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One Degree-of-Freedom Haptic Device

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Abstract

Over the years, haptics has gained popularity as an additional feedback to enhance human experience of the environment. The extensive applications of haptics include virtual reality simulation, medical, education, manufacturing and rehabilitation. Many types of haptic devices have been developed to provide the variety of tactile feedback required for different applications. This paper describes the design and development of a low cost haptic knob, with only one degree of freedom, for use in rehabilitation or training hand pronation and supination using a microcontroller. This haptic knob can be attached with different form of end-effectors to cater for various training objectives and hand sizes or orientation.

Keywords: Microcontroller, haptic device, real time, rehabilitation.

1. Introduction

SCIENTISTS have conducted research on haptics for many years. The surge of interest in haptics technology was mainly due to the development in virtual reality systems, where haptics was used to enhance user experience by providing tactile feedback. Currently, haptic technology is used for many other applications, in particular, education and training [1,2], skill acquisition in surgery [3], rehabilitation [4-8], exploration of environments [3,9], manufacturing and design. Students were able to grasp scientific theories much easier when taught with the help of haptic devices, besides the common audio-visual aids, due to the combination of multiple modalities to represent information. Besides virtual reality and education, haptics is now widely used for rehabilitation for example, Gentle/S [4] uses Haptic Master to provide the haptic feedback during arm training. Tele-haptics provides a safe method to explore hazardous or remote environment [3, 9]. Haptic technology relies on the use of haptic interfaces to relate tactile information between human and computer [10]. From the first attempt of force feedback for robotic tele-operation by Goertz in 1954 [11], to light-weight force feedback wearable glove by Burdea in 1992, haptic devices have come a long way. Now, commercially available haptic devices include simple and relatively cheap consumer hardware equipped with motors and sensors, such as joysticks and steering wheel with force feedback. The more sophisticated PHANTOM devices [12] are commonly acquired for medical and scientific research, product design, computer-based sculpturing and gaming. The Haptic Master [4] has been widely used as a rehabilitation device for stroke survivors. Research-based haptic products are generally very costly, and may not be easily modified to cater for various applications, paving the way for cheaper alternatives in the form of custom-made haptic interfaces for specific applications.

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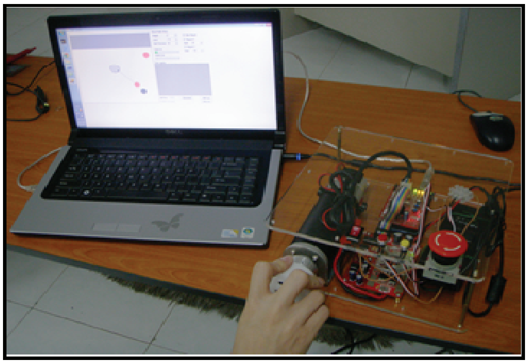
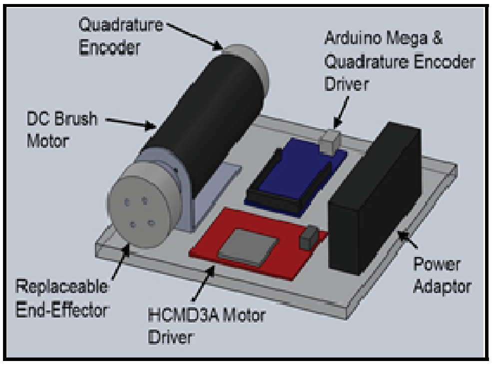
(a)  (b) 

Fig. 1. (a) Low cost haptic knob and (b) CAD drawing

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This paper presents the design, development and control strategy of a low cost haptic knob as shown in Fig 1(a). The haptic knob is intended to be used for training of hand pronation and supination, as part of robotic rehabilitation exercises for stroke patients. The knob can be replaced with other forms of end effectors, using a coupling, to train for activities of daily living involving the hand, such as eating using a spoon or drinking from a glass. Ludovic has previously designed a haptic knob for hand rehabilitation [13], while Yeong has developed an upper limb rehabilitation robot called ReachMAN that uses only 1 degree of freedom (DOF) to train hand pronation and supination [14]. Both systems used the Maxon RE40 motor with gear reduction to create haptic capability. Although this project will adopt similar design concept utilizing a single motor as actuator, a different motor without gear reduction will be selected to reduce cost. The justification of hardware, control algorithms and graphical user interface (GUI) for the system are presented in the following sections.

