

# Teaching Mechanism Dynamics using a Haptic Device

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**Abstract**—Haptic devices play a significant role in conveying physical feeling of real objects through their computer simulation with force feedback. Apart from their standard applications in medical surgery, gaming, entertainment etc., teaching dynamics and control with haptic devices has been gaining popularity. Educational haptics has been recognized as an effective method to improve the understanding of a learner about the physics of a system, say, a mechanism, which does not exist in reality or is difficult to realize physically. The effect of change in inertial and kinematic properties of the mechanism is reflected and conveyed to the learner in the form of torque at the actuated joints. In this work, we demonstrate how a simple low cost 1-DOF (Degree of Freedom) haptic device can be utilized in teaching a typical course on dynamics of mechanisms. The methodology can be extended to higher-DOF systems as well, to understand the effect of kinematic and inertial properties of actual mechanisms, even though they do not physically exist.

**Keywords** – Education Haptics; Teaching Mechanisms; Teaching Dynamics

## I. INTRODUCTION

Haptics refers to the technology that enables physical interaction with virtual environments through force-feedback. A special robotic device referred in haptics literature as haptic device with manipulandum, is used to convey the feedback forces. The term manipulandum distinguishes the haptic device from a typical robot which is referred to as manipulator. Manipulandum is associated to a haptic device since it is operated or manipulated by a human operator rather than a manipulator which manipulates without needing a human operator for performing any activity.

Haptics has greatly changed the way we perceive things in the virtual environment. Apart from visual and audio feedback, haptics enhances communication with the virtual environment by enabling physical feedback in the form of forces and torques. This has been possible mainly due to the advent of high speed computing facilities that allowed virtual environment be stably perceived with a haptics device.

Applications of haptics are exponentially increasing even in newer fields like nanotechnology [1], etc. In particular, haptics has been used in studies of the behavior of human

brain by carrying out various psychophysical studies. In training and rehabilitation, haptics has played an important role in the contemporary techniques to improve the patient's performance [3]. The type of forces, their quantity, directions etc. could be varied easily in the software without making any changes in the hardware. Other applications include training medical residents using virtual surgery, thus, avoiding the use of rough estimation techniques like cadavers and plastic models [2]. In addition, the user experience has been improved in applications like virtual flight simulators, virtual excavation, etc. Various gaming and entertainment devices have already been developed incorporating haptics technology in them.

Apart from the above major applications, haptics has been recently recognized as an effective tool in teaching various physical concepts to the students in a class-room. It has been quite agreed upon that the VR (Virtual Reality) based teaching is generally seductive, invokes attention, and makes students learn based on the context that they finally could apply wherever needed. In a more specific case, haptic interface has been recently used for teaching dynamics to mechanical engineering undergraduate students as reported in [4], [5], [6]. The numerical results of otherwise simulations and tests were converted into forces/torques that the user could perceive physically, in a way enhancing the plots and graphs. In [7], authors used a haptic device for teaching mechanisms to the under-graduate students of the theory of mechanisms and machines course. In order to increase the realism of the simulation, the authors collocated virtual mechanism model with the user's real hand (attached to crank/haptic device) using augmented reality techniques and see-through featured head mounted display [7]. In [8], the authors carried the dynamic simulation of virtual mechanisms with haptic feedback using the industrial robotics equipment. In their experiments, a PUMA robot was explored for its feasibility as a haptic device. An admittance control paradigm was used in their analysis. Teaching mechanism dynamics with a haptic device is thus an emerging area of research. We believe that this type of teaching can aid strongly in improving the perceptual capability of a learner and would encourage strong interest among the students to learn dynamics.

