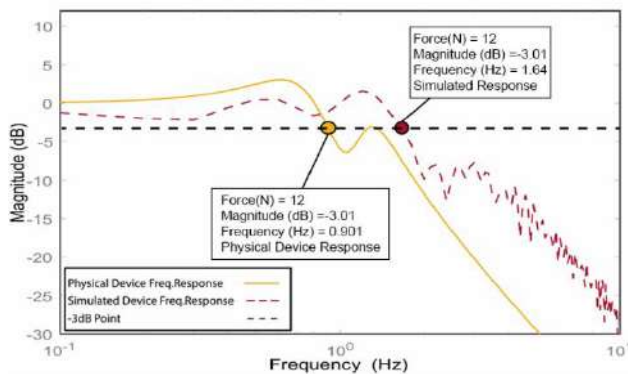


Figure 12: Frequency Response of 12-N Force Bode Diagram

- 1) Virtual Wall of the Haptic Device: The Virtual wall is the most basic haptic rendering task since most haptic scenarios can be simplified to a collection of virtual walls having varying stiffness and damping. The Virtual Wall can be seen at  $\pm 10$  cm from the workspace as shown in Figure 13.

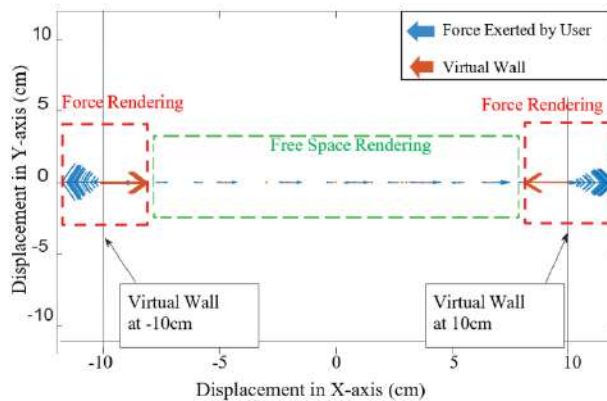


Figure 13: Virtual Wall of the Device

- 2) Qualitative Measure of Haptic Rendering Ability: The performance of the device is qualitatively assessed using the virtual wall simulation. The user encounters two different reactions, as shown in Figure 14, maximum force on the virtual wall during force rendering and no force in free space rendering.

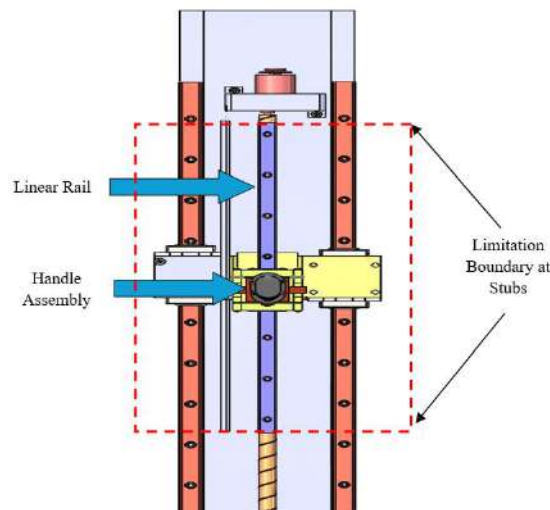


Figure 14: Virtual Object Placement Limitation

This demonstrates that the device successfully distinguishes between force rendering and free space without being influenced by device dynamics and is consistent with theoretical models. A haptic device should, in theory, prohibit the user from moving past the location of the virtual wall. Rendering lapses are introduced in practice, though, by fixed rate data sampling and analog-to-digital and digital-to-analog conversions. Oscillations are caused by these gaps because they permit a small amount of device movement over the wall, requiring more energy to stop the user.

### III. RESULTS AND DISCUSSIONS

Two haptic scenarios have been implemented that showcase the advantage of using the single DOF

linear haptic simulation device. These scenarios demonstrate how the device provides accurate force feedback and simulates different textures, all lowering users to feel resistance when interacting with virtual objects.

#### A. Implementing a Pulley System in Virtual Environment:

The understanding of mechanical advantages offered by pulleys and their working under different conditions is rudimentary. Using a haptic device, the student can be taught these concepts in-depth, as conventional laboratory equipment is limited in implementing complex pulley systems.

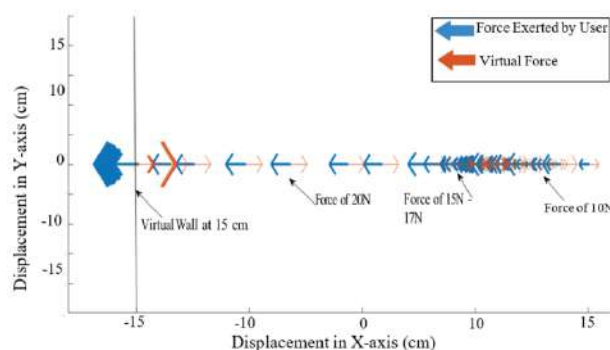


Figure 15: Forces Exerted by Pulley System

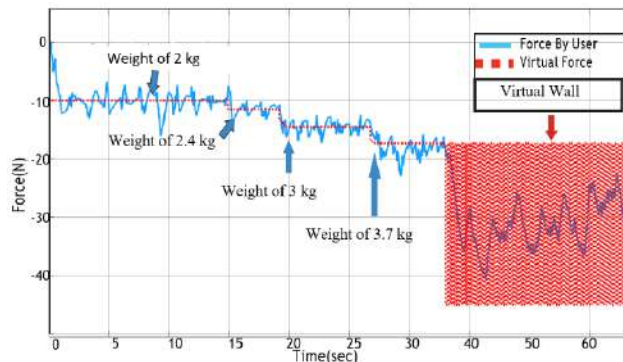


Figure 16: Forces Exerted on Pulley System with Displacement

The advantage of implementing a pulley system on this device is that a larger workspace and more force range give us a complete understanding of the workings of a pulley system. A simple pulley system with a mechanical advantage of two will have half the force required to lift the object but the cable connecting the pulley system will have to travel twice as far. A larger workspace shows the distance traveled by the object which cannot be implemented by a confined workspace and the larger force resolution can give a good sense of mechanical advantage as shown in Figure 15. In the implemented example there is a varying load that changes between 2 kg to 3.7 kg and the user

needs to apply greater force to lift the weights as they change as shown in Figure 16.

