

Low-Cost Wearable Bilateral Teleoperation Platform with Grip-Force Feedback

Design Review

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1 Introduction

1.1 Problem

Many tasks require a person to manipulate objects without being physically present in the operating environment. Hazardous-material handling, remote equipment inspection, and disaster response are common examples. A conventional camera-and-joystick teleoperation system provides visual information but gives the operator little physical information about contact. The operator cannot feel when the gripper touches an object or how strongly the object is being held. Too little force allows the object to slip, while too much force can permanently damage a fragile object. The appropriate grip also changes with the object: a force that securely holds a rigid block may crush a thin-walled cup.

Commercial bilateral teleoperation systems can address this problem with force/torque sensors, torque controlled actuators, and precision mechanical structures, but those systems are too expensive and complex for a small instructional platform. Our project therefore targets the missing electrical and embedded functions in a low-cost proof of concept: wearable motion sensing, robotic motion reproduction, bidirectional digital communication, grip-force sensing, haptic feedback, and automatic grip-force protection. A successful platform would make these ideas easier to study and could support later research in remote maintenance, hazardous inspection, assistive robotics, and carefully supervised medical or emergency-response research. It is not intended or certified for real hazardous, medical, explosive-ordnance, or military operation.

The problem has direct safety and welfare implications because a remote system can separate a person from a dangerous environment, but an unreliable system can also create new pinch, impact, and misuse hazards. Economically, a modular platform built from common sensors, microcontrollers, and small servos can lower the barrier to teleoperation experiments. Socially and globally, lower-cost designs may improve access for teaching and research groups that cannot purchase an industrial bilateral robot. These benefits depend on honest capability claims, careful supervision, and a design that fails safely.

1.2 Solution

The system consists of a wearable leader and a three-axis robotic follower with a gripper. Because new arm-body and glove-body design is not the technical focus, the project will reuse the published 3D printable robot-arm and robotic-glove frameworks described by SmartBuilds and their linked Thingiverse models [1]-[3]. Only the mechanical framework is adopted. The original Arduino, Bluetooth, flex-sensor, inertial-sensor, servo-driver, power, and control implementation is not part of our design. Our team will design the sensing interfaces, custom PCBs, microcontroller firmware, wired protocol, grip-force electronics, haptic feedback, adaptive force limiting, and safety behavior.

The adopted glove frame, together with simple adjustable arm straps and sensor mounts, will carry four team-selected rotary position channels: two principal arm-direction measurements, one elbow-flexion measurement, and one thumb-index measurement. These mounts support the team's sensors without requiring a new wearable-body design. A leader microcontroller samples and filters the signals, maps the calibrated user range to follower joint targets, and sends a command frame through a wired serial link. The adopted follower frame provides the arm and gripper structure; the team integrates and controls the selected base, shoulder, elbow, and gripper axes. Wrist axes present in the source framework will be fixed or left inactive for the three-axis project scope. A clutch button allows the user to freeze the transmitted targets while repositioning the wearable frame.

The reverse path begins at a force-sensitive resistor inside the gripper. The follower measures contact force together with actual gripper position, returns force and status data to the leader, and drives a vibration motor near the operator's index finger. The follower also performs local protection: after contact, it estimates object compliance from the extra gripper travel required for the measured force to

rise between two reference levels. It then selects a conservative force limit for the detected compliance class. Once the limit is reached, further closing commands are rejected even if the user continues to close their fingers. A physical emergency stop, communication timeout, mechanical stops, joint limits, and slew-rate limits provide independent safety layers.

Relationship to ECE 398. Two team members, Godrein Owusu and Junghyun Kim, are also enrolled in a separate ECE 398 independent study that may use the same physical platform; Junseo Kim is not part of that study. The ECE 445 project covers the physical and embedded system, including sensing, custom PCBs, communication, haptic feedback, force limiting, and safety. The ECE 398 study evaluates motion-scaling algorithms and will not claim the ECE 445 hardware or force-feedback system as its contribution.

