A. Significance

Teleoperated Surgical Robotic Systems (TSRSs) allow surgeons to perform minimally invasive surgery (MIS). The benefits of robotic MIS are improved dexterity and precision, restored hand-eye coordination, and enhanced operation environment [1, 2, 3, 4, 5, 6, 7]. The level of significance of each of these benefits is dictated by the surgeon's ability to control the robot and understand the impact of the robot's operations, namely, the technical prowess of the control and feedback methods.

Robot assisted surgery is a relatively young practice in the medical world, and refining their robustness is needed to solidify their place in the operating room [8]. The oldest, and most widely used, TSRS is the Da Vinci Surgical System. The Da Vinci uses robotic arms that are teleoperated by a surgeon at a control console. The surgeon operates the arms with a joystick-like controller. While these controls offer an impressive amount of precision to the robotic arms, they sacrifice the free-hand movement and dexterity a surgeon is used to in a device free operation. The most common TSRSs in the field lack sufficient haptic feedback, including the Da Vinci [9, 10, 11, 12, 13]. Haptic feedback is important information the surgeon needs to avoid exceeding the necessary applied force and ultimately harming the patient [14, 15, 16, 17, 18, 19, 20].

The goal of our project is to develop a TSRS, with haptic feedback, that can be manipulated with the user's hand movements. Future iterations of this device will be scaled down for multiport or single port surgeries, and also include full pinching and grasping capabilities.

B. Innovation

Our device's end effectors are controlled with the user's hand movements. Hand movements offer finer motor control and will allow the system to replicate delicate maneuvers that a traditional robotic interface may struggle with [21]. This design provides an interface for surgeons to directly translate their skills onto the end effectors. The natural control our device offers will reduce the learning curve and make robotic assisted surgery more accessible. Pneumatic haptic feedback is placed under the user's index and middle fingertips. The pressure felt by the pneumatics is mapped to the force applied by the system's end effectors.

Raheja et. al. describes their innovations to hand controlled robotics in a paper submitted to the International Conference on Machine Learning and Computing [22]. This method uses computer vision to capture and assess hand movements. The movements are then identified and matched with pre-existing database of hand gestures. After a gesture is recognized, the system determines the corresponding action to be performed. The researchers were able to replicate 11 hand movements with 90% accuracy. This method is dependent on the user performing gestures that the robot has been trained to repeat, meaning there is no room for unknown movements. This is a problem for surgeons, who need complete control over their tools and have to react to any changing situation. This method will need to become more adaptable to dynamically changing environments for effective use. Our method is taking a similar approach in terms of replicating specific hand movements, but ours allows for a more representative motion because it does not rely on a predetermined data set.

The first iteration of our device used optical sensors to map the angle of bending fingers to end effector articulation. We made the decision to implement optical sensors as they can improve manipulating accuracy and provide shape feedback to the surgeons, as confirmed in Jiang et al [23]. According to Danisch et al. and Sareh et al. optical sensors can provide data to map the bending of an object [24, 25]. This can then be used as a control by taking that mapped bending and applying it to an actuator.

Ultrasound sensors are effective in detecting fine motion [26]. We use these as our back up after running into problems with the optical waveguide sensors. Ultrasound is effective at picking up precise changes in motion as described by Yang et al [27]. The paper describes the use of ultrasound to sense finger motion in real time. This type of sensing is able to penetrate beneath the skin allowing for precision detection of both surface level and muscular changes. The researchers were also able to accurately predict fingertip position and applied force with their sensors.

C. Approach

Aim 1: Integration of haptic feedback into a glove based on force applied to teleoperated robot grasper.

The first aim of our project was to successfully integrate haptic feedback into the glove used to control the robot. Our base glove was made of a semi-elastic cloth material that could stretch to accommodate a range of hand sizes. The control glove was designed to be used on the right hand, since all of our group members were right-handed. A separate glove could be easily fabricated for left-handed users as well. The wearable glove design was chosen due to its inexpensive cost and since its use is generally intuitive [28]. To include haptic feedback, 3D printed attachments were designed to hold a small balloon and attach to the fingertips of the index and middle fingers of the glove via an adjustable elastic strap. We chose to place the balloons for haptic feedback on the fingertips due to the low threshold for sensing pressure-based feedback in this area of the body [29]. The index and middle fingers were chosen as the controlling fingers as well as the fingers that received haptic feedback because a natural grasping motion can be achieved using these two fingers and a stationary thumb.

