Inclusion Of Audio Feedback to Enhance A Haptic Feedback Sleeve for Robotic Surgery

Group 7: Isabella Beortegui, Juan De La Espriella, Shane Gleason, Avantika Kothandaraman, Joanna Koshy

A. Significance

The inclusion of haptic feedback within surgical robots is becoming an increasingly relevant topic as autonomy in robotics progresses.[1] Although robots have an unmatched level of precision and accuracy, the question of feedback concerning delicate human anatomical structures (such as organs and tissue) must be addressed as robots are not built with the same tactile judgment that human surgeons have.[2] Even partially autonomous robots will still lack notifications of tissue damage if haptic feedback features are not oriented soon. Sensors are commonly used to notify the robot and the surgeon whether or not contact is made, but sensor strength varies and the amount of information that can be drawn from the sensor is limited.[3] Our project incorporates a piezoelectric buzzer in an attempt to make up for a certain loss of touch with an enhanced sense of hearing.[4] This has been implemented in an attempt to provide the surgeon and the robot with multiple modes of haptic feedback. This added sense should strengthen the surgeon's control and physical understanding while performing surgery. The addition of audible cues to the robot's sensor feedback leads to our proposition of a much more intuitive environment for the surgeon that could make a groundbreaking difference in both accuracy and safety in robotic-assisted surgeries. Prior literature and trials affirm our robotic sleeve's ability to accurately notify the user of important information regarding dangerous forces that could potentially be exerted on healthy tissue. More sophisticated surgeries question the potential danger of tissue damage, especially as robotic-assisted surgeries become increasingly more complex, as the threshold for error is minimal.[5] Our project bridges an attention-seeking gap within robotic-assisted surgeries, and may also create a stronger base for a greater human-machine interface in a surgical context.[6] By pushing the limits of existing technologies, our goal is to create a safer, more reliable, and more intuitive interface for robotic-assisted surgeries that could aid in the high-speed development of healthcare as we know it. The scientific premise for this project is that auditory signals reach the brain at a much quicker rate of 8-10ms, according to a research study by Kemp than a visual cue of 20-40ms.[7]

B. Innovation

The project seeks to provide a proof of concept of a method to incorporate haptic feedback in Minimally Invasive Surgeries (MIS), with additional immediate audio feedback. Ex-vivo testing on porcine bowels demonstrated that a combination of both kinesthetic and tactile feedback helped in the reduction of overall applied force in surgical end-effectors by about 50%, thus establishing the need for haptic feedback in MIS[5]**.** One of the major challenges in incorporating haptic feedback into MIS systems is the lack of available space for additional components that are capable of providing quality haptic feedback[8]**.** Researchers have proposed a multi-level stiffness soft robotic module that provides haptic feedback for endoscopic purposes[9]. This proposed system, although a novel approach, does need to be downsized, without compromising on the quality of haptic feedback. Recent research in the development of haptic feedback systems in MIS has focused on force feedback typically through vibrations (vibrotactile feedback) transmitted to the surgeon's hands (triggered by the force applied on the target tissue) or kinesthetic feedback[10], by initiating a squeezing action through the apertures worn by the surgeon on some part of their body, for example, the wrist[11]. It has also been shown that immediate audio feedback was more effective in reducing the number of attempts needed to reach surgical proficiency when compared to visual feedback[12]. In the cases of vibrations or wrist-squeezing bands as feedback, there is a possibility that such triggers could obstruct the surgeon's ability to carry out the surgery. Vibrotactile feedback was more effective than pneumatic feedback in isolating the necessary target areas for surgical manipulation[5]. Therefore, a more compact electro-pneumatic pump is proposed. A Force-Resistive Sensor detects the applied pressure and triggers a pump, inflating a glove worn by the surgeon. When the force exceeds the acceptable range, a buzzer is triggered to provide immediate audio feedback to notify the surgeon. In a broader perspective, the proposed system is novel in the sense that it uses an electro-pneumatic system as opposed to just a single type of actuation, while also reducing the complexity of the system's architecture and cost. It is built off prior research in the area and works to overcome some of the limitations associated with haptic feedback as previously mentioned: complex architecture, large system size, type of feedback, etc. Immediate auditory feedback was a simple, yet effective addition to the project, the aim of which was to refine the existing system by adding another "protective layer" of sensory feedback that notified the surgeon to quickly reduce the applied pressure.

