Design for Manufacture of a Low-Cost Haptic Degree-of-Freedom

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***Abstract*—Haptic technology enables systems to interact with the human's sense of touch, and has been proposed for applications across a wide variety of domains. The cost prohibitive nature of most haptic devices however remains a contributing factor in preventing widespread real-world implementation. While some low-cost commercial-off-the-shelf haptic devices have been introduced, they do not provide the range of capabilities required by many applications. One solution to achieving the capability required using these devices is through the addition of adaptors and mechanisms. In doing so however there are distinct challenges in maintaining low-cost implementation. This work proposes an additional degree of freedom for the commercially available Phantom Omni haptic device. Torque feedback around the roll axis of the user-held stylus is achieved through a custom detachable stylus attachment. To maintain low-cost design while achieving realistic force feedback commercial off-the-shelf hardware including a positional encoder and DC actuator is employed. In terms of the required mechanical fabrication, manufacture through low-cost rapid prototyping was utilised as discussed in this paper. In order to demonstrate the operation of the system, spring-based haptic rendering simulating a screw insertion task was implemented.**

***Index Terms*—Haptic DOF, 4DOF Device, phantom omni**

I. Introduction

Haptics relates to the human's sense of touch and haptic interaction has been proposed for many applications including medical simulation, gaming and education [1]. One area which can significantly benefit by utilising haptic interaction is the simulation of medical operations such as Minimally Invasive Surgery (MIS). Research suggests that the use of haptics in MIS training can lead to reduction in surgical errors [2].

The Phantom Omni by Sensable Technologies is a low-cost Commercial-Of-The-Shelf (COTS) haptic device providing users with stylus interaction with 3 active (force feedback capable) Degrees-Of-Freedom (DOF) and 6 passive (positional measurement only) DOF The device is packaged with the Sensable HDAPI and HLAPI offering developers different levels of abstraction from the device's lower level control systems. There are higher-cost models within the Phantom range of devices which do provide a full 6 DOF force feedback functionality however are substantially more expensive than the Phantom Omni [3].

The work presented in this paper focuses on the low-cost addition of an active roll DOF able to provide torque feedback to the stylus about its longitudinal axis. The addition of this 4^{th} DOF is well suited to applications where 3 DOF Cartesian force feedback (X,Y,Z) and 1 DOF torque feedback (Stylus roll) provide adequate interaction and full 6 DOF haptic feedback is cost prohibitive. Such applications may include the simulation of surgical screw insertion as used in MIS surgery for stabilising fractures [4].

Our earlier works have proposed other low-cost functional additions for the Phantom Omni. In [5] low-cost 5 DOF haptic interaction was achieved by combining two Phantom Omni devices to share a common stylus. In [6] a grasping attachment was introduced providing multipoint haptic feedback to a user's individual fingers. The work by others [7] modified two commercially available Novint Falcons to introduce 5 DOF haptic interaction.

The added DOF presented in this paper is designed to retrofit to an unmodified Phantom Omni device. The DOF is a working prototype providing torque feedback and designed to work with the open-source CHAI3D software library [8]. The DOF was designed to maintain low-cost so as to provide an alternative to the commercially available 6 DOF devices when only 4 DOF is required. This was not only addressed in the selection of components but in the use of low-cost rapid prototyping fabrication of required mechanical components.

The following sections discuss the design of the additional DOF.

II. 4th DOF Mechatronic Design

The system prototype comprises three main components: an actuator for providing torque, a rotary encoder for position measurement, and the physical stylus which is held by the user and houses most of the system's components. Important design criteria include the ability

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to retrofitted to an unmodified Phantom Omni, to have low mass, be low-cost and to provide adequate torque.

A. Brushless DC Actuator

The Phantom Omni haptic device uses cable drive mechanisms between the DC motors and serial links enabling mechanical torque to be both transmitted and increased with zero backlash, near-zero friction and low inertia. In order to provide a force feedback capable roll DOF careful consideration must be given to the design so as to not reduce the capability of the Phantom Omni device. In our earlier work [9] cable drives and cable-sheath arrangements were used to transmit forces from desktop mounted actuators to the Phantom Omni's end-effector. In the work presented herein, to reduce complexity it was decided to mount the actuator within the stylus. Maxon Electronic Commutated (EC) brushless DC motors were chosen based on high torque, speed, power characteristics and an excellent life span [10]. The system employs the EC-max 16 (part no. 283828) brushless DC actuator based on satisfying size, weight and torque requirements [11].The motor's cost was also considered reasonable relative to the low-cost requirement for the system.