Figure 1. Control glove haptic feedback setup. Balloons are attached to the 3D printed parts which are secured to the fingertip with an elastic strap.

The robotic grasper was designed with a fixed, stable surface and two controllable graspers that curl toward the fixed surface [30]. We installed a force sensor on the stable surface of the robotic hand so that when the graspers close around an object the force transmitted to the fixed surface is recorded. The recorded force triggered an air pump that inflated the balloons located on the palmar surface of the distal phalange on the index and middle fingers. The inflation was scaled based on the amount of force recorded by the force sensor, with the balloons inflating more with additional force and deflating as the applied force decreased. For testing this aim, we manually applied force to the force sensor instead of using the graspers since the control of the robotic grasper was designed and implemented in the second aim. During testing we had to go through some trial and error to correlate the force recorded on the force sensor with an appropriate amount of inflation in the balloon. In future iterations, we will fabricate our own inflatable pads for the fingertips to better control the size and placement of the pads during inflation. Fabricating our own pads would also allow us to attach the pads to the 3D printed parts better, instead of using the glue and zip ties that can be seen in the image of the current glove. In the future, we would also like to troubleshoot the uneven inflation of the balloons, which we believe may be solved by fabricating the pads using the same material with the same compliance. Despite these challenges, we were able to successfully integrate the haptic feedback based on applied force into the glove on the index and middle fingers (shown in Figure 1).

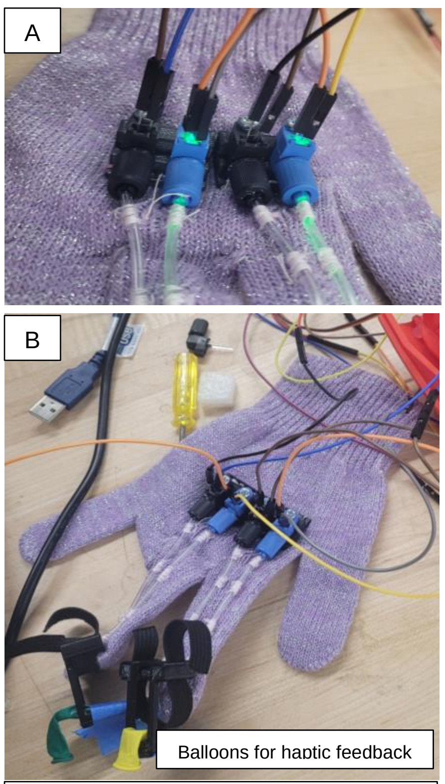

Figure 2. A) Close up of optical sensing setup (black photodiodes, blue LEDs). B) Complete control glove with haptic feedback and optical sensing on index and middle fingers. The balloons can be seen attached to the 3D printed fingertip attachments.

Aim 2: Teleoperation of a robotic grasper using optical sensing attached to a glove.

The second aim of our project was to operate the robotic grasper using the wearable glove briefly described in Aim 1. We attached thin tubes to the dorsal surface of the index and middle fingers starting and ending near the knuckle and looping around the 3D printed fingertip attachment described in Aim 1. One end of each tube was connected to a light emitting diode and the other end was connected to a photodiode. 3D printed mounts were used to hold the LEDs and photodiodes, and the mounts were stitched to the glove to hold them in place. The tubing was also stitched into the glove to hold it straight along the length of the finger. The completed control glove can be seen in Figure 2. In this design, the light from the LED travels through the tube to the photodiode, and when a user bends their finger less light reaches the photodiode resulting in a decrease in the measured voltage. The angle of the finger can be calculated from this voltage loss using an experimentally determined equation. On the side of the robotic grasper, the angle of the bending of the grasper was mapped to the rotation of the motor. The angle calculated based on the change in voltage recorded from the photodiode could then be translated to rotation of the motor to bend the robotic grasper an equivalent amount using finger movements. The robotic grasper is pictured in Figure 3. In future iterations we would miniaturize the robotic grasper so that it can be used as a laparoscopic tool. This addresses the lack of haptic feedback in current laparoscopic instruments and introduces an intuitive control mechanism that could lead to less mental demand on the surgeon.