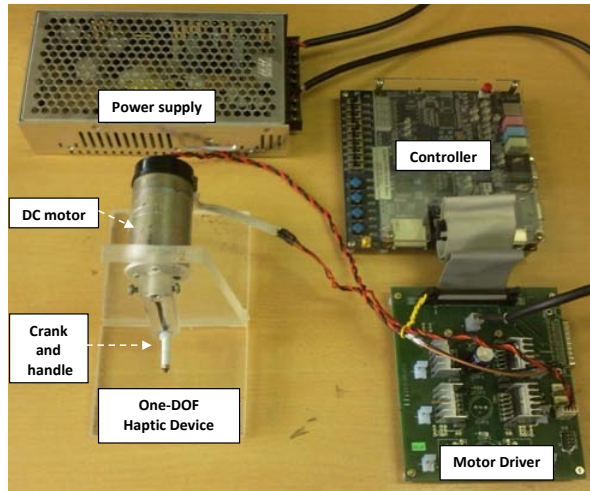


Fig. 1. one-DOF haptics setup

In this paper we present our study which is aimed at analyzing the effect of mass on the various capabilities of a human hand using our custom built simple haptic device. Towards that we present some experiments with a compound pendulum and a four-bar mechanism as a part of our preliminary work. The rest of the paper is organized as follows: Section 2 details the one-DOF haptic setup, Section 3 discusses the components of mechanism dynamics simulation while Experiments are detailed in Section 4. Results and discussions are provided in Section 5 with Conclusions in Section 6.

## II. ONE-DOF HAPTICS SETUP

We developed an acrylic based low cost one-DOF haptic device, as shown in Fig. 1, that utilized a DC motor with collocated optical encoders. The collocation in actuator and sensor is usually preferable for its ease in placement and avoidance of play. A crank was attached to the motor axis directly without any gear in between. Gears are usually avoided in haptic devices on account of backlash and high back-drive friction.

Digital signals from the optical encoder are sent to the controller (FPGA - Field Programmable Gate Array) that utilizes a quadrature decoding algorithm along with a counter module to calculate the current position of the device. This positional information from the controller is then sent to the PC via an enhanced parallel port (EPP). A communication protocol is written in FPGA to communicate with the PC which runs the dynamic simulation of the mechanism to be taught.

A VC++ program is written on the PC to communicate with the controller which sends and receives signals through EPP. Usually position commands are received by the PC and the necessary actuation (torque) commands are sent to the controller. This bidirectional information is communicated at a very high speed ( $\sim 10$  Mbps). A graphical display of a

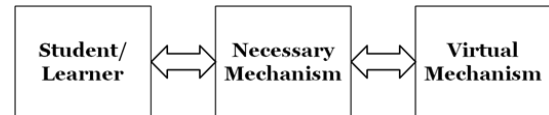


Fig. 2. Paradigm of mechanism dynamics simulation

system was created using OpenGL libraries in VC++. The positional information was taken as input to the graphics which generates the necessary animation accordingly. These animations are displayed on the PC instantaneously and in accordance to the motion of the haptic device. On the other side, the FPGA receives necessary torque command from the PC and converts it to an equivalent PWM signals along-with the suitable direction of applied torque. The motor driver developed using LMD18200 IC (Texas Instruments), accepts the PWM input, direction of rotation and the brake command from FPGA controller, and provides necessary voltage to the motor terminals.

## III. MECHANISM DYNAMICS SIMULATION

The paradigm of our experiments is shown in Fig. 2. We used a custom made one-DOF haptic device detailed in Section 2. A similar mechanism or any mechanism with the same number of DOF as of the haptic device (here,  $\text{DOF} = 1$ ) can be realized. The virtual mechanism can be controlled online using the positional commands from the controller. The active joints of the mechanism can be directly controlled from the input commands while the passive joint motion, usually, in a closed-loop mechanism, is achieved by solving the loop-closure constraints. The expressions for passive joint variables are written as a function of active joint variables. Based on a particular set of kinematic parameters of any mechanism, a corresponding virtual mechanism can be easily built/ modeled in OpenGL environment using the VC++ platform. The virtual mechanism was displayed on the monitor screen that provided the visual feedback of the actual motion of the mechanism. As the user manipulated the haptic device, corresponding animation was displayed on the computer screen.

An interesting feature of our work is to employ dynamics of the mechanism in the haptic device. In other words, we endeavour to teach a learner the effect of variation in the kinematic and dynamic properties of the mechanism on the required torque to drive it. Of the simplest of these mechanisms is a compound pendulum. In fact, it acts as a basic example to demonstrate the philosophy behind this work.