C. Approach

Aim 1: Replacing visual cues with auditory feedback in a haptic feedback design.

In the last few weeks, we have developed a functional haptic feedback sleeve that incorporates the usage of LEDs as a warning system to the user as another means of feedback. The haptic sleeve works by pressurizing when the connected force sensor detects a force that exceeds the threshold set by the current pressure of the sleeve. As the force is being detected, the Arduino also verifies the value and compares it to the threshold values set for the LEDs so that they light up as the amount of weight/force changes. In Aim 1, we look to improve the feedback being granted to the user through the LEDs by changing the type of feedback being received from visual to auditory because the visual was hard to see in the room's lighting and unreliable as our LEDs were broken. The methods for making these adjustments are broken down into two tasks. Task 1 will be adjusting the code to produce different means of feedback and testing with a single LED. This is to ensure that feedback can be delivered through the means of a single device. Task 2 will incorporate an active piezoelectric buzzer into the existing haptic feedback system[13]. The benchmark for success in this aim will be determining if audible feedback is delivered alongside the haptic feedback when a force is applied to the sensor.

C.1.a Methods.

Task 1: Adjusting the code and testing with LED. Using the existing code for powering the different LEDs, we modified it so that it only had to power a single device. The code for the LED worked by setting different thresholds for the amount of force being applied. At each threshold, the three LEDS were being sent an output, one received a value of HIGH (5V) while the other two received a value of LOW (0V), to control whether it turned on or off. With transitioning to feedback being delivered by a single device, the output at each threshold had to be adjusted accordingly. At the lower end of the threshold range, we made the single output to be constantly LOW so that no power was being sent to the device This was meant to indicate that the user is applying a safe amount of force. At the upper end of the threshold range, the output was set to an alternating sequence loop that sent a HIGH and then a LOW value to the device with a delay of 250 ms between each to mimic an alarm. This was meant to warn the user that they have exceeded the threshold for a safe amount of force being applied and could potentially cause harm. In between the two bounds of the threshold range, the Arduino outputs a constant value of HIGH to the device so that it's constantly on. This is to indicate that the user should be cautious of the amount of force being applied but that they are still in a safe range. To test whether the code produced the desired outcomes, we first tested with the current configuration of the electrical components having the LEDs attached. The finalized code is included in Appendix B. Once the code was uploaded, we began applying varying amounts of force to the sensor and were able to see the LED go from off with little to no force, to on when slight amounts of force were applied, to flashing when excessive force was registered.

Task 2: Integrating piezoelectric buzzer: Once the proper feedback was being delivered by the code, we then went on to exchange the necessary components. Since we were working with Arduino Uno, we had to choose a buzzer that was capable of handling the constant input of 5V while not changing pitch. This led to the selection of using an active piezoelectric buzzer that is capable of producing a constant pitched sound when a DC voltage is applied. To ensure that the buzzer was working properly, we set up a small circuit where 5V was being applied to the buzzer and then connected directly to the ground[14]. We were testing the system with a green LED, so when we were ready we switched the LED with the buzzer and matched the placement of the pins accordingly as shown in Figure 1. We then tested our entire system and received a very quiet sound from the buzzer when force was applied. We then re-evaluated the electrical components and noticed that the two other LEDs were still plugged into the breadboard, causing a slight disbursement of the current from the Arduino to every connected component. Once we removed the two remaining LEDs and cleaned up the wires, we tried the system once again and our buzzer produced a clear audible cue that changed when applied force to the sensor.

