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Haptically enhanced VR surgical training system

https://doi.org/10.1515/cdbme-2022-1188

Abstract: This paper proposes a cost-effective VR surgical training system which computes haptic feedback forces when a VR surgical tool interacts with virtual tissues. A 3 degrees of freedom (DoF) reverse linear Delta mechanism is used to render computed force feedback data which are then received by the fingertip of the operator. Additionally, the moving plate allows rendering of surface properties and lateral forces occurring due to a tumor with different stiffness parameters below the skin surface. Controllers are designed and implemented to regulate the haptic feedback device's end-effector position and applied force. The virtual surgical instruments are controlled by a 7DoF serial link manipulator which captures the operator's movement by the utilization of various sensors. The controllers to regulate forces as well as the positions are evaluated with the proposed haptic feedback device. The mean RMSE of the force and mean error of the angular displacement are 0.0707 N and 1.95°, respectively. The presented system can provide multisensory feedback including visual, auditory and haptic feedback interactively depending on the operator's input in the presented VR surgical training system.

Keywords: VR training, surgical simulation, haptic feedback device

1 Introduction

Robotic surgical systems benefit both patients and surgeons, for example reduced operating time, recovery time and post-operative pain with high surgical precision. A tele-operative surgical system requires transparency to enhance the outcome of the surgery. In this regards, haptic feedback plays an important role to compensate the drawbacks of typical tele-operative surgical system suffering from lack of haptic sensation. Haptic feedback can present haptic properties of remote patient side based on the measurements from sensors embedded in surgical tools or create an active constraint to assist a surgeon for better performance in surgery. Pacchierotti et al. [1] showed improved performance achievements in all of the considered metrics (e.g. contact orientation, RMS pressure, completion time) when using a 3DoF (degrees of freedom) cutaneous and force feedback device in a palpation task scenario. The device is actuated by servo motors tilting a mobile platform through a connected cable-spring mechanism around the palmar finger pulp. Abiri et al. presented multi-modal haptic feedback device driven by vibration and pneumatic actuation and showed that multi-modal haptic feedback helps to reduce forces to avoid applying excessive force which can damage the tissue [2]. Another 3DoF haptic device delivers normal and tangential skin stretch deformations through skin tactors back to the user [3]. Most surgical training systems allow trainees to practice surgical procedures in immersive VR environment (e.g. dV-Trainer- Mimic Technologies, LEO training system - BBZ [4][5]). While these simulation systems offer as similar as possible to the actual surgical system which still lacks haptic feedback, we propose a cost-effective and compact VR-based surgical training system with integrated haptic feedback. The presented haptic feedback device can be mounted on the surgeon's manipulators of the VR training system and provide rich haptic feedback.

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2 System

The proposed haptically enabled VR surgical training system is comprised of a surgeon console, haptic feedback display mounted on the end-effectors of the surgeon console and VR display.

2.1 Haptic feedback device

The ultimate goal of the haptic device is to present richer haptic feedback during surgical procedures such as palpation tasks during prostatectomy. By providing shape and stiffness of a tumor, the surgeon could adapt better to the current course of the surgery and attempt to remove the entire cancer in a targeted manner while sparing as much healthy tissue as possible. In order to render these haptic sensations, the proposed haptic feedback device can provide 3DoF force feedback as shown in Figure 1.

The device consists of a fingernail grounded platform, that supports and houses three geared DC-motors with incre-