Figure 3 represents a line diagram of a compound pendulum (i.e., one link arm with a revolute joint) hinged about the origin  $O$  where  $(X, Y)$  represents the base coordinate frame, while  $(X_1, Y_1)$  is the coordinate frame attached to the end of the compound pendulum. The length of the pendulum being equal to  $a$ , i.e.,  $op = a$ , while  $c$  represents the location of centre of mass of the pendulum from the origin. The angle

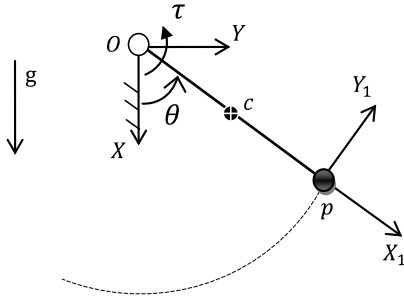


Fig. 3. A compound pendulum

$\theta$  is the joint position from vertical X-axis, as shown in Fig. 3. Equation of motion of the compound pendulum can be easily derived either from the Euler-Lagrange or Newton-Euler equations of motion. The same is given as

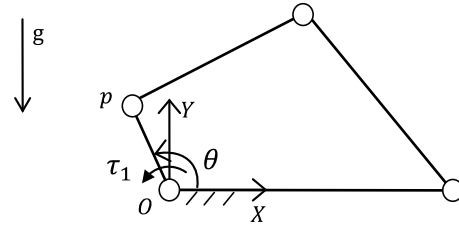
$$\frac{1}{3}ma^2\ddot{\theta} + \frac{1}{2}mga \sin \theta = \tau \quad (1)$$

where  $m$  is the mass of the pendulum or the arm,  $a$  is its length,  $\theta$  is the angle of rotation,  $g$  is the acceleration due to gravity, and  $\tau$  is the driving torque required to move the link. Equation (1) gives us the value of the dynamic torque for a particular joint position  $\theta$  and joint acceleration  $\ddot{\theta}$ . In this work, we try to simulate this torque at the motor corresponding to the motion of the haptic device. This type of setup enables us to convey the feeling of the effect of change in length and mass on both the static and dynamic torque of the pendulum. Based on a set of inertial and kinematic parameters of the pendulum, the user would feel dynamics through the haptic device. In this preliminary work, we however simulated only the static torque component of (1). This is based on the assumption that the operator would hardly accelerate the pendulum.

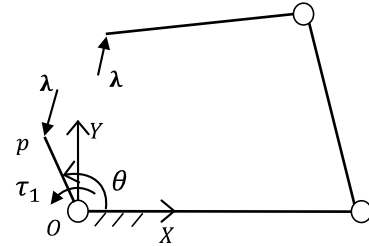
We also attempted to study one closed-loop mechanism, namely, a four-bar mechanism. The four-bar mechanism represents a simplest closed-loop mechanism, which is shown in Fig. 4(a). The mechanism consists of four joints and has 4 links (including ground), hence, according to the Grashoff's criteria, the DOF of the system is  $3(n-1)-2j = 3(4-1)-2(4) = 1$ . Therefore, the crank of the current haptic device in Fig. 1 can act as the driving link (or crank) of the four-bar mechanism denoted with  $op$ . So, for a particular set of kinematic parameters satisfying Grashoff's criteria, the variation in its inertial as well as the kinematic parameters can be reflected as the variation of the driving torque at joint  $O$ .

It must be noted that the closed-loop systems generally consist of dependent as well as independent joint variables. These joint variables are related by loop-closure constraints that represent the relative motion of each link with the other link in a particular loop. These loop-closure constraints at the velocity level are given as

$$\mathbf{J}\dot{\mathbf{q}} = 0 \quad (2)$$



(a) closed-loop



(b) open-loop after introducing cut

Fig. 4. A four-bar mechanism

where  $\mathbf{J}$  represents the mechanism Jacobian and  $\dot{\mathbf{q}}$  represent the vector of joint rates. The dynamic equation of motion for the closed-loop systems is usually formulated by the method of cuts. A closed-loop system is cut at appropriate locations (usually joints) to convert it into an open-loop system. The place of cut is replaced by appropriate Lagrange multipliers  $\lambda$  that represent the otherwise constraint forces in the closed-loop mechanism, as shown in Fig. 4(b). The dynamic equations of motion for the four-bar mechanism can then be written as