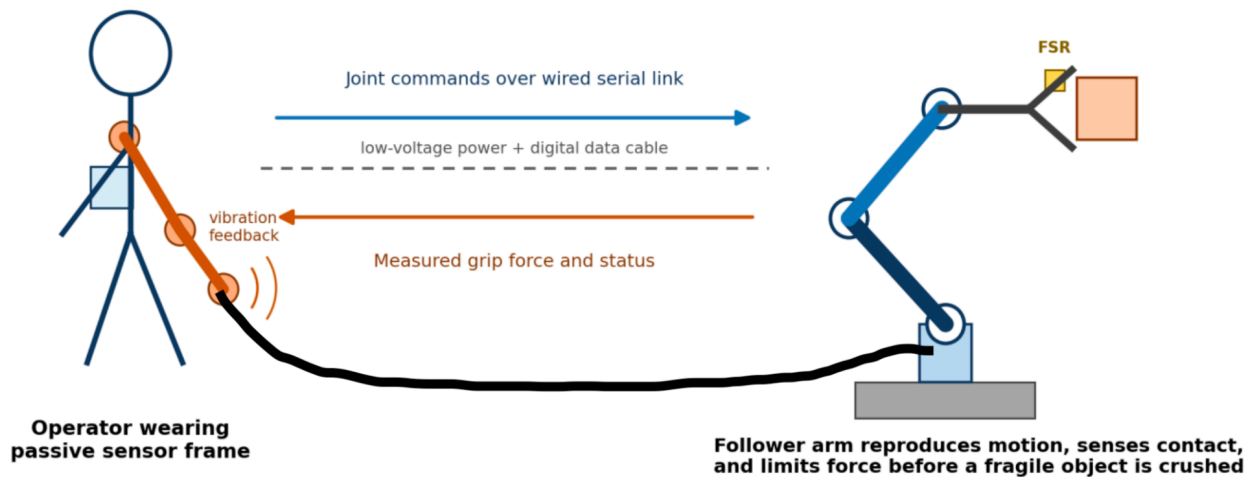


Figure 1 System use in context showing the forward motion path and reverse force feedback path