Due to mechanical failure and issues with the software we were using, we were unable to use the optical sensing for fine motor control of the robotic graspers while also receiving haptic feedback. In order to test the teleoperation of the robotic grasper along with the haptic feedback we used ultrasonic distance sensing to control the robot for our final prototype. Since the ultrasonic sensor required less power from and fewer attachments to the Arduino, we were able to easily control the robot and relay haptic feedback to the glove. We programmed the ultrasonic distance sensor to trigger the robotic graspers to close when the user's hand was 0-10 centimeters away from the sensor, open when the user's hand was 10-20 centimeters away from the sensor, and stay at the current position if the user's hand was more than 20 centimeters away from or not over the sensor. This allowed the user to control the grasping motion of the robot and also receive haptic feedback based on the force applied to the fixed surface of the robotic grasper. To test the device, we developed a test where the user had to grasp a balloon (simulating an organ) using the robotic grasper controlled with the ultrasonic distance sensor. The user had to try to meet a correct force range where the balloons on the fingertips would inflate slightly to provide haptic feedback. If the user applied too much force (outside the target force range) the balloons would continue to expand until the user opened the grasper. If the user applied too little force (below the threshold of the force range) the balloons would not inflate. All group members completed the task, the NASA Task Load Index [31] scores can be seen in Table 1. Based on these scores, controlling the robotic grasper was fairly intuitive and required little mental demand, though the ultrasonic sensor was more frustrating for users to use than we predict the optical sensor to have been. All of the users were able to learn to use the control glove and ultrasonic distance sensing to control the robotic graspers in under five minutes. The graspers also responded well to this type of control mechanism, so it would be interesting to look into incorporating this type of control for different movements like insertion or lateral/vertical movement of the tool.

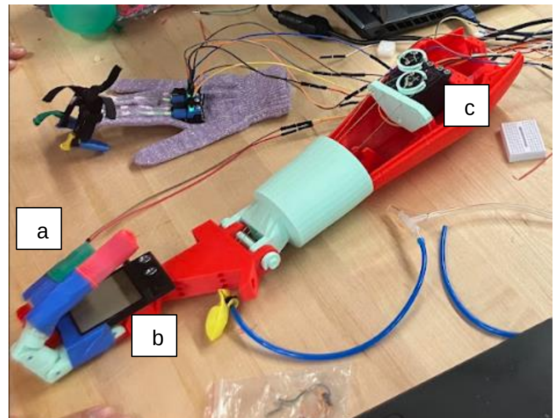

Figure 3. Robotic grasper. A) the two controllable graspers curl towards the b) fixed "palm." The force sensor is mounted on this fixed surface. C) the graspers are cable-driven controlled by the motors on the "forearm."

In the future, we would like to miniaturize the robotic grasper system so it could be used in laparoscopic surgery. Since miniature force sensors that can be used on the tip of laparoscopic instruments have been designed and fabricated before [32], these could be included and connected to the haptic feedback setup we made in Aim 1.

Member	Advaith	Armaan	Celina	Liam	Odin
Mental Demand	50	60	0	150	40
Physical Demand	0	0	5	0	0
Temporal Demand	80	120	250	30	40
Performance	180	140	40	200	200
Effort	100	180	60	60	50
Frustration	100	500	120	120	100
Weighted Total	34	66.66666667	31.66666667	37.33333333	28.66666667
Mean Task Load:		39.66666667	**Standard Deviation:**		15.42364707

Table 1. NASA Task Load scores for each member.