$$\mathbf{I}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} = \tau^E + \tau^G + \tau^\lambda \quad (3)$$

where  $\mathbf{I}$  represents the generalized inertia matrix,  $\ddot{\mathbf{q}}$  is the vector of joint accelerations,  $\mathbf{C}$  is the matrix of convective inertia terms,  $\tau^E = [\tau_1 \ 0 \ 0]^T$  represents the vector of driving torques,  $\tau^G$  represents the vector of gravitational torques and  $\tau^\lambda = \mathbf{J}^T \lambda$  represents the vector of constraint wrenches due to cut joints. For a planar mechanism  $\lambda = [\lambda_x \ \lambda_y \ 0]^T$ . Again assuming here that the subject rotates the crank slowly, the expression in (3) would reduce to

$$\tau^E + \tau^G + \mathbf{J}^T \lambda = 0 \quad (4)$$

Equation (4) represents a set of three equations that are used to solve the three unknown quantities,  $\tau_1$ ,  $\lambda_x$  and  $\lambda_y$ . Applying the method of substitution, the expression for these variables can be written in VC++ environment and the required torque  $\tau_1$  can be calculated. The driving torque

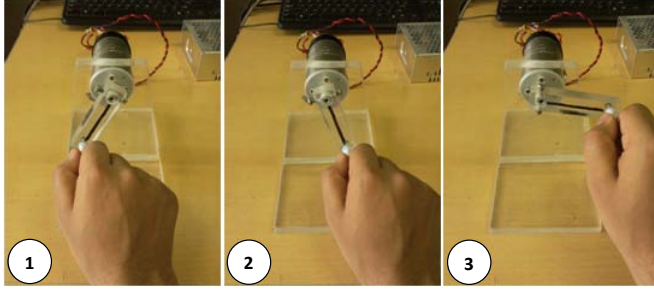


Fig. 6. User rotating the crank anti-clockwise

$\tau_1$  in Fig. 4(b) therefore consists of two components: one due to the mass of crank  $op$  and the other due to Lagrange multipliers at joint  $p$ . The same is given as

$$\tau_1 = \frac{1}{2}mga \cos \theta - \frac{1}{2}(a \sin \theta)\lambda_x + \frac{1}{2}(a \cos \theta)\lambda_y \quad (5)$$

where  $m$ ,  $a$  are the mass and length of the crank  $op$  of the four-bar mechanism respectively.

#### IV. EXPERIMENTS

In all our experiments, we made sure that the user was made familiar with the setup and its working first. This would avoid possible damage to the device during the experiments and ensure smooth operation. In the experiments, the user was asked to look into the graphical display (animation) and avoid looking at the actual device (Fig. 1). Figure 5 shows the OpenGL model of the pendulum and various four-bar mechanisms displayed on the screen of PC.

The experiments and evaluations started with a one-DOF simple pendulum shown in Fig. 5(a). The experiment consisted of the user holding the handle of the crank attached to the DC motor. The user was asked to hold the crank's handle with the dominant hand (usually Right Hand in our experiments). The user was then asked to rotate the crank from an initial position (vertical) anticlockwise till the pendulum on the screen reached the horizontal position. Fig. 6 depicts the user rotating the crank of one-DOF haptic device anticlockwise. The user was asked to make himself conscious of the feeling of the torque applied by the motor during the trial. Next, the user was asked to take the crank back to its original position. A change in the mass of the pendulum was made now, i.e., the mass of the pendulum was increased to maximum possible mass (limited by DC motor's stall torque). The simulation was again run and the user was asked to again lift the crank from vertical position to the horizontal position. The feelings of the user were enquired and the position of the user's motion and the torque thereby were plotted. A change in length was also tested by changing the virtual length of the pendulum to twice the initial length. This however would have similar effect on the torque output since, according to (1), both mass and length are directly proportional to the torque, as  $\ddot{\mathbf{q}} = 0$ .