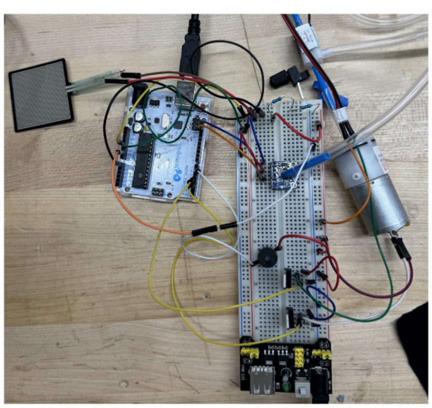

Figure 1: Circuit with integrated piezoelectric buzzer

C.1.b Potential Pitfalls and Alternative Strategies. The audible cue is similar to common operating room noises. Surgeons might miss the cue and damage tissue accidentally. An alternative strategy would be to place the auditory component closer to the sleeve with the haptic feedback so that the sound that is produced is directly next to the surgeon.

Aim 2: Testing the effectiveness of an active piezoelectric buzzer for audio cues for additional haptic feedback

In Aim 2, we will investigate the effectiveness of our haptic device by drawing comparisons between the NASA TaskLoad without additional audio cues and with additional audio cues. The audio cues are given by an active piezoelectric buzzer at a specific force range to provide the surgeon with sensible audio feedback[14]. The additional cues will be tested in two tasks. Task 1 will test that there are different frequencies emitted at different weights and forces. This is to ensure the accuracy of the device. Task 2 involves testing the device's effectiveness using a piece of boiled potato in a plastic bag to determine if the audio cue will aid in picking up the boiled potato without damaging its integrity. The benchmark for success in this aim is determining if the audible will decrease mental stress for the surgeon by making them aware when they are exerting a force that will damage the object they are operating on, as there are studies on a positive correlation between mental stress and performance[15].

<u>C.2.a Methods.</u>

Task 1: Testing with known weights: We tested the ranges of the cues using weights. Using our calibration from our code, we modified the Arduino to emit different frequencies of sound at different ranges of weight[16]. As mentioned in Aim 1, no audible cue from the device corresponds to voltage ranges of zero to 0.2 V. For ranges of 0.2V to 0.7V, there is a constant audible sound from the buzzer. Lastly, for ranges 0.7V and onwards there is a pulsing audible sound from the buzzer. The pulsing audio cue translates to the surgeon that the force they are exerting is a damaging force. We chose pulsing because pulsing is not easily missed in a medical setting. We must test these ranges to determine the device's integrity. We must ensure the audible cue coming from our device is trusted to represent the forces we assumed in our code. To test the audible cues, we used weights to determine which weights allowed for which audible cue. We used 100 grams, 200 grams, and 500 grams and placed them on the FSR (force sensing resistor) one at a time. Then we observed which audible cue was triggered by each weight. From this experiment, we determined that the 50 grams triggered no audible cue, and the 100 grams triggered the constant audible cue. The 200 grams triggered the pulsing audible cue. These results showed that our device along with the inflatable glove emits a different audible cue at increasing forces on the FSR.

Task 2: Testing high forces on delicate material: We followed up on testing the accuracy of the device by testing the feasibility of the device. We did this by picking up a delicate item that would break under high forces. The buzzer will provide a cue if the surgeon or operator is performing at a higher force than needed. We first attached the FSR to a pair of tongs to mimic the end-effectors of a surgical robot. This experiment will entail two participants. The goal of both participants is to pick up the boiled potato in a plastic bag without crushing the potato as shown in Figure 2. The first participant will pick up the boiled potato without any audible cue. Then the second participant will pick up the potato with the audible cue and also determine if the audible cue is a good indicator if the potato is crushed. The pulsing audible cue notifies the participant that their force will damage the potato. Both participants performed a NASA TaskLoad after their tasks. The result from the Nasa TaskLoad is included in Appendix A. In Participant 1, their NASA TaskLoad was higher with the mental demand dominating the TaskLoad (adjusting rating was 300). After all, they were not aware whether the force they were exerting on the object was damaging it. Participant 2 had a lower NASA TaskLoad, especially the mental demand which had an adjusting rating of 90, because they were notified when the exerted force was crushing the potato. The pulsing audible cue was also a good indicator of a crushing force as the pulsing cue occurred as the force crushed the potato.