2. System Design

2.1. Hardware

This project aims to develop a simple haptic device for training hand pronation and supination. To generate the haptic capability for this device, the selected motor must meet specific conditions. The motor torque of 1.5Nm is sufficient for rehabilitation purpose [13,14]. The motor should have the capability to record the position, has low inertia and small in size. Fig 1(b) shows the Computer Aided Design (CAD) drawing of the proposed design. A DC motor equipped with encoder is chosen for this project. The motor is attached firmly to a base. Motor driver, controller and other components are attached to the same base allowing small size design and portability. Different handles or knob can be interchanged easily by using a custom-made coupling attached to the DC motor.

2.2. Control

Most of the existing robotic rehabilitation devices with haptic capability use a computer with Labview Real-Time (RT) or Matlab RT for real time processing, which incur higher cost. This project proposes the use of a low cost solution with a microcontroller as the main controller, without jeopardizing the real time control. Microcontroller will function as the main controller to process the motor control commands for real time applications and the GUI running from a separate laptop computer (PC) will be the display for virtual reality output and setup input.

3. Implementation

3.1. Hardware

Arduino Mega is the main controller for the system, which communicates with PC for the GUI virtual environment output and also environment setup input (Weight, StickLength and WallThickness). For motor control, Arduino Mega interfaces with a high current motor driver (HCMD3A) for the motor Pulse Width Modulation (PWM) and direction control, while the Quadrature Encoder Controller is used for the motor position sensing.

3.1.1. Industrial Servo Motor

The motor chosen for the haptic knob is a DC brush motor without gear reduction, which is used as industrial servo motor. The reason for using DC brush motor without gear reduction is to minimize friction caused by the gear head and thus maximizing the virtual reality tactile sensation felt by a user. This industrial servo motor comes with a built-in quadrature encoder system for position sensing.

3.1.2. Arduino Mega

The Arduino Mega 2560 is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analogue inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button [15]. The USB connection creates a virtual COM Port on the PC for UART communication link between Arduino Mega and PC.

3.1.3. Laptop PC

Function of Laptop PC in the system is to run the GUI for virtual reality output and environment setup input for the haptic knob. The updating of the display is run from the PC to separate it from motor commands processing at the microcontroller, to ensure faster response rate of the motor for real time haptic applications. Display rate is being set to lower frequency, at about 50Hz because human sensorial capabilities impose much lower refresh rate for visual feedback than for haptic feedback.

3.1.4. HCMD3A Motor Driver

HCMD3A is a high current DC brushed motor driver that supports up to 40A peak current [16]. This enables Arduino Mega to directly control the motor using a simple 3-pin interface: Direction, PWM and Enable.

3.1.5. Encoder & Quadrature Encoder

The built-in encoder support Quadrature Encoder Output that allows up to 4000 step per revolution for precise position sensing of the motor movement in both directions. To efficiently read the position of the motor, a Quadrature Encoder Controller has been designed using a microcontroller (PIC18F2431) for the signal processing from the Quadrature Encoder. The reason of using a separate controller for the Quadrature Encoder signal processing is to reduce the processing burden on Arduino Mega.