As a practical application to this study, we conducted a

line following experiment with the pendulum. The idea of a colleague *Mr. Rajeevlochana C.G.* is acknowledged, who actually proposed this application. As a preliminary study, the user was asked to follow the animated line as shown in Fig. 7. The line could be given any predefined trajectory in the program. We gave a simple harmonic motion trajectory to this line on screen. Each trial was conducted for about 28 seconds that would actually be taken by the animated line to complete one and a half cycle of the oscillation. The mass of the virtual pendulum was varied from maximum to minimum for a set of two conditions. The maximum mass was restricted by the stall torque of the DC motor whereas the minimum would be restricted by the apparent mass of the actual device and the friction. The subjects were asked to follow the motion of animated line closely with the virtual pendulum. We plotted the desired trajectory with the actual one of the subject.

The next section details the experimental results and discussions.

#### V. RESULTS AND DISCUSSIONS

Figure 8 shows the position input and torque output plots of the virtual pendulum in a case of lifting it to a particular position and then letting it fall free. A heavy and a light pendulum were considered. As seen from the figure, when the pendulum was lifted slowly towards the horizontal plane, the torque due to gravity increased to maximum which corresponds to the value from (1), i.e., maximum gravitational torque at the horizontal position. When it was let free, an oscillatory behavior on account of the pendulum falling freely under gravity was noticed. The oscillations lasted for longer time in heavier pendulum compared to the pendulum with lighter weight, as expected. Figure 9 shows the position and torque plots for the pendulum when given a one full rotation by the subject. As seen from the figure, the effect of pendulum mass on its corresponding motion was observed. As the heavy pendulum was rotated