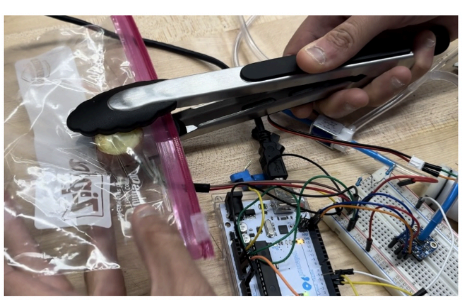

Figure 2: Performing stress test on boiled potato

<u>C.2.b Potential Pitfalls and Alternative Strategies.</u> The calibration is not specific to the boiled potato. An alternative strategy is to add a calibration task for any tested material. The calibration task would involve placing a weight on the object observing which weight crushes the object and updating the Arduino code accordingly. A risk of our device is the amount of power drawn by the buzzer, which limits the number of components that can be added to the device[17].

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Appendix A

NasaTask Load for Specific Aim 2

Appendix D.

Picking up boiled potato without audible cue

Subject ID: Group 7 Date: ____________

SOURCES-OF-WORKLOAD TALLY SHEET		
Scale Title	*Tally*	*Weight*
MENTAL DEMAND	卌	5
PHYSICAL DEMAND	II	2
TEMPORAL DEMAND	0	0
PERFORMANCE	I	1
EFFORT	III	3
FRUSTRATION	IIII	4

Total count = 15

(NOTE - The total count is included as a check. If the total count is not equal to 15, then something has been miscounted. Also, no weight can have a value greater than 5.)

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Appendix E.

Picking up boiled potato without audible cue

Subject ID: Group 7 Task ID: ____________

WEIGHTED RATING WORKSHEET			
Scale Title	*Weight*	*Raw Rating*	*Adjusted Rating (Weight X Raw)*
MENTAL DEMAND	5	60	300
PHYSICAL DEMAND	2	10	20
TEMPORAL DEMAND	0	10	0
PERFORMANCE	1	10	10
EFFORT	3	50	150
FRUSTRATION	4	50	200

Sum of "Adjusted Rating" Column = 680

WEIGHTED RATING =
[i.e., (Sum of Adjusted Ratings)/15] $\boxed{45.3}$

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Appendix D.

Picking up boiled potato with audible cue

Subject ID: Group 7 Date: ____________

SOURCES-OF-WORKLOAD TALLY SHEET		
Scale Title	*Tally*	*Weight*
MENTAL DEMAND	III	3
PHYSICAL DEMAND	III	3
TEMPORAL DEMAND	I	1
PERFORMANCE	卌	5
EFFORT	III	3
FRUSTRATION	0	0

Total count = 15

(NOTE - The total count is included as a check. If the total count is not equal to 15, then something has been miscounted. Also, no weight can have a value greater than 5.)

18

Appendix E.

Picking up boiled potato with audible cue

Subject ID: Group 7 Task ID: ____________

WEIGHTED RATING WORKSHEET			
Scale Title	*Weight*	*Raw Rating*	*Adjusted Rating (Weight X Raw)*
MENTAL DEMAND	3	30	90
PHYSICAL DEMAND	3	10	30
TEMPORAL DEMAND	1	10	10
PERFORMANCE	5	50	250
EFFORT	3	30	150
FRUSTRATION	0	20	0

Sum of "Adjusted Rating" Column = 530

WEIGHTED RATING =
[i.e., (Sum of Adjusted Ratings)/15] $\boxed{35.3}$

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Appendix B

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/*****************************************************************************
ME 571 Tutorial 3 - Part 1
Using a Force Sensitive Resistor (FSR) to trigger the mini-pump on/off.

This tutorial relies on creating a voltage divider circuit with the FSR
and reading the analog voltage at pin A0. A conversion equation will
return the force in grams.

Create a voltage divider circuit combining an FSR with a 3kOhm resistor.
- The resistor should connect from A0 to GND.
- The FSR should connect from A0 to R_DIV
As the resistance of the FSR decreases (meaning an increase in pressure), the
voltage at A0 should increase.

