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Development of a 6-DOF Haptic Feedback Device for Intubation Training

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I. INTRODUCTION

Endotracheal intubation is a common surgical procedure that involves inserting a flexible tube into a patient's airway to facilitate breathing. This task requires precise control and haptic sensitivity. Surgeons typically use a laryngoscope to lift the jaw, allowing a clear view of the trachea and esophagus for proper tube insertion. Correct use of the laryngoscope depends heavily on haptic feedback, and therefore, medical trainees must repeatedly practice the action to develop muscle memory for applying appropriate force and maintaining stability.

Previous studies suggested that combining haptic feedback with VR significantly enhances trainee performance [1]. A 6-DOF (degrees of freedom) haptic system can simulate multi-directional force and torque, offering a more realistic training experience by replicating the physical sensations encountered during intubation. However, most commercial haptic feedback devices rely either on serial linkage mechanisms, which offer sufficient degrees of freedom but lack adequate force feedback, or on parallel linkage mechanisms, which provide stronger force feedback but are limited in their range of motion, making them unsuitable for realistic laryngoscope manipulation [2]. To address these limitations, this research proposes the use of a 6-DOF haptic feedback device integrated into a virtual reality (VR) environment, as shown in Fig. 1. The objective is to help medical students develop the muscle memory necessary for precise and effective laryngoscope operation.

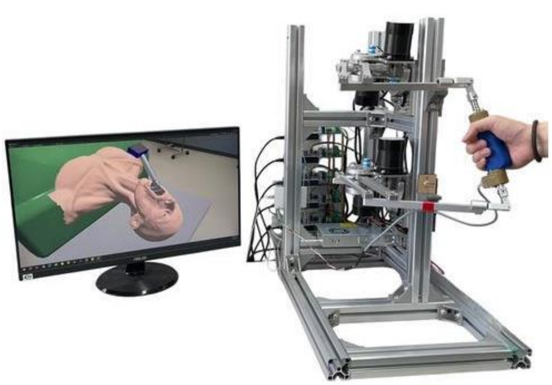

Figure 1. Larngoscope manipulation in a VR environment

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II. DESIGN OF HAPTIC DEVICE

A. Design Goal

In this study, the maximum force for the haptic feedback device was determined based on clinical measurements. According to [3], based on the data, the maximum force during clinical use is approximately 28 N. Therefore, this study targets a maximum feedback force of 30 N to ensure sufficient realism.

The device is designed to provide 6-DOF for haptic feedback. The operational range must cover at least 30 × 30 × 30 cm³ to include the head movement area during training.

B. System architecture

The operation workflow of the haptic feedback system developed in this study is illustrated in Fig. 2. The architecture is divided into three modules: the virtual environment module (Unity), the control module (Teensy), and the device module (haptic feedback device). In the virtual environment, Unity serves as the development environment, which includes scripts for position transformation calculation, force transformation calculation, gravity compensation, and a virtual environment with force feedback algorithms, providing the basis for the haptic output. In the control module, the Teensy board is responsible for signal conversion, encoder information transmission, and current monitoring data processing. In the device module, there are linkages, motors, encoders, and motor controller boards that integrate current sensors for closed-loop control.

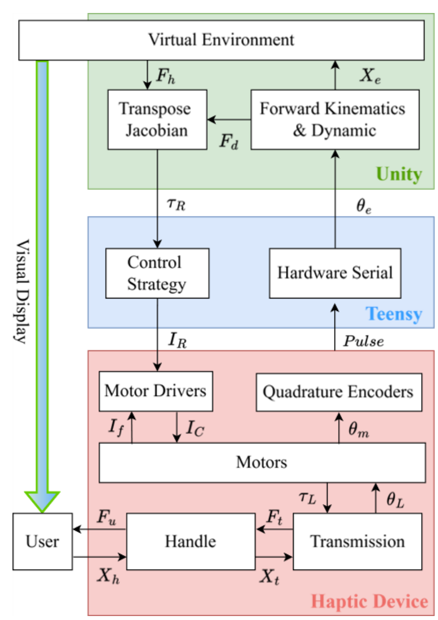

Figure 2. System architecture

C. Mechanism design

The 6-DOF mechanism is realized by combining two 3-DOF RRR serial robots in parallel and integrating them using universal, revolute, and helical joints. Equation (1) show how the DOF is calculated. As illustrated in Fig. 3, this configuration enables six independent actuators to control the mechanism [4].