3.2. Control Algorithm

Fig 2 shows motor control algorithm block diagram where three different models were implemented in the setup which were Weight Control, Wall Control and Magnet Control. The resulting motor command, MotorPWM is given by following:

$$MotorPWM = WeightControl + WallControl + MagnetControl \tag{1}$$

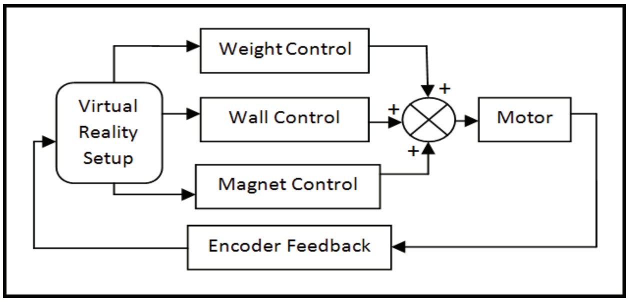


Fig. 2. Motor control algorithm diagram

3.2.1. Weight Control

Fig 3(a) shows the weight control diagram for haptic knob and its equation is as shown in Equation (2). KW is the Weight Control gain that determine how much Weight Control affect the output, Weight is the virtual weight attached to the haptic knob that can be configure under haptic knob GUI, Lever is the length of the lever connecting the weight to the haptic knob, θ is the angle of rotation of the knob, derived from the Quadrature Encoder Feedback.

(a) (b)

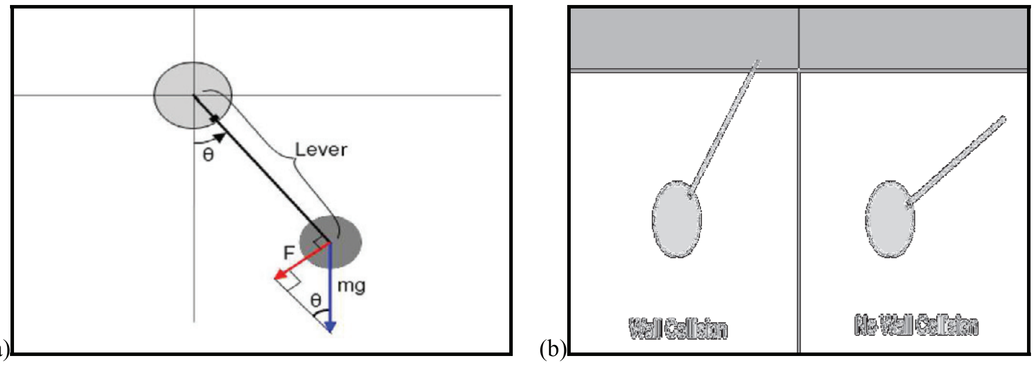


Fig. 3. (a) Weight control diagram and (b) Wall control with and without collision.

$$WeightControl = K_W \times Weight \times Lever \times \sin(\theta) \quad (2)$$

3.2.2. Wall Control

$$WallControl(t) = \begin{cases} K_P e(t) + K_D \dfrac{d}{dt} e(t) & , \; With \;\; collision \\ 0 & , \; No \;\; collision \end{cases} \quad (3)$$

Fig 3(b) shows the Wall Control with and without collision and its equation is shown as Equation (3). KP is the Wall Control proportional gain. This constant is tuned using trial and error method. e(t) is the error on the wall collision, derived from the error between the tip of the Lever and the wall position. KD is the wall control derivative gain. This constant is tuned using trial and error method.

3.2.3. Magnet Control

Fig 4 (a) shows the relationship between the Length, Lever, α and θ, for Magnet Control. The 270 value is from the GUI numerical up down value in the Visual Studio software. The equations for magnet control are shown in Equation (4)-(9). Fig 4 (b) shows the relationship between β angle, F and FM. According to Newton's universal law of gravity [17], the attraction of the magnetic force can be simulated using Equation (4), this is because, each particle in the universe exert a gravitational on each other particle. Where G is gravitational constant (6.673x10-11Nm2kg-2), M1 and M2 is the mass of the object 1 and 2 respectively and Length is the distance between two objects.