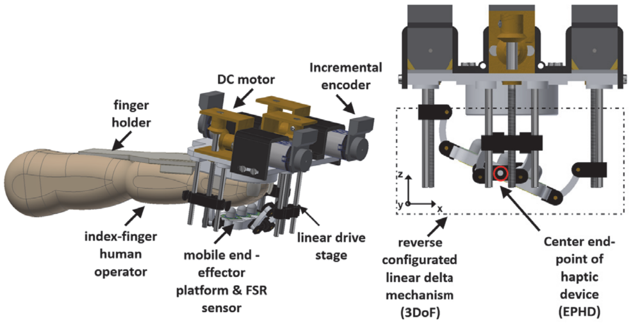

Fig. 1: 3DoF haptic feedback device

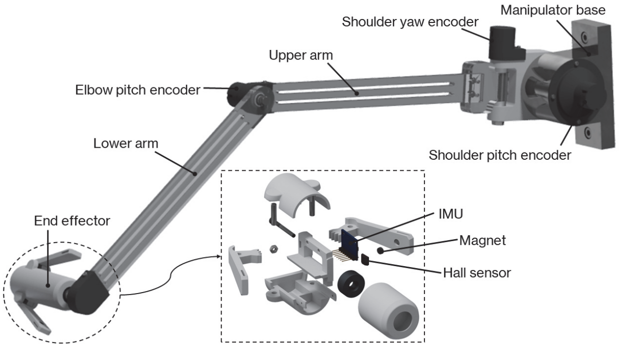

Fig. 2: A CAD model of the left surgeon console arm and exploded view drawing of the gripper/end-effector.

mental encoders. A mobile end-effector platform in a reverse linear delta configuration rotates in two degrees of freedom around the x-axes (pitch angle) and y-axes (roll angle) and a translational movement along the z-axes, towards the palmar fingertip. The end-effector linkage mechanism is attached by three linear drive stages. Overall height and inclination of the platform can be adapted respectively to the kinematic description. The device platform is supported via the lateral joint axes through elastic bands to compensate the gravity. A PID controller is implemented for the position control of the mobile platform. The calculation of inverse kinematics is performed based on the computed haptic rendering algorithm. Additionally, three force sensitive resistors (FSRs) are integrated in the end-effector platform, in order to measure the actual applied force on the fingertip. The maximum range in rendering forces is up to $4\,N$. The FSR is therefore implemented in a voltage divider network and can be scaled via a second resistor according to the desired force and voltage range which is specified for the application. For sensing the actual force a 10 Bit ADC with a reference voltage of $3.3\,V$ is used. The resulting resolution for the force is therefore approximately $4\,mN$. A PD-Controller enables an intrinsic stable force imposition.

2.2 VR training system

The VR training system allows an operator to interact with virtual surgical scenes by sensing the operator's movement in 7DoF. An inertial measurement unit (IMU), three absolute magnetic encoders, and a Hall sensor are implemented to monitor 3DoF of wrist orientation, 3DoF translations of the end-effector and 1DoF grasping motion respectively. One of the surgeon console arms is displayed in Figure 2.

VR Surgical scenes are implemented in Unity game engine and acquired sensor data are transmitted to Unity via serial communication from a micro-controller. Graphical virtual surgical tools are rendered based on the user's motion and the penetration depth, d and the instrument velocity, v are updated to compute the force

$$F = K\,\vec{d} + B\,\vec{v} \tag{1}$$

where, $K = [k_x,\, k_y,\, k_z]$ denotes the spring and $B = [b_x,\, b_y,\, b_z]$ damping coefficients. This way we can simulate anisotropic behavior by assigning different spring and damping parameters for each dimension in space. A visualization of the acting forces and their direction during tool-tissue interaction is depicted in Figure 4. In order to acquire the absolute value of the normal palpation force $|\vec{F_n}|$, which can be rendered by the haptic display, vector $\vec{F_{ext}}$ needs to be projected onto the surface normal $\vec{S_n}$. Lateral forces $\vec{F_{lat}}$ are indicated by tilting the plate according to the angle α. The plate angle α is computed as described in Eq. 2.

$$cos(\alpha) = \frac{\vec{F_{ext}} \cdot \vec{F_n}}{||\vec{F_{ext}}|| \cdot ||\vec{F_n}||} = \frac{\vec{F_{ext}} \cdot \vec{s_n}}{||\vec{F_{ext}}||} \tag{2}$$

In order to reduce the computational effort, the deviation angle α is computed between the vector of the actual interaction force $\vec{F_{ext}}$ and the surface normal $\vec{S_n}$, which is considered to be a directional unit vector.