B. MR Positional Encoder

The EC-max 16 brushless DC motor is provided coupled to a 512 count per turn (CPT) Magnetic Rotary (MR) encoder as a requested bundled system at minimal cost. The encoder (part no. 201940) was deemed to provide adequate resolution and low inertia while only adding 7.3mm to achieve an overall motor-encoder length of 31.3 mm .It includes a built-in line driver with the signal output provided in transistor-transistor logic (TTL) levels [12].

C. Stylus

In order to incorporate the active 4th roll DOF without detrimentally affecting the operation of, or requiring modifications to the Phantom Omni haptic device, a replacement press-fit keyhole system on the stylus was designed. The stylus was required to be of low mass so as to not affect the low inertia of the Phantom Omni, to efficiently house the required components, and to have an ergonomic user friendly design, all while being low-cost to prototype and produce.

In order to achieve this, various fabrication methods were investigated. Subtractive fabrication technologies such as manual and Computer Numerical Control (CNC) machining continue to be a valuable method for mechanical fabrication. While hard materials such as steel typically require the use of relatively expensive equipment and labour, the growth of DIYCNC machines has enabled increased accessibility to low-cost rapid manufacture of other materials such as wood, aluminium and plastic that are becoming more assessable [13].

In recent years there has been an increasing interest in additive 3D printing technology. This technology provides designers with easy access to printing in materials such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene**(**ABS) plastic [14]. Interestingly, new materials such a wood and stone are also being introduced [15].

Fused Deposition Modelling (FDM) is an additive manufacturing technology perhaps the most common used in 3D desktop printing applications due to its cost and simplicity. An FDM printer uses a nozzle heated to the printing material's melting temperature (in the case of ABS approx. 220 °C) while the print material is feed at the rate required to print the particular design. The material feed speed is proportional to the amount of material extruded. The print head is CNC controlled by generated G-code and follows the CAD design as specified in a file (normally an .STL) that prints in the x and$y$ planes until a layer is completed. The print heads then increments along the$z$-axis to print the next layer. Once all layers have been printed the 3D printing is complete [16]. Dual extrusion is also common where a second extruder is used to print support material, preferably water soluble, for overhangs within the design. After the print process is complete the support material can be removed [17].

Sterolithography (SLA) is the other widely used 3D printing process where material is hardened through the use of ultraviolet laser. The material placed on a table and cured upon exposure to the laser. The table moves along the z-axis, and the laser moves, in a similar manner to FDM technology, in the x and y planes until a layer is completed. SLA printing process can offer higher resolution than FDM [18]. This improved resolution however does come at increased cost with the starting price for SLA printers around $3000AUD [19].

The emerging market of low-cost FDM printers has increased competition and innovation, 3D printers can now be obtained for as low as $1000AUD [20]. These printers do however have limitations such as smaller printable workspaces, resolution and tolerances.

In order to minimise cost a low end single extruder FDM 3D printer was employed to fabricate the stylus. Using this technology required careful consideration so as to compensate for large print tolerances, support material (single extruder) and other print related issues. Of particular importance was compartmentalising the stylus design into simple shaped components as shown in Fig. 1. This not only improved the print quality by removing the need for unnecessary support material which can be difficult to remove, but also better supports post print procedures (such as sanding) which leads to higher quality components.

Large print tolerances are expected in low end FDM 3D printers. These tolerances can be improved if the equipment is understood and well calibrated. In order to compensate for this extensive test prints were conducted and the CAD models adjusted accordingly. Print quality also relies on having a level surface and in the case of common 1 μm resolution printing this can prove challenging. In the case of this design ABS printing with a hot bed plate and a layer kapton tape was used in order for the first layer to adhere, this helped reduce any warping of components at the foundation layers.

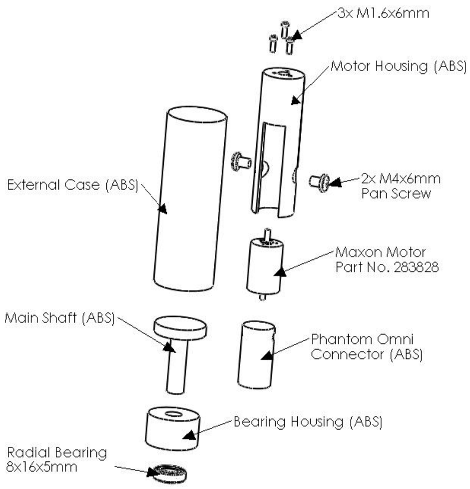

Figure 1. Exploded view of stylus and drive system

Fig. 1 depicts an exploded view of the stylus and drive system components. The stylus is compartmentalised into five components to optimise the print quality. Communication cabling is located at the bottom of the design insuring minimal interference during operation. All holes are post drilled and some parts were glued or screwed together after printing. The radial bearing, Maxon motor and M1.6 screws were obtained as COTS components.