$$F_M = G\frac{M_1 M_2}{Length^2} \tag{4}$$

Where,

$$Length = \sqrt{Lever^2 + 270^2 - 2 \times Lever \times 270 \times \cos(\theta)}$$

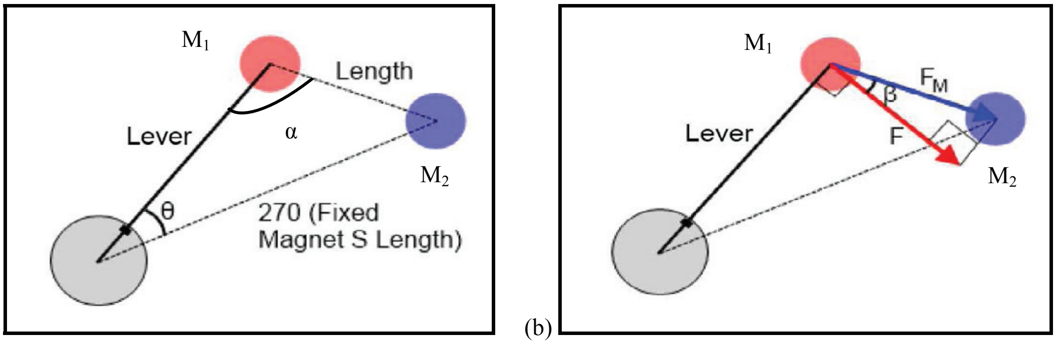


Fig. 4. (a) Magnet control Length and α and (b) Magnet control Forces and β.

To simplify the algorithm, M1 and M2 assumed to be one. Thus, the new resulting FM is as follow:

$$F_M = G\frac{1}{Length^2} \tag{5}$$

Equation (5) represents the attraction between two objects. To implement the magnetic attraction and repulsion using a DC motor, a representative value will be calculated to fed to the motor called as MagnetControl. the equation is as follow:

$$MagnetControl = F \times Lever \tag{6}$$

Where,

$$F = F_M \times \cos(\beta) \tag{7}$$

$$\beta = \alpha - 90° \tag{8}$$

$$\alpha = \arccos\left(\frac{Lever^2 + Length^2 - 270^2}{2 \times Lever \times Length}\right) \tag{9}$$

3.3. Haptic Knob GUI

Fig 5(a) and (b) show the Haptic Knob GUI descriptions. All variables to control the haptic knob will be transferred from the GUI to Arduino Mega whenever there are changes to these variables at the GUI. At the Arduino Mega, these variables will be used in the control algorithm that will be run every 4ms under interrupt powered routine for stable processing result, and the output of the MotorControl value will be fed to the Motor PWM.

3.3.1. Virtual Reality Setup Variable

Under Virtual Reality Setup, there are few variables that are configurable under the GUI which are Weight Setup, Lever (length of the mass less rod), Wall Thickness, Main Magnet, Magnet North Pole, Magnet N angle, Magnet South Pole, Magnet S angle.

3.3.2. Communication Between Laptop PC and Arduino Mega

Arduino Mega communicates with the PC by sending and receiving standardized data packet through UART. The basic data packet consists of Start Bytes, ID, Length, Data(s) and Checksum. Table 1 shows the communication protocol between laptop PC and Arduino Mega. Arduino Mega will send a data packet consist of the Micros value, Encoder reading, and Motor PWM to PC to be displayed on the Haptic Knob GUI every 4ms. Conversely, data packet from PC to Arduino Mega consist of all the Virtual Reality Setup variables for the Motor Control processing. This data packet from PC to Arduino Mega is sent whenever any of these Virtual Reality Setup variables is changed under the GUI.

Table 1:Comunication between laptop PC and Arduino Mega protocol.