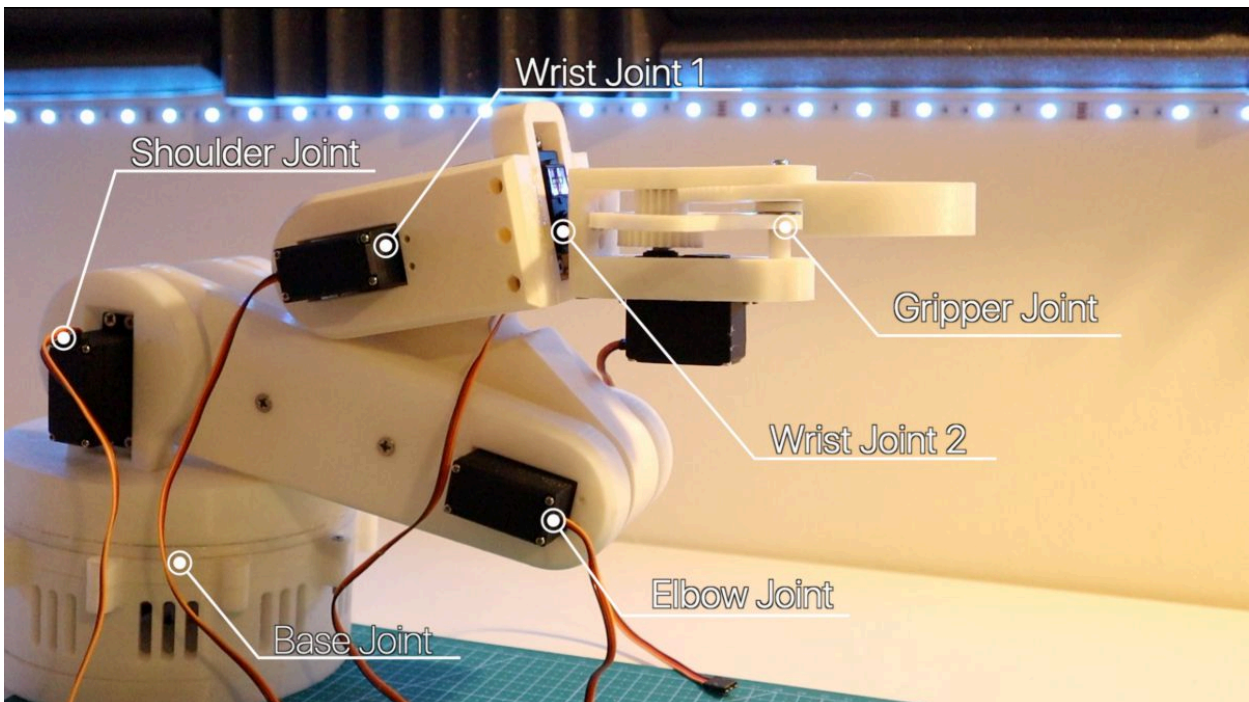


Figure 2 3D printed Robot arm used to pick up items

1.3 High Level Requirements

The following three requirements define whether the completed system solves the stated problem. They are system-level outcomes rather than individual component specifications.

HLR 1. Across the calibrated working range, the follower base, shoulder, and elbow shall reproduce the corresponding leader commands with a mean absolute steady-state angular error of 7 degrees or less. At least 90 percent of valid command messages shall update the follower target positions within 150 ms of leader-side sampling. The latency measurement excludes mechanical servo settling time.

HLR 2. After the configured grip-force limit is reached, the system shall automatically prevent additional gripper closure within 100 ms. With a conservative force limit configured, the follower shall transport an empty paper cup over a distance of at least 200 mm without dropping it or causing a visible tear, permanent crease, or wall collapse in at least 8 of 10 trials.

HLR 3. The system shall provide distinct haptic feedback for no contact, light grip, and strong grip. A blindfolded operator shall correctly distinguish these three conditions using only the haptic feedback in at least 75 percent of 24 randomized trials, with eight trials conducted for each condition.

2 Design

2.1 System Architecture and Interfaces

The design is divided into a wearable leader, a robotic follower, and a power and safety subsystem. Separate microcontrollers keep the wearable analog traces short and allow the connecting cable to carry digital data rather than multiple noise-sensitive sensor voltages. The proposed physical link is half-duplex RS-485 at 115200 bit/s. During every 10 ms control cycle, the leader sends a 16-byte command frame and the follower returns a 12-byte status frame. With one start bit, eight data bits, and one stop bit per byte, the total wire time is $28 \times 10 / 115200 = 2.43$ ms, leaving margin for sampling, filtering, validation, and control while meeting the 150 ms latency requirement in HLR 1.