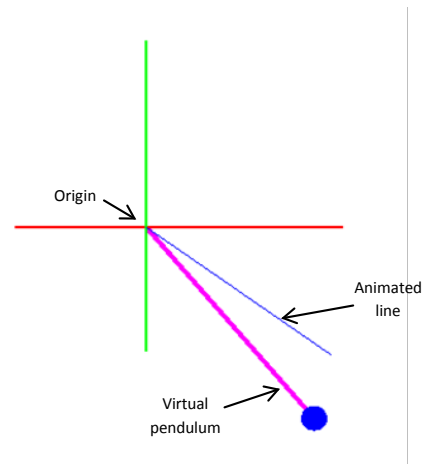


Fig. 7. Animation of one-DOF device for a line following experiment

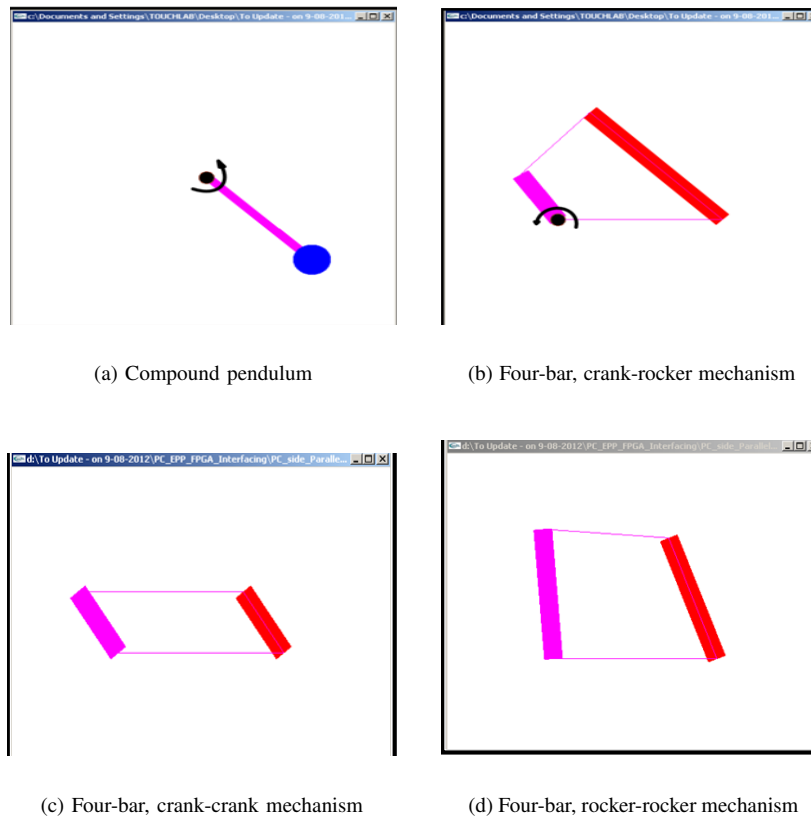


Fig. 5. OpenGL display of one-DOF pendulum and several 4-bar mechanisms

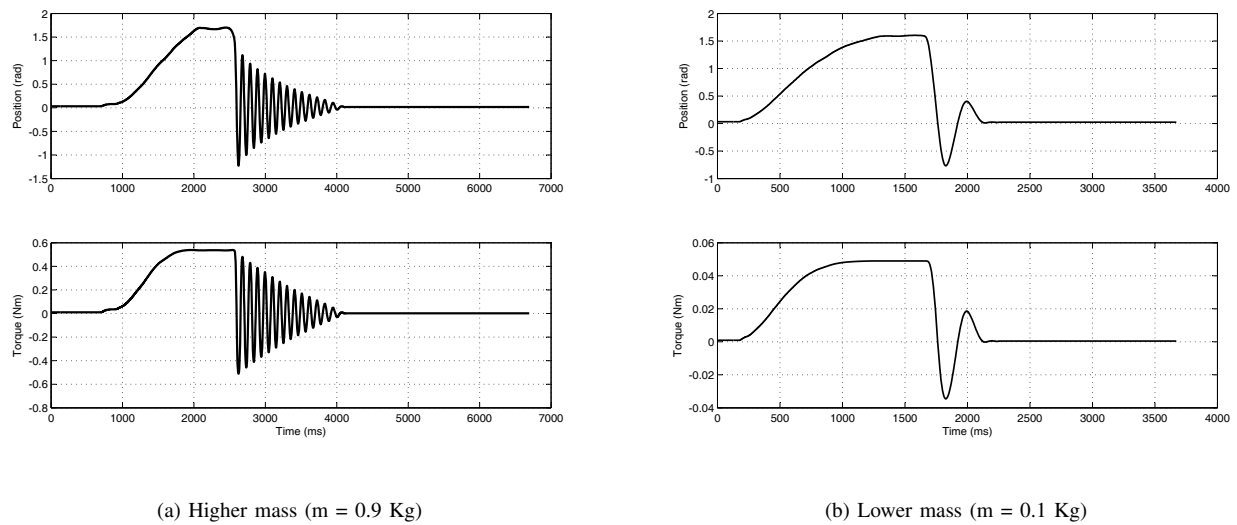
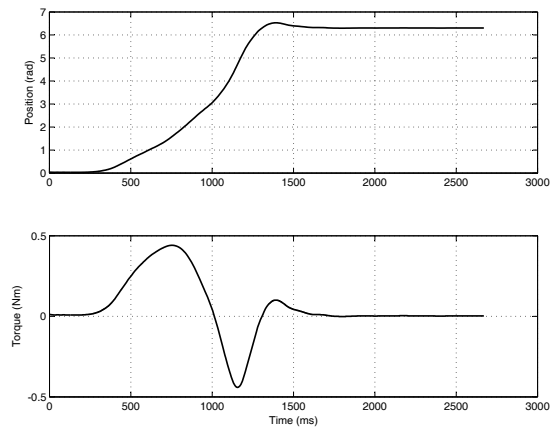
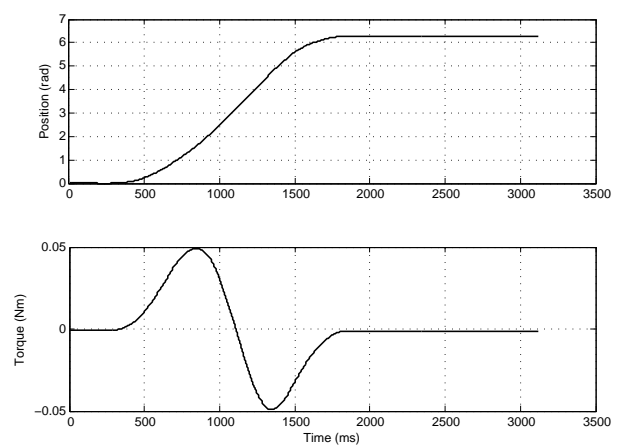


