UNIVERSITY OF PITTSBURGH | SWANSON SCHOOL OF ENGINEERING | DEPARTMENT OF BIOENGINEERING

Visualization and Image Analysis Laboratory

Development of the 1DoF Haptic Renderer: Controller-Based Membrane Modeling for Haptic Devices

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INTRODUCTION

During procedures, microsurgeons primarily make use of visual feedback, because the involved forces are below the threshold of touch. Current haptic platforms that model tissue interaction, such as the Geomagic Touch and the Butterfly Haptics Magnetic Levitation Haptic Device (MLHD), are expensive, limited in force output, or subject to inertial effects due to their heavy actuators platforms. The 1DoF Haptic Renderer was developed to address these limitations [1]. It uses a woofer loudspeaker actuator with force and displacement sensors to simulate tissue interaction.

THE 1DOF HAPTIC RENDERER

- Actuator: 80W subwoofer speaker (Faital PRO 5FE120) 5 inch (12.7 cm) diameter and a cone mass of 11 grams (Figure 2)
- Can undergo 9.5 mm displacement and can move steadily against forces up to 10 N [1]
- Uses direct electromechanical transduction, with force related simply to the voltage across the speaker coil
- Stereolithographic scaffold with a Honeywell FS03 Force Sensor for force sensing
- Optical IR transceiver (Vishay TCRT5000L) used to measure speaker cone position
- Total mass of 23.6 grams
- Controlled by Analog Devices ADuC7026 microprocessor
- Wixel USB module (Pololu; Las Vegas, NV) enabled communication between the "master" microprocessor and a "slave" computer for data logging and mode selection

METHODS

A Proportional-Integral-Derivative (PID) feedback controller was used to regulate speaker current based on force and displacement measurements [2]. The error (e) was determined by subtracting the sensor voltage at some set point from the current sensor voltage. Proportional control multiplies a proportional gain (Kp) by the error, while the integral (Ki) and differential (Kd) controls summate previous errors and predict future errors with their respective gains [2] (Figure 1).

Two primary modes of PID were developed: (1) Virtual Wall (VW) mode, in which a set-point was chosen based on the desired displacement, with the error used to resist displacement from the set-point with maximum force, and (2) Zero Stiffness (ZS) mode in which speaker voltage was used to minimize force detected by the sensor and thereby simulate open air. These modes were compared with the actuator on mute, with no compensation of force (Figure 3).

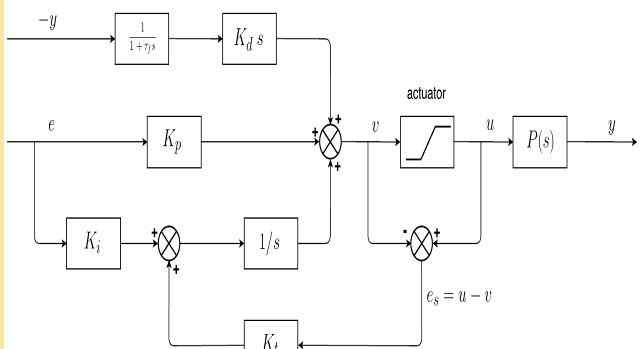

Figure 1: Block diagram of PID controller. Output "v" of controller limited between 0-2.5V due to actuator saturation, resulting in speaker output voltage (u). System receives actuator output and calculates appropriate sensor voltage (y)

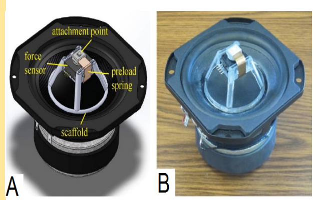

Figure 2: The 1 DOF Haptic Renderer (A) Solidworks model and (B) Physical prototype

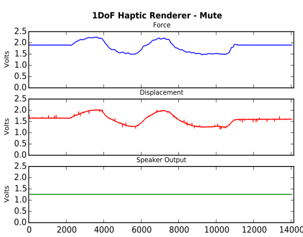

Figure 3: Force and displacement sensor measurements of perturbations when controller is turned off

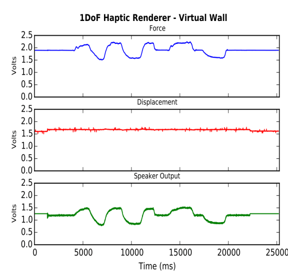

Figure 4: Reaction forces are created by the actuator, shown by an increase in speaker output. Counteracting forces reduce displacement from rest.

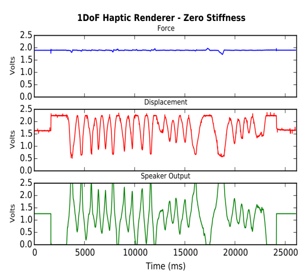

Figure 5: Actuator response to applied forces is almost full compliance. Force application by user results in reduction of counter forces with low latency

In each case, PID control was used determine the output voltage based on the error (Equation 1).

$$V_{out} = K_p * e(t) + K_i \int_0^t e(t')dt' + K_d \frac{de(t)}{dt}$$

Equation 1: PID Controller tuning equation

Open-loop Ziegler-Nichols tuning was performed to empirically determine the PID gains from the ultimate gain (Ku), the value of Kp at which the system began oscillating, and the period (Tu) of oscillation for each mode. Anti-windup control was implemented by scaling down the integral component by the difference in the calculated controller output and the maximum actuator output [2]. A slew-rate limiter and a low pass filter were added to compensate for high frequency signal noise accentuated by the derivative gain term.

RESULTS & DISCUSSION

- Tyreus-Luyben PID controller settings were adopted over Ziegler-Nichols due to their greater stability.
- Final K_u and T_u were found for each operation mode
- PID control of Virtual Wall mode produced forces opposite to the user, resulting in almost zero displacement (Figure 4)
- The new rendition of Zero-Stiffness mode actively removed the tension at all positions of the speaker cone (Figure 5)

Dynamic control of the actuator was achieved with PID and successfully rendered both a very stiff membrane in VW mode and an empty space simulation in ZS mode. In both modes, PID control of the speaker actuator minimized errors with lower latency than simply P or PI methods. The addition of derivative control predicted future errors and balanced the error averaging conducted by the integral term. Prior to anti-windup control, the actuator suffered from repeating integration of previous errors. Anti-windup eliminated "stickiness" related to actuator saturation at the ends of the displacement range.

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REFERENCES

[1] Khera et al. *One-Dimensional Haptic Rendering using Audio Speaker with Displacement Determined by Inductance*, Machines, 2016, 4, 9; doi:10.3390/machines4010009

[2] Astrom, K. J., & Murray, R. M. (2008). PID Control. In Feedback Systems: An Introduction for Scientists and Engineers (pp. 293-312). Princeton, NJ: Princeton University Press.