The main shaft is press fitted to the Maxon motor at one end with the bearing's inner race press fitted to the shaft at the other end. The bearing housing is glued to the outer surface of the motor mounts and the bearings outer race press fitted into the housing. The Phantom connector is glued to the end inside the motor mount and allows connection to the Phantom Omni haptic device using a press-fit keyhole system.

III. 4TH DOF ELECTRONIC CONTROL SYSTEM

The control system is responsible for reading the rotational position of the stylus using the encoder and then generating a torque using the DC actuator. The control loop is refreshed at $1kHz$ so as to support realistic haptic interaction as discussed in Section IV.

A. ESCON 50/5 Actuator Controller

The Maxon 50/5 ESCON controller is used to control the EC-max 16 actuator. The controller was configured using ESCON Studio software and set to use current control via a Pulse Width Modulation (PWM) signal. Controlling the current directly enables the generated torque to be known based on the EC-max 16's *current-torque* constant. This was selected over PWM voltage control where the motor windings may provide varying resistance for different positions in a full rotation and consequently inconsistent torque for a given voltage.

Direction control was set using a single digital input each for clockwise and counter-clockwise rotation. The controller requires a power supply providing between $10 - 50\ VDC$ and $5A$ continuous or $15A$ non-continuous current. The provided supply voltage for the 50/5 controller was determined to be $\geq 13.3V$using (1) as specified by the hardware manufacturer [21].

$$V_{CC} \geq \left[\frac{U_N}{n_o}\left(n + \frac{\Delta n}{\Delta M}M\right)\frac{1}{0.98}\right] + 1 \qquad (1)$$

where V_{CC} is the supply voltage to the controller, U_N is the nominal voltage required by DC motor, n_O is the no load speed, $\frac{\Delta n}{\Delta M}$ is the speed/torque gradient, M is the operating torque and n is the operating speed.

B. ATMega 128 Microcontroller

The ATMega128 microcontroller is used as an interface between Windows-based haptic applications and the hardware including 50/5 ESCON controller (controlling the actuator) and MR encoder. The firm ware on the ATMega128 controller reads position information from the actuator's MR encoder as well as sending a PWM signal to the ESCON controller. A series of different serial commands are used to control the motor's direction, PWM duty cycle and request the current rotational position of the actuator.

The PWM signal is created using the ATMega128's16 bit timer. The encoder is connected directly to the ATMega128's external interrupts as used to count pulses and determine the actuator's rotary position.

IV. 4TH DOF HAPTIC RENDERING

Haptic rendering relates to the mapping of virtual objects to forces and torques displayed to the user by a haptic device. The user can then interact with the rendered virtual objects using their haptic sensory modality. Haptic rendering algorithms typically run on a PC where specific software will receive positional information from the haptic device hardware and send back commands of desired forces and torques. In this typical situation the haptic device hardware is responsible for converting commanded torque to corresponding electro-mechanical feedback.

This separation of low-level device control performed by the device hardware, and the high-level analysis of positional measurements and command of desired forces (haptic rendering) performed by the PC, has supported the development of a range of different Software Development Kits (SDKs) for developing haptically enabled virtual environments. These SDKs run on the PC and allow developers to use predefined functions to design haptically enabled applications without the need for intimate knowledge of the devices lower-level operation. The Phantom Omni haptic device is packaged with two APIs, the HDAPI and HLAPI, providing varying levels of abstraction from the operation of the device itself.

The haptic DOF introduced herein is designed to retrofit to the Phantom Omni device, and may be valuable for those intending to achieve haptic simulation of screw insertion-type actions (twisting) such as those encountered in surgical operations. In such scenarios the 3 DOF Cartesian forces of the Phantom Omni can be used for haptic feedback relating to positioning of the tool, and the 4th roll DOF can provide feedback relating to exerted torque in the twisting motion to simulate the insertion (twisting) of the screw. The DOF introduced in this paper is able to provide the user with torques of up to $89N/mm$.

A Windows-based application was developed to demonstrate the provision of torque feedback in a screw insertion task. Fig. 2 depicts the parameters relating to the virtual screw.

The application employs an undamped spring model (2) as is common in haptic rendering [22]. The basis of operation of a spring model for haptic rendering is that before the position of the haptic device has penetrated a virtual object no force feedback is generated. Once penetration of the virtual object's boundaries does occur the rendered force is proportional to the depth of penetration. The spring model is given by

$$F = \begin{cases} 0 & x > x_o \\ k(x_o - x) & x \le x_o \end{cases} \tag{2}$$

where F is the output force, x is the end effector's (stylus) position, x_o is the object's surface boundary and k is a proportional constant.