Fig. 8. Position and torque plots for pendulum's free fall motion

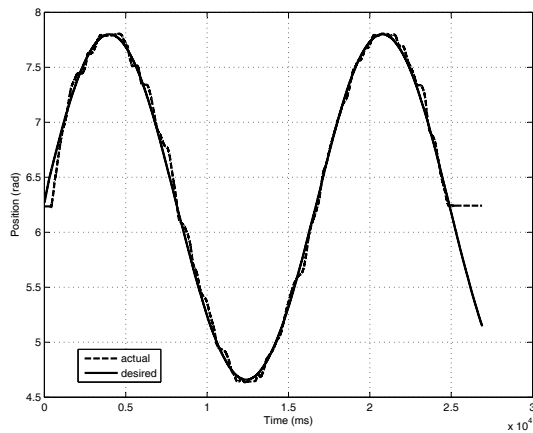


(a) Higher mass ( $m = 0.9 \text{ Kg}$ )

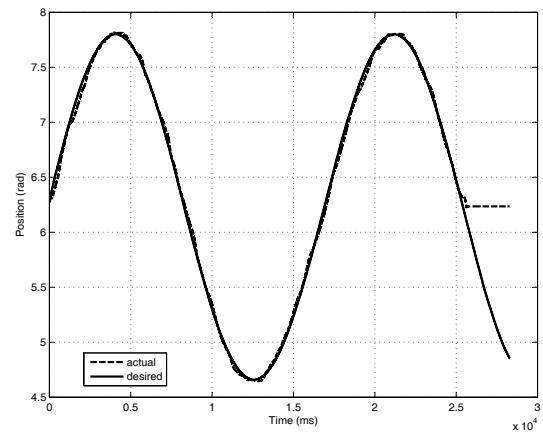


(b) Lower mass ( $m = 0.1 \text{ Kg}$ )

Fig. 9. Position and torque plots for full rotation of the pendulum



(a) Initial trial

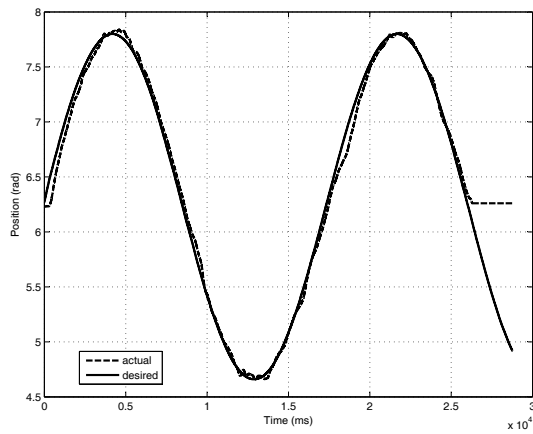


(b) Trial after 5 attempts

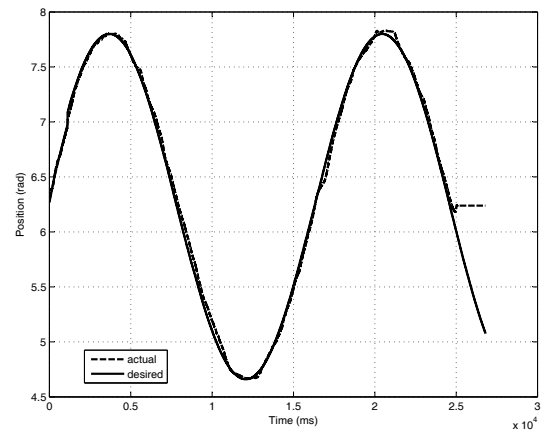
Fig. 10. Plots of position of the pendulum in a line following experiment with lower mass

beyond the top vertical position, the pendulum motion was faster compared to the lighter pendulum. The effect could be compared from the position and torque output for the two pendulums. Hence, the subjects could feel the effect of the mass of different pendulums without actually utilizing/constructing so many pendulums. For the line following experiment, the trajectory plots for four combinations were plotted: 1) initial trial was with low mass of the virtual pendulum; 2) subsequent trial after 5 attempts with low mass; 3) initial trial with high mass of the virtual pendulum; 4) subsequent trial after 5 attempts

with high mass. They are plotted in Figs. 10 and 11 for the low and high masses, respectively. As could be seen from Figs. 10, 11, the subject performed better on subsequent trial after 5 attempts. Note that this study is at a preliminary stage, however the results are similar to the study carried out in [9], where the effect of haptic feedback on the learning capability of the students was investigated. In fact such study has a good application in physiotherapy rehabilitation, where the patient could be asked to follow certain trajectories with different masses of the virtual pendulum and performance assessment could be carried