2.3 Integrated system

The integrated system including the haptic device and VR training system is illustrated in Figure 3. The derived haptic rendering algorithm [6] can be used in combination with the device. Figure 4 shows 2D virtual haptic interaction between the virtual tissue and the haptic device. In a neutral state position the tool centre point is accommodated at the end-point of the haptic device (EPHD). For collision detection an imaginary ray r is attached to the instrument and aligns into the virtual object. If collision is detected, a constraint collision plane C_{pi}, a collision contact point C_i and a contact normal $\vec{S_n}$ are

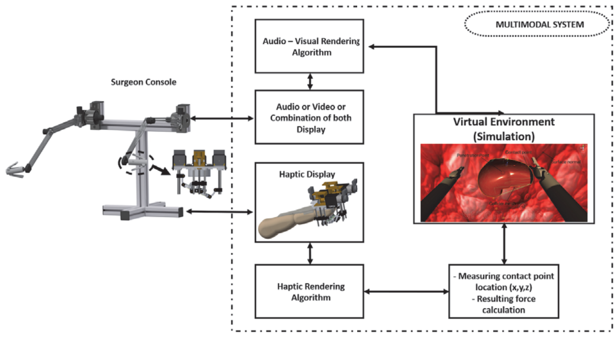

Fig. 3: Multimodal training system with integrated haptic feedback

generated on the virtual object obj_i^{CD} surface. Outgoing from the collision contact point C_i, a haptic interface point (HIP) is introduced by the virtual simulation. The HIP intersects and penetrates into the object.

Through a second collision point and a generated constraint plane C_{pi+1}, the HIP causes a deflection out of the contact normal $\vec{S_n}$. This leads in the 2D plane relatively to the coordinate system $(z_{col,o}, x_{col,o})$ to a second force component called $\vec{F_{lat}}$. This gives back the information that a second underlying structure is recognized, which causes a deflection angle α. The external force $\vec{F_{ext}}$ is computed according to the Voigt model [7][p.41], whereas distance d between HIP and C_i and velocity v are constantly updated during Unity runtime.

The haptic projected normal external force component $\|\vec{F_{re,ext}}\|$ can be calculated according to Equation 3.

$$\|\vec{F_{re,ext}}\| = \|\vec{F_n}\| = \|\vec{F_{ext}}\| \cdot \cos\alpha \qquad (3)$$

The virtual simulation transfers the deflection angle α and normal force component $\|\vec{F_{re,ext}}\|$ back to the haptic device. In this case the motions of the user's index finger are tracked, in which the actual position and force is reflected by the mobile end-effector platform.

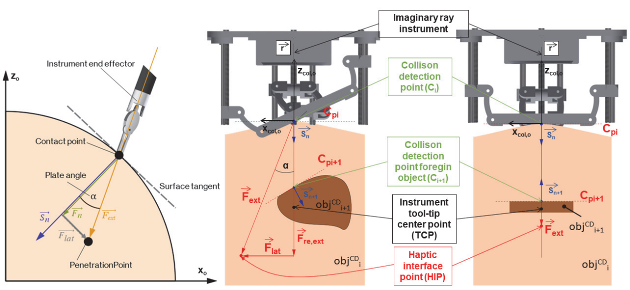

Fig. 4: Illustration of 2D haptic rendering algorithm that translate contact force points between tool tissue interactions through the haptic device back to the surgeons volar fingertip

3 Evaluation

3.1 Force control of the haptic feedback device

The force control system of the haptic feedback device is evaluated with a sinusoidal reference force signal (r_f). The reference force is applied along the z-direction to the fingertip, with a maximum peak force of $1\,N$, which can be seen in Figure 5.

The root mean square error (RMSE) values for each force measurement cycle ($F_i, i = 1, 2, 3$) are shown in Table 1 and overall mean RMSE is $0.0707\,N$.

Tab. 1: RMSE results of the force control accuracy verification

RMSE F_1 / N	**RMSE** F_2 / N	**RMSE** F_3 / N
0.073	0.068	0.071

Before the force control, the VR environment computes the feedback forces and the corresponding plate angles when the virtual surgical tool travels into the virtual tissue. Figure 6 shows the computed force measurements as well as the course of the force vectors angular deviation α from the surface normal, as explained in Subsection 2.3. Predefined spring and damping parameters are used to mimic the material behaviour of viscoelastic model. Since the distance in Unity is dimensionless we assume that a translation by one unit equals a real world translation by one millimetre.