**B. Implementing Control Column Forces due to Elevator Displacement in Aircraft:**

Control of column forces due to elevator displacement is an advanced concept that can be taught by using the device. Pilots in aircraft use the forces exerted by the control column to gauge stresses on the control surface of the aircraft which depend on many factors, some of which are air speed, control surface area, air density, and angle of attack.

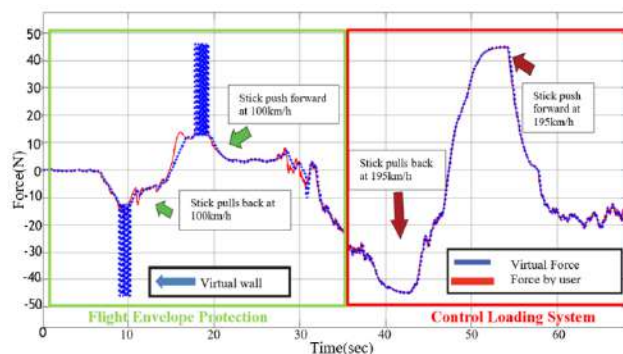


Figure 17: Forces of Control Column and Displacement of Elevator

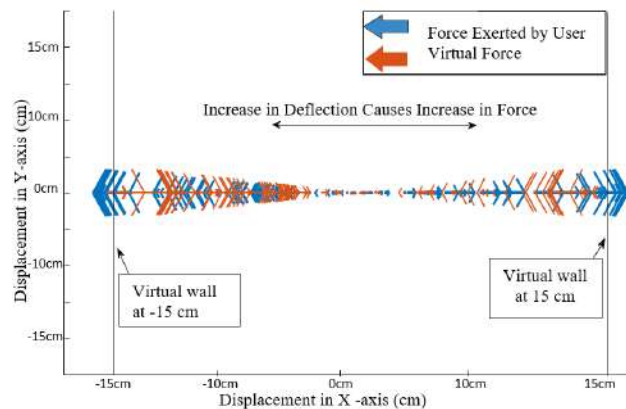


Figure 18: Control Column Forces at different Air Speeds

These stick forces are bases of flight envelope protection systems and control loading systems that are required in flying by wire aircraft which is an important concept to learn for the safe operation of modern aircraft. By using the device this concept of how control stick forces help in controlling the aircraft and the variables on which these forces depend can be introduced to students learning aircraft controls. In this example a simple elevator of a known cross-sectional area is simulated, the forces that are simulated to the user depend upon the airspeed, elevator angle, and the air density. Here the elevator deflection is correlated to the movement of the device handle on the x-axis, the larger the movement the greater the deflection. In one part of the simulation, the air speed of the aircraft is low, so the stick forces exerted by the user to move the elevator are also low, but the movement is restricted by a virtual wall as analogous to keeping the aircraft in operational boundaries. These boundaries are the most basic part of understanding flight envelope protection systems, as shown in Figure 17.

The other part of the simulation shows an increase in speed and thus the increase in forces acting on the user. The stick never reached the virtual wall or the boundary of operation in this part of the simulation because of the high stick forces preventing the pilot from overstressing the control surface. This is analogous to the control loading of aircraft control surfaces, as shown in Figure 18.

#### IV. CONCLUSIONS

The device developed in this research offers significant advantages over existing pedagogical devices by enabling wide-ranging and immersive educational haptic scenarios. It is easy to assemble using widely available surplus parts, making it accessible and cost-effective for educational institutions. The device can be easily modified and configured to meet various educational requirements, offering flexibility in application. By maintaining an increased workspace without compromising force feedback and transparency, the device overcomes common limitations faced by traditional educational haptic devices. The device successfully demonstrated its capabilities in various haptic scenarios through simulation and physical testing, showcasing its potential as an effective educational tool. In addition to its educational uses, the control system developed in this work can be used in medical haptic devices, providing an affordable option with fast reaction times and easy operation. By adapting the system for medical usage, this ongoing effort aims to improve the efficiency and accessibility of healthcare technologies. For future research, enhancing the device's capabilities can be explored to develop a higher DOF version of the device to expand its application and versatility in educational settings. Additionally, explore the feasibility of mass production and distribution of the device to make it widely available to educational institutions worldwide. Moreover, investigate the integration of the device into online courses to provide an

immersive learning experience, particularly in response to the growing need for remote education solutions.

#### List of Abbreviations

SEA Series Elastic Actuation  
MOOCs Massively Open Online Courses  
DOF Degree of Freedom  
AR Augmented Reality

#### Declarations

##### Availability of Data and Material

The datasets used and analyzed during this study are available at Google Drive. Access will be granted upon reasonable request.

##### Competing Interests

The authors declare that they have no competing interests.

##### Funding

This research did not receive external funding.

##### Authors Contributions

Research, experiments, data analysis, and manuscript writing were all done by MS. HU oversaw the project, offered directions during the research, and confirmed that the findings and conclusions were accurate. The final text was reviewed and approved by all authors.

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