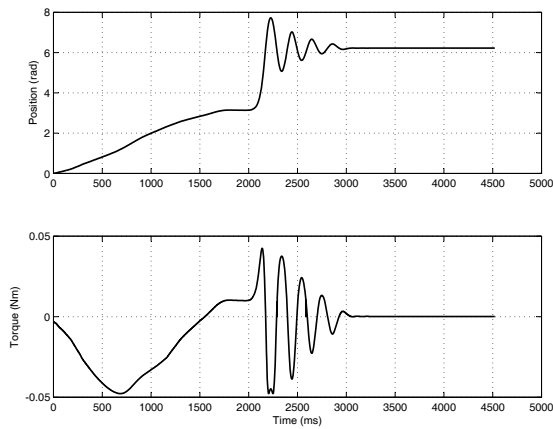


(a) Initial trial

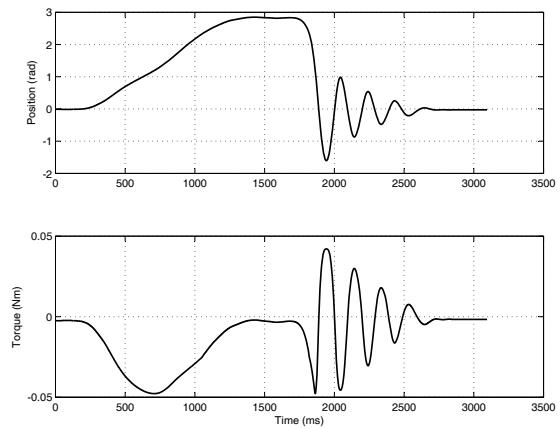


(b) Trial after 5 attempts

Fig. 11. Plots of position of the pendulum in a line following experiment with higher mass



(a) full rotation ( $m = 0.9 \text{ Kg}$ )



(b) quarter rotation ( $m = 0.1 \text{ Kg}$ )

Fig. 12. Position and torque plots for four-bar mechanism simulation

out.

Similarly, some initial experiments with a 4-bar mechanism were carried out, as a part of this work. The motion of the crank was mapped to the motion of the haptic device. The commanded torque on the crank  $\tau_1$  due to gravitational forces on the mechanism was computed using (5). Figure 12(a) depicts the position and corresponding torque plots of the four-bar mechanism (Fig. 5(b)), when the crank was rotated from vertically down position to the vertical up position (anticlockwise) and let fall freely under gravity. As seen from the figure above, the commanded torque

was positive at the vertically up position and hence the mechanism moved anticlockwise (under gravity) when left free. This effect is also depicted from the increase in the position value of the crank. Similarly, in Figure 12(b), the crank was rotated (anticlockwise) from the vertically down position to a point where the commanded torque was almost zero. This is seen from the torque plot in Fig. 12(b), where the commanded torque is nearly zero at around 1.5 seconds. Further the crank was let fall freely under gravity (clockwise). This is seen from Fig. 12(b), where the position and torque values decrease after around 1.7

seconds depicting the motion in clockwise direction. In addition, the kinematic parameters of the four-bar mechanism can also be varied based on the Grashoff's criteria and different configurations could be tested. The inertial parameters of each link could also be easily varied by changing their values in the program.

## VI. CONCLUSIONS

We have been able to show how a system's physical behavior can be displayed using a haptic device. In particular, we have shown the effect of variation in mass of the pendulum on a low cost one-DOF haptic device. It is concluded that the integration of computer simulation based on the equations of motion and a haptic device would play an important role in the teaching/learning process of mechanisms. The present research is certainly a contribution towards that direction. In future, we intend to consider more mechanisms and study the effect of variation in their inertial and kinematic properties on the learning capabilities of the subjects.

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