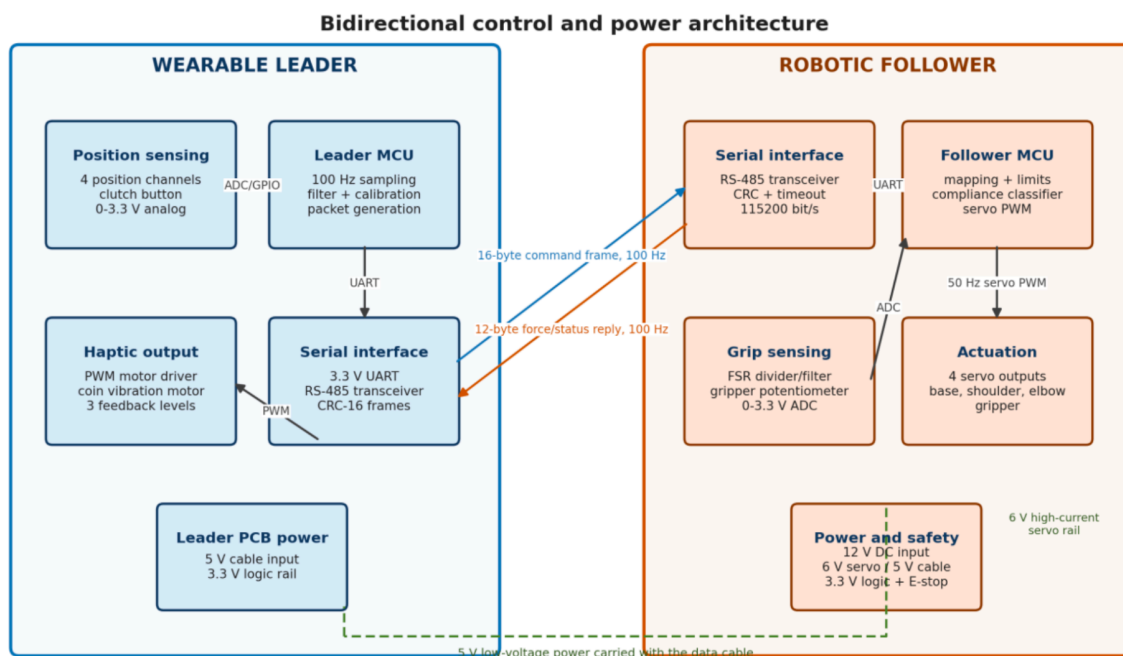


Figure 3 Block diagram with supply rails data interfaces and update rates

Table 1 defines the interfaces shared across subsystem boundaries. These values are design requirements and will be verified at the integrated-system level.

Connection	Signal or protocol	Quantitative definition
Leader sensors -> leader MCU	Four analog channels + clutch GPIO	0-3.3 V ADC; sampled at 100 Hz
Leader MCU <-> follower MCU	UART over half-duplex RS-485	115200 bit/s; CRC-16; 100 Hz request/reply cycle
Follower MCU -> servos	PWM command outputs	50 Hz; software rate and angle limits
FSR / gripper sensor -> follower MCU	Two analog channels	0-3.3 V ADC; sampled at 100 Hz
Follower status -> haptic motor	Force level in reply packet; PWM driver	No contact, light, strong; update at 100 Hz
Power subsystem -> electronics	6 V servo, 5 V cable, 3.3 V logic	Common reference at defined star point; servo return kept off sensor path

Table 1 Quantitative subsystem interfaces

2.2 Wearable Leader and Position Sensing Subsystem

2.2.1 Overview

The adopted passive glove chassis attaches to the hand, while adjustable straps and small sensor mounts locate the remaining team-selected rotary sensors on the forearm and upper arm. Two channels measure the principal arm directions, a third measures elbow flexion, and a fourth measures thumb-index closing. The human shoulder does not rotate about an exposed fixed hinge, so the mechanism is not expected to recover an anatomically exact angle. Instead, the mounted sensors must produce repeatable and monotonic signals that can be calibrated to the follower range. At startup the user holds minimum and maximum comfortable poses; the leader stores those endpoints and maps the resulting ADC range to safe follower joint limits. A low-pass digital filter reduces contact noise without adding excessive delay, and the clutch button freezes the last safe command during user repositioning.

2.2.2 Requirements

- The subsystem shall sample all four position channels and the clutch input at 100 Hz or faster and shall deliver one calibrated command set during every 10 ms control cycle.
- For each arm joint, repeating the same marked user pose ten times shall produce a mapped command with a standard deviation no greater than 3 degrees.
- Each calibrated sensor channel shall use at least 70 percent of the ADC input span over the user's comfortable range without clipping below 0.05 V or above 3.25 V.
- Pressing the clutch shall prevent any newly measured pose from changing the transmitted joint targets within 20 ms. When the clutch is released, the firmware shall re-zero the pose-to-target offset so that control resumes from the held target and the first updated target differs from it by no more than 5 degrees.
- The wearable structure shall remain passive except for sensing and vibration feedback and shall allow the user to remove all straps without tools in less than 5 s.

Contribution to system requirements. Repeatable sensing and bounded filter delay support HLR 1.

The clutch and passive construction reduce the chance that a fitting error or user repositioning creates an unintended robot motion.

2.3 Follower Actuation and Mechanical Integration Subsystem

2.3.1 Overview

The follower reuses the Wonder Tiger 3D-printed arm, base, turntable, and gripper geometry linked by the SmartBuilds build [1], [3]. The mechanical shell is a starting framework rather than an ECE 445 technical contribution. The team will integrate and characterize three selected arm axes - base yaw, shoulder pitch, and elbow pitch - plus the gripper. Unused wrist axes will be mechanically fixed so they cannot move unexpectedly. Because a commanded actuator angle is not a reliable measurement under load, a separate gripper-joint potentiometer measures actual closure. Team-designed mounting features may be added only where necessary for the force sensor, position sensor, PCB enclosure, cable routing, and hard stops. Software joint limits, rate limits, and mechanical stops constrain the operating envelope.