The application relies on a timer function to maintain a 1kHz control loop frequency. The MR encoder is sampled at this frequency and the desired torque is then calculated and sent to the system using a PWM signal and direction code. The result is the magnitude and direction of torque output by the actuator.

An algorithm is used within the timer function which uses expression (2) and a state machine (Table I) to create the haptic rending expression (3).

$$PWM = \begin{cases} 10 & x > x_o \\ 0.3125(x_o - x) & x_o \le x \le (x_o + 256) \\ 90 & x > (x_o + 256) \end{cases}$$

$$\Gamma = \begin{cases} 0 & x > x_o \\ rI_{max}\left(\frac{PWM}{100}\right)\mathrm{k}_\tau & x_o \le x \le (x_o + 256) \\ rI_{max}k\tau & x > (x_o + 256) \end{cases} \tag{3}$$

where x is the rotational position of the stylus, x_o is the screw's boundary position, Γ is the output torque, k_τ is the torque constant, PWM is the duty cycle, I_{max} is the actuators max. current and r is the radius ratio $\left(\frac{shaft}{handle} = \frac{30mm}{2mm} = 15\right)$.

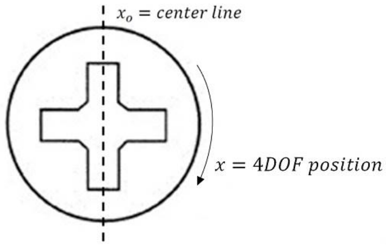

Figure 2. Screw haptic rendering parameters.

The screw's center line is used as the reference boundary position in the application. Given that the screw's center line is dynamic due to user interaction (as depicted by Fig. 3 the object's boundary position (center line) must be continuously updated. This situation is depicted Fig. 3 where the upper-half of the figure demonstrates the screw's initial position, and the lower-half after the user has rotated the stylus by 45 degrees in a clockwise direction.

The algorithm needs to determine if the user is turning the screw, and if so to determine a reference point for the rendering expression (3) as used for generating the torque to be displayed. If the user stops turning the screw in the single motion, the previous boundary position must be cleared and ready to be updated for the next interaction.

This is achieved by comparing the stylus' previous and current positional movement states. Table I shows the state table representing all possible states able to occur between single transitions as well as the corresponding actions to be undertaken. As can be observed, in most cases the operation simply requires the torque to remain in the same state and the boundary position un-altered. The forward and backward states represent movement of the stylus in the clockwise or counter-clockwise directions respectively.

The positional information referred to in Table I as used by the application is obtained through serial communication with the ATMega128 microcontroller. The application also transmits serial information relating to directional rotation and the PWM duty cycle to the microcontroller. The PWM duty cycle is represented by a single byte integer value between $10 - 90$ andall other commands are in decadal steps greater than 100.

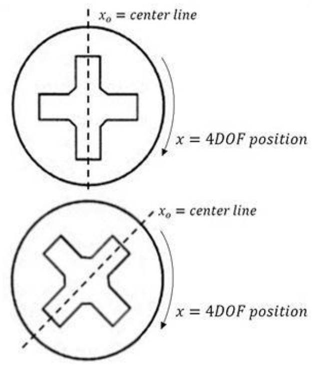

Figure 3. Dynamic object boundary position.

TABLE I. HAPTIC RENDERING STATE TABLE

Previous State	***Current State***	***Operation***
Forward	Forward	Assign current position to boundary position x_o and apply torque.
Forward	Backward	Resume same torque state.
Forward	No change	Resume same torque state.
Backward	Forward	Resume same torque state.
Backward	Backward	Clear boundary position x_o. Stop torque.
Backward	Same	Resume same torque state.
No change	Forward	Resume same torque state.
No change	Backward	Resume same torque state.
No change	Same	Resume same torque state.

V. Conclusions and Future Work

This paper introduced a 4th roll Degree-Of-Freedom designed to retrofit to the Phantom Omni haptic device. The system is intended for applications where the addition of a low-cost attachment to an already low-cost 3 DOF force feedback device may be desirable over more expensive 6 DOF haptic devices. The system was achieved at a low-cost while satisfying the functional requirements by using COTS components, a simple bearing drive system with extensive investigation and fabrication using low-cost 3D printing technology.

To demonstrate the operation of the system, a Windows application providing haptic simulation of a screw insertion task was developed.

Future work includes investigation into the ability to combine more complex cable drive systems with the low-cost fabrication techniques employed in this paper. This will allow the generation of much higher torque outputs which is currently not possible due to the confined space within the stylus.

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