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APPENDIX

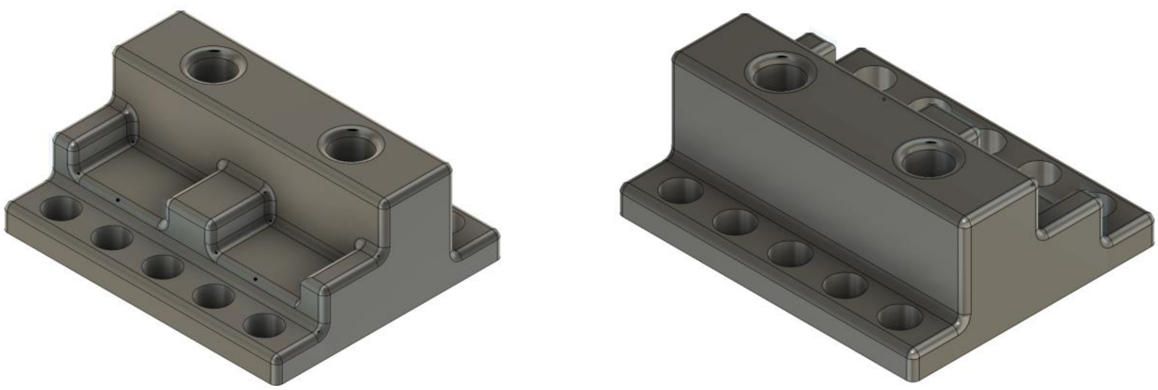

Figure 1: Front and back views of the LED and fiber optic photodiode mount.

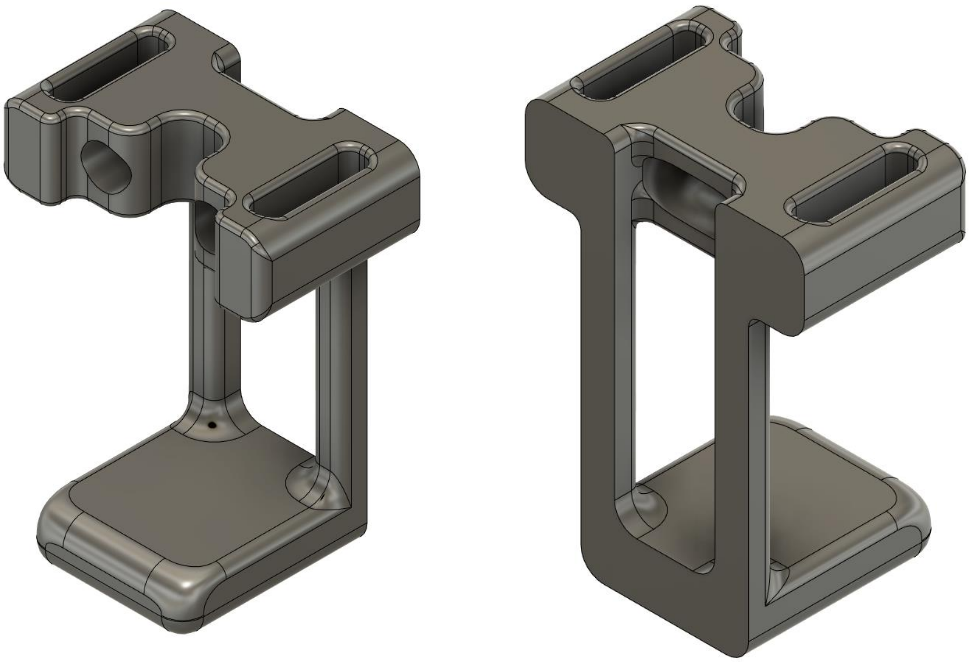

Figure 2: Front and back views of the fingertip balloon mount and optic tube guide.

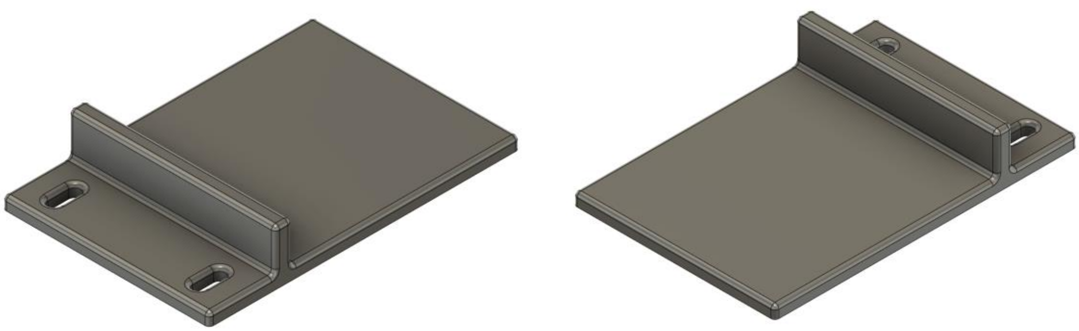

Figure 3: Front and back views of the force sensor mount.