*****************************************************************************/
#include <Wire.h>
#include <Adafruit_MPRLS.h>
#include "MapFloat.h"
#include <math.h>

#define RESET_PIN  -1  // set to any GPIO pin # to hard-reset on begin()
#define EOC_PIN    -1  // set to any GPIO pin to read end-of-conversion by pin
Adafruit_MPRLS mpr = Adafruit_MPRLS(RESET_PIN, EOC_PIN);
/**************************/
int pumpPin = 3;
int solenoid = 4;
/**************************/
const int FSR_PIN = A0; // Pin connected to FSR/resistor divider
const float VCC = 5.0;
const float R_DIV = 3000.0;
double Pmap;
double Fmap;

int Buzzer = 6;

float TotalRange =1.5;

/*****************************************************************************
/

void setup() {
```

```
  //Begin Serial Monitor *******************************************************
  Serial.begin(115200);

  //Establish communication with MPRLS Pressure Sensor ************************
  if (! mpr.begin()) {
    Serial.println("Failed to communicate with MPRLS sensor, check wiring?");
    while (1) {
      delay(10);
    }
  }
  //Serial.println("Found MPRLS sensor");

  //declare pin I/O
************************************************************
  pinMode(pumpPin, OUTPUT);
  pinMode(solenoid,OUTPUT);
  pinMode(Buzzer, OUTPUT);

  //Initial deflate routine that will run once. Will depressurize any air
that's
  //already in the line.
  digitalWrite(solenoid, LOW);   //open inlet valve
  delay(3000);                         //wait 3 seconds for system to deflate
}

float RangeLower = 0;
float RangeUpper = 1.5;


void loop() {
//digitalWrite(solenoidInlet, LOW);
//digitalWrite(solenoidExhaust, LOW);
//delay(10);
// NOTE:(Above) With better solenoids you can close both valves before reading
the pressure in order to get a static pressure
// instead of dynamic. This will lead to much more accurate matching and less
jumping.

  float forceVal = analogRead(FSR_PIN); //reading force pin
  float pressure_Psi = mpr.readPressure()/68.947572932; //reading pressure in
PSI
  Pmap = mapFloat(pressure_Psi,14.5,16,RangeLower,RangeUpper); // mapping force
and pressure to the same range
```

```
    Fmap = mapFloat(forceVal, 0, 1023, RangeLower,RangeUpper);

    //Printing force and pressure values
    Serial.print("Pressure:") ; Serial.println(Pmap);
    Serial.print(",");
    Serial.print("Force:") ; Serial.println(Fmap);

  //simple control loop, if Force > pressure, glove is filled. If Force <
  pressure, glove is deflated
    if (Fmap > Pmap) {
      digitalWrite(solenoid, HIGH);
      digitalWrite(pumpPin, HIGH);
    }
    else {
      digitalWrite(solenoid, LOW);
      digitalWrite(pumpPin, LOW);
    }
    //Add LED controls to loop

    if (Fmap >= 0 && Fmap < (.5)){
      digitalWrite(Buzzer, LOW);}

    else if (Fmap >= (.5) && Fmap < (1)){
      digitalWrite(Buzzer, HIGH);}

    else if (Fmap >= (1)){
      while (Fmap >= (1)){
       digitalWrite(Buzzer, LOW);
       delay(150);
       digitalWrite(Buzzer, HIGH);
       delay(150);
       float forceVal = analogRead(FSR_PIN); //reading force pin
       float pressure_Psi = mpr.readPressure()/68.947572932; //reading pressure
  in PSI
       Pmap = mapFloat(pressure_Psi,14.5,16,RangeLower,RangeUpper); // mapping
  force and pressure to the same range
       Fmap = mapFloat(forceVal, 0, 1023, RangeLower,RangeUpper);
       Serial.print("Pressure:") ; Serial.println(Pmap);
       Serial.print(",");
       Serial.print("Force:") ; Serial.println(Fmap); }
    }
    delay(100);
}
```