Start Bytes	ID	Length	Data(s)	Checksum
Two 0xFF as the start byte	ID for the receipient	Length of the Data(s) + Checksum	Data(s)	1 Checksum byte for the verification

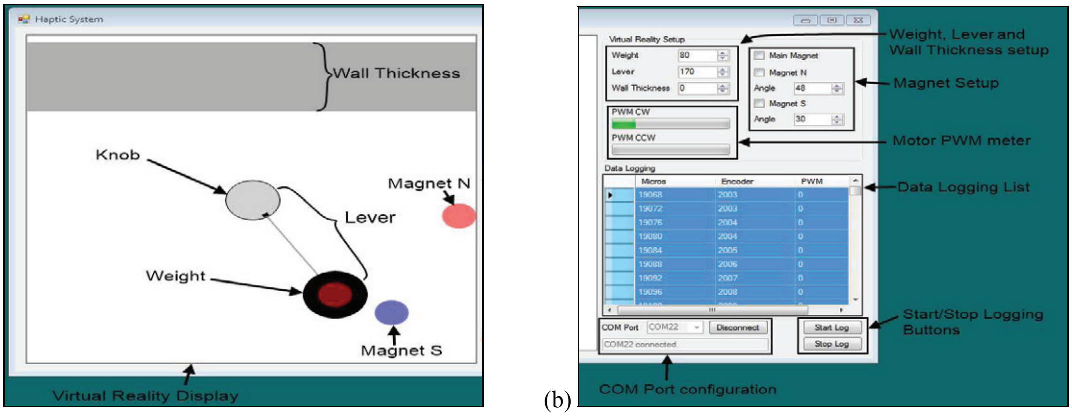
(a) 

Fig. 5. (a) Haptic Knob GUI description Part I and (b) Haptic Knob GUI description Part II

3.3.3. GUI Data Logging

Fig 5(b) shows the data logging for Haptic Knob GUI. The Start Log and Stop Log buttons controls the start and stop of the data logging, and the logged data will be listed out on the GUI. The data logging of the GUI will automatically log at each incoming data from Arduino Mega every 4ms. The logged data for the Haptic Knob are Micro (time in mili second), Encoder value and PWM value.

4. Results

The developed haptic knob supports 4 types of virtual reality setup variables which are Weight, Lever, Wall Thickness, and Magnets configurations. The motor control processing by Arduino Mega will change the response of the knob according to the values given to these setup variables. The motorized knob provides haptic feedback to user. For example, if collision happens between the wall and the weight, user will feel that the knob is being blocked or stopped as if there is a real wall preventing the weight from moving further to the collision side. A higher value for Weight or Lever gives a heavier feeling to the knob, as if a heavier weight has been tied to the knob and user will have the feeling of lifting this heavier weight attached to the knob. For the Magnets configurations, user will feel as if a magnet attracts the haptic knob to a particular angle or repel the haptic knob at a certain angle. This design has been able to provide realistic haptic sensation although more systematic and thorough experiments are required to quantify the quality of the haptic feedback, and to vary the haptic sensation provided by the system. However, these 3 type of virtual reality method (weight, wall and magnet) are not for rehabilitation purpose, this virtual reality setup is for control study since this project still ongoing. The next step of this project is to develop new virtual reality setups for rehabilitation purpose and conducting several experiments based on real stroke patient to validate this device.

5. Conclusion

This paper describes the design and development of a low cost haptic knob which is the alterative required for home therapy. The estimated hardware cost for this project is $500 USD compare to the commercialized Armeo arm exoskeleton device has a cost approximate $40,000 USD [18]. Additionally, sample modules and data logging for this system are presented. The main contribution in the design is the use of a microcontroller to provide real time control at 250Hz, to generate realistic haptic sensation. The choice of hardware, including motor and controller, bring down the cost and size substantially as compared to other available systems that train hand pronation and supination. However, a slight drawback is the inconvenience associated with programming sophisticated control algorithms on a microcontroller.

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