$$\mathrm{DOF} = 6 \cdot (10 - 1) - 5 \cdot (7 + 1) - 4 \cdot 2 = 6 \qquad (1)$$

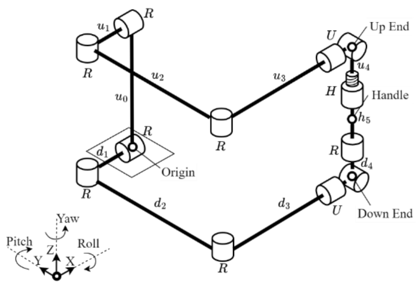

Figure 3. Equivalent linkages and joint diagram

D. Forward kinematics, Dynamic

Fig. 4 is the kinematics diagram of the mechanism construct. The kinematic structure of the mechanism is analyzed using Denavit-Hartenberg (DH) parameters, dividing the system into upper and lower segments, as well as the handle, and utilizes DH parameters to separately derive the forward kinematics for the upper and lower parts.

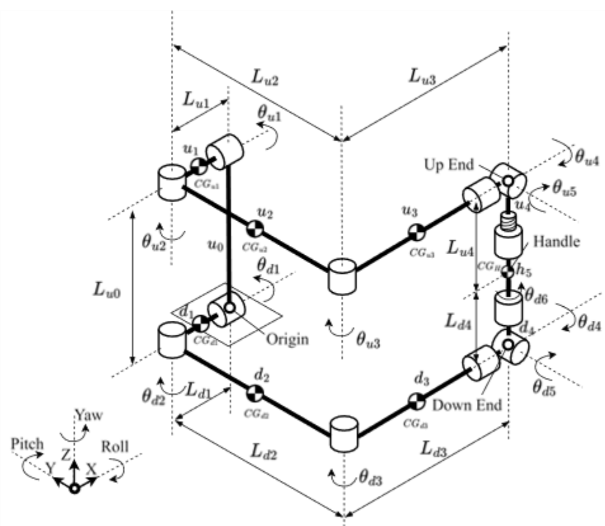

Figure 4. Kinematics and Dynamic diagram

The handle posture can be derived based on the forward kinematics of the 2 RRR serial robots. The UP End and Down End from Fig. 4 is utilized to calculate the posture using Equation (2).

$$\boldsymbol{P}^{w}_{handle} = \boldsymbol{P}^{w}_{downEnd} + ((\boldsymbol{P}^{w}_{upEnd} - \boldsymbol{P}^{w}_{downEnd}) \times L_{d4} / \left| \boldsymbol{P}^{w}_{upEnd} - \boldsymbol{P}^{w}_{downEnd} \right|) \quad (2)$$

Then, Lagrange's equation is used to calculate how much additional torque needs to be applied to the motors in order to compensate for the dynamic-induced force from the handle, as shown in Equation (3).

$$\boldsymbol{\tau}_R = \boldsymbol{M(\theta)\alpha} + \boldsymbol{C(\theta,\omega)\omega} + \boldsymbol{g(\theta)} + \boldsymbol{\tau}_h \qquad (3)$$

E. Optimization

The workspace and maximum output force are optimized with a genetic algorithm to determine the optimal lengths of links u_2, u_3, d_2, d_3 for Laryngoscope manipulation. The optimization can be formulated as shown in Equation (4), L_{Link} denoted the link length for link u_2, u_3, d_2, d_3. The result is shown in the TABLE. I, which matches the design goal set for endotracheal intubation.

$$\begin{aligned} &maxzimize\ F(L) \\ &= [\, f_1 : D_x, f_2 : D_y, f_3 : D_z, f_4 : F_{\max\_z} \,]^T \qquad (4) \\ &subject\ to : 10 \le L_{Link} \le 30 \end{aligned}$$

TABLE I. OPTIMIZATION ANALYSIS RESULTS

Link length	Work space and maximum force			
L_{Link}[a] (cm)	D_x (cm)	D_y (cm)	D_z (cm)	F_{max_z} (N)
20.00	59.50	47.15	63.51	31.98

a. L_{Link} denoted the link length for link u_2, u_3, d_2, d_3

III. CONCLUSION AND FUTURE WORK

This study presents the design of a 6-DOF haptic feedback device utilizing a parallel linkage structure and a helical joint to fully exploit the output degrees of freedom of six motors, enabling the device to provide comprehensive 6-DOF feedback. Initial results indicate that the system meets the targeted feedback force. However, further verification of the device's effectiveness is required.

Future research will focus on developing an algorithm to calculate the force/torque interaction between the laryngoscope and the throat. Following this, ergonomics experiments will be carried out, starting with peg-in-hole tasks and progressing to user testing to determine whether the haptic feedback enhances surgeon performance. Additionally, Dynamic force compensation will be applied to accurately simulate laryngoscope manipulation for endotracheal intubation training.

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