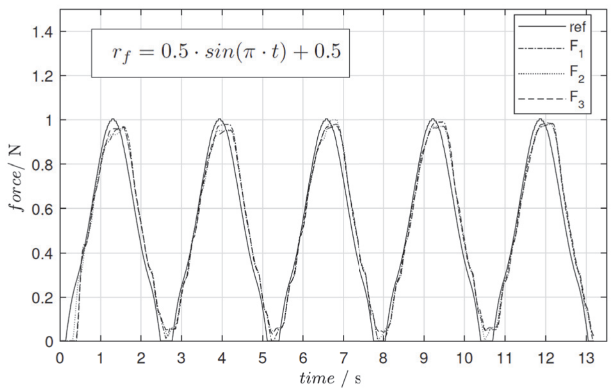

Fig. 5: Measurement results of the closed loop force control system evaluation when applying a peak force of $1\,N$

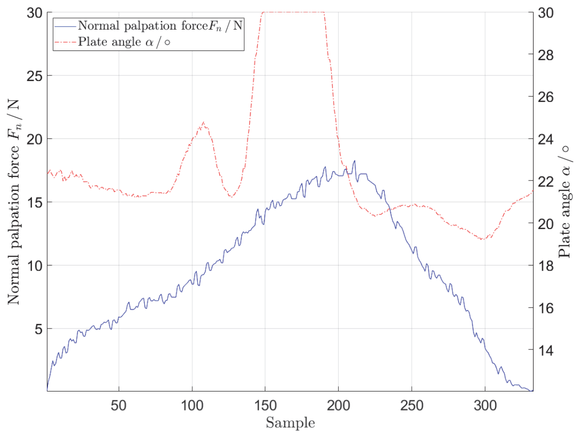

Fig. 6: Results of haptic feedback algorithm for stiffness parameters for spring coefficients of $K = [0.80, 0.70, 0.65]$ and damping coefficients of $B = [0.050, 0.045, 0.055]$ in unit $N\,mm^{-1}$ and $kg\,s^{-1}$ respectively, are assigned to the virtual model. Since the maximum plate angle is limited to 30°, the higher angles are saturated.

3.2 Position accuracy of the haptic feedback device

At each repetition, the system choose a random platform configuration $\alpha_{ref,i}$ or $\beta_{ref,i}$, , $i = 1...N_s$, with accordance to the degrees of freedom of the end-effector platform specifications, $-30^\circ \leq \beta \leq 30^\circ$ (pitch angle β) and $-20^\circ \leq \alpha \leq 20^\circ$ (roll angle α), while the yaw angle ($\gamma = 0^\circ$) is constrained. The reference configuration ($\alpha_{ref,i}$, $\beta_{ref,i}$) is then compared with the actual configuration ($\alpha_{m,i}$, $\beta_{m,i}$) measured by the IMU. The evaluated mean error (e_p) is calculated by the below stated Equation 4:

$$e_p = \frac{1}{N_s}\sum_{i=0}^{N_s}\sqrt{(\alpha_{ref,i} - \alpha_{m,i})^2 + (\beta_{ref,i} - \beta_{m,i})^2} \quad (4)$$

Statistic measurement evaluation shows an overall mean error of 1.95° and standard deviation of the position of 1.5° respectively.

4 Conclusion

In this paper, a haptically enhanced VR surgical training system is presented. The surgeon console enables the operator to conduct surgical procedures in VR environment by measuring operator's movements in 7DoF for each hand. The rendering algorithm is to compute feedback force and the plate tilt angle for the palpation scenario. The designed PID controllers allow to regulate the computed force and angular displacement of the haptic device. For simple palpating scenarios, the proposed system shows good performances in force and position control. Further haptic rendering methods in addition to a more specific palpation scenario should be explored and user studies are conducted in the future.

Author Statement

Research funding: The author state no funding involved. Conflict of interest: Authors state no conflict of interest. Ethical approval: The conducted research is not related to either human or animal use.

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