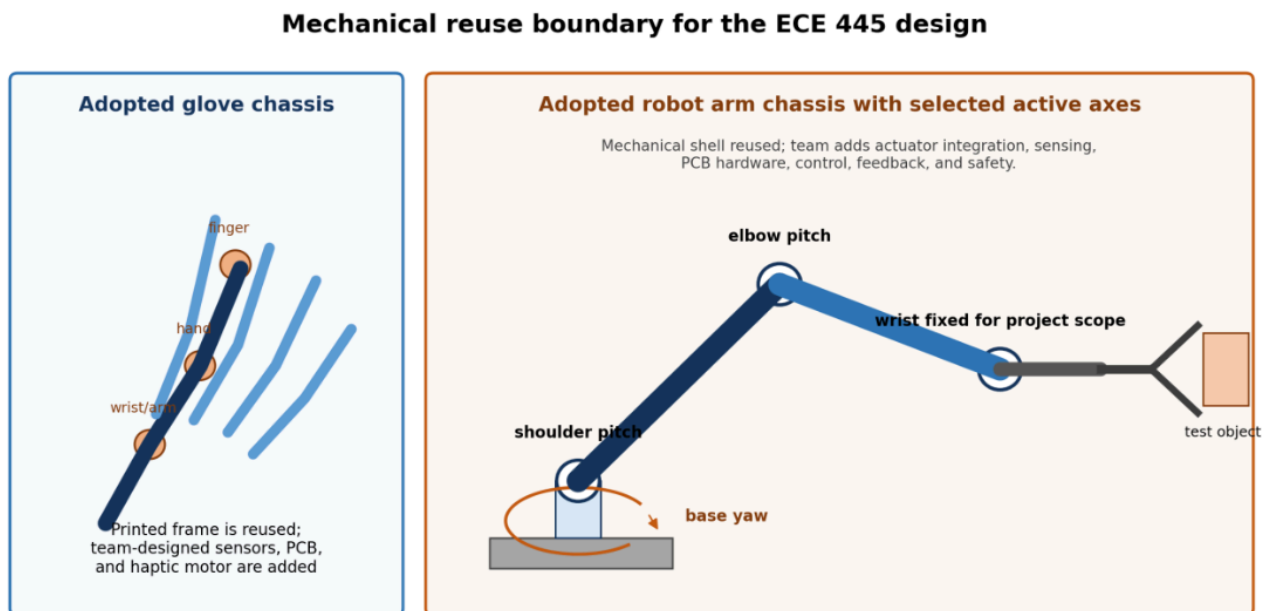


Figure 3 Adopted mechanical frameworks and the boundary of the team designed work

2.3.2 Requirements

- After actuator and sensor integration, the base, shoulder, and elbow shall each traverse the calibrated range without contacting the frame, cable, or adjacent joint, and physical stops shall prevent travel beyond the tested safe range.
- With no external load, the measured arm-joint angle shall settle within 5 degrees of its target within 300 ms after a 20-degree step command.
- The integrated arm shall carry a 100 g object through a path of at least 200 mm for ten repeated trials without an actuator reset, loose fastener, cable snag, or structural interference.
- Normal operation shall limit commanded arm-joint speed to 30 degrees per second or less; a separate test mode may use a different limit only inside a cleared work area.
- The gripper shall provide a measured opening range of at least 40 mm and its added position sensor shall resolve changes of 1 degree or less after filtering.

Contribution to system requirements. Angular response and the payload path directly support HLR 1 and HLR 2. Independent gripper-position measurement is also necessary for the compliance

estimate used to protect the paper cup in HLR 2.

2.4 Grip Force Sensing and Adaptive Force Limiting Subsystem

2.4.1 Overview

A force-sensitive resistor beneath a compliant pad in one gripper finger forms a voltage divider whose output is filtered and sampled by the follower ADC. The FSR is used as a repeatable relative force sensor rather than a precision load cell because its response is nonlinear and depends on the contact interface [5]. Known weights and the final finger pad will be used to establish contact, low-reference, high-reference, and maximum-safe ADC thresholds. The pad spreads contact over the active area and reduces local pressure peaks.

After contact is detected, the controller slows the gripper and records the measured gripper angle when force crosses the low and high reference levels. Let $\theta(F)$ be the actual gripper angle at measured force level F . The compliance index is:

$$D = \theta(F_{\text{high}}) - \theta(F_{\text{low}}) \quad (1)$$

A rigid object needs little additional travel for force to rise between the two levels, so D is small. A compliant object deforms farther, so D is larger. Reference objects establish the classification boundary. The method does not require converting every runtime ADC sample into a highly accurate absolute force value, but it still requires repeatable sensor response, a fixed pad geometry, and calibration. Once a class is selected, the controller applies its corresponding force limit and rejects further closing commands when that limit is reached.

2.4.2 Requirements

- The subsystem shall sample filtered FSR voltage and actual gripper position at 100 Hz or faster and shall detect a calibrated contact threshold within 30 ms of threshold crossing.
- Across ten repeated loading cycles with each reference object, the measured low and high force thresholds shall remain inside non-overlapping calibration bands selected before integrated testing.
- Using at least one rigid reference and one compliant reference, automatic compliance classification will be evaluated as an additional design goal and is not required for successful system operation.
- After the selected force limit is crossed, the controller shall stop increasing the closure target within 50 ms and shall permit no more than 1 additional degree of commanded closure.
- If the force input is disconnected, shorted, or outside its calibrated electrical range, the system shall report a sensor fault and shall prevent further gripper closing.

Contribution to system requirements. Force measurement and bounded closing after the configured force limit provide the object-protection mechanism for HLR 2. The calibrated force levels returned to the leader provide the haptic feedback evaluated in HLR 3. Automatic compliance classification is an additional design goal rather than a high-level acceptance requirement.

2.5 Communication Control and Haptic Feedback Subsystem

2.5.1 Overview

The two microcontrollers communicate over a differential wired serial link. A fixed frame contains a start field, message type, sequence number, joint or force data, status bits, and CRC-16. The follower rejects frames with the wrong length, sequence, or checksum. A fresh valid command resets a 100 ms watchdog; expiration holds the arm targets and disables further closing rather than continuing stale motion. In the reverse direction, the follower sends filtered force, contact state, compliance class, fault state, and sequence acknowledgement. The leader maps the returned force to three clearly separated vibration levels. The cable also carries low-voltage power to the wearable board, so no battery is attached to the operator.

2.5.2 Requirements

- The communication link shall complete one command and one status transfer every 10 ms at 115200 bit/s or faster, with total serialization time no greater than 3 ms per cycle. • Every command and status frame shall include a sequence number and CRC-16; frames with an invalid checksum, length, or sequence shall not update any actuator target.
- If no valid command arrives for 100 ms, the follower shall hold arm targets, prohibit additional gripper closure, and set a communication-fault status until valid traffic resumes or the system is reset. • The leader shall update haptic intensity at least 50 times per second and shall implement three non overlapping output levels for no contact, light grip, and strong grip.
- In 24 randomized blind trials, with eight trials for each feedback state, the operator shall identify the three feedback states with at least 75 percent overall accuracy.

Contribution to system requirements. The update rate and serialization budget support HLR 1, while the feedback-state test directly implements HLR 3. The timeout behavior is retained as a subsystem level safety function.

2.6 Power Safety and Custom PCB Subsystem

2.6.1 Overview

An external 12 V DC supply feeds the follower enclosure. A high-current regulator produces a nominal 6 V servo rail, while regulated 5 V and 3.3 V rails supply the cable and logic. Servo return current is routed directly to the power entry instead of through the sensor ground path. Bulk capacitance near the servo connectors and local decoupling at each board reduce voltage transients. The emergency-stop switch interrupts the servo-power enable path in hardware while leaving the microcontrollers powered so that a fault can be reported. An input fuse and reverse-polarity protection limit damage from wiring faults.

Two custom PCBs partition the design. The leader PCB contains the leader microcontroller, four buffered and filtered sensor inputs, clutch input, haptic driver, serial transceiver, and local regulation. The follower PCB contains the follower microcontroller, four servo connectors, FSR conditioning, gripper-position input, serial transceiver, power regulation, fuse/enable circuitry, and test points. Keeping the boards separate prevents the wearable analog wiring from sharing long paths with high current servo wiring.

2.6.2 Requirements

- With all four servos operating through the demonstrated 100 g motion path, the servo rail shall remain between 5.7 V and 6.3 V and neither microcontroller shall reset.
- The logic rail at each microcontroller shall remain between 3.14 V and 3.47 V during simultaneous servo starts, and sensor readings shall not show a step larger than 2 percent of full scale solely because of a servo transition.
- Pressing the emergency stop shall remove enabled servo power within 50 ms without relying on microcontroller software; logic power and fault reporting may remain active.
- The servo branch shall include overcurrent protection sized below the continuous rating of the installed wiring and connectors, and reverse input polarity shall not energize either PCB. • Each analog input, power rail, serial pair, and safety signal shall have an accessible labeled test point, and the two-layer return layout shall keep high-current servo paths out of the FSR and position-sensor return path.

Contribution to system requirements. Stable rails prevent resets and corrupted measurements that would violate all three high-level requirements. Hardware power interruption and overcurrent protection reduce the consequence of software or wiring faults.

2.7 Tolerance Analysis

The highest technical risk is whether a low-cost FSR and gripper-position sensor can distinguish a rigid object from a compliant one well enough to choose different force limits. The following first-order analysis checks whether the expected separation is larger than measurement uncertainty. Near the contact point, approximate gripper gap g as a linear function of gripper angle θ :

$$g(\theta) = g_0 - k_g \theta \quad (2)$$

where k_g is the measured change in jaw gap per degree. If an object's small-signal compression is $x = C F$, where C is effective compliance in mm/N, then the additional gripper angle between two force references is

$$D = \Delta\theta = C \Delta F / k_g \quad (3)$$

The preliminary geometry target is $k_g = 0.70$ mm/degree. Choose $F_{\text{low}} = 0.5$ N and $F_{\text{high}} = 1.5$ N, so $\Delta F = 1.0$ N. Bench reference objects are expected to bracket a rigid-object compliance no greater than 0.50 mm/N and a compliant-object compliance no less than 3.0 mm/N. Equation 3 then predicts

$$D_{\text{rigid}} \leq 0.50 \times 1.0 / 0.70 = 0.71 \text{ degrees} \quad (4)$$

$$D_{\text{compliant}} \geq 3.0 \times 1.0 / 0.70 = 4.29 \text{ degrees} \quad (5)$$

Assume a conservative plus or minus 0.5 degree uncertainty when recording each threshold angle. Adding endpoint errors linearly gives plus or minus 1.0 degree uncertainty in D . The possible rigid interval is therefore 0 to 1.71 degrees, while the compliant interval begins at 3.29 degrees. A decision threshold of 2.5 degrees leaves 0.79 degrees of margin to each interval. Using the 12-bit ADC specified for the selected microcontroller [4], quantization of a 90-degree gripper-sensor range is approximately $90/4096 = 0.022$ degree per count, so quantization is negligible compared with the assumed mechanical and filtering uncertainty.

This calculation demonstrates feasibility only under the stated compliance and repeatability assumptions. The single-servo bench test will measure k_g , determine force-reference bands with known loads, and repeat each reference-object trial at least ten times. If the measured intervals overlap, the team will increase ΔF within the safe range, change the compliant finger pad to improve repeatability, or reduce the algorithm to a fixed conservative force limit. The fallback preserves contact sensing, haptic feedback, and object protection even if adaptive classification is not reliable. Automatic compliance classification is therefore treated as an additional design goal rather than a high-level acceptance requirement.

2.8 Verification Summary

Verification is organized around the three high-level requirements. Joint accuracy will be measured by comparing marked leader poses with follower angles over repeated trials. Timestamped firmware logs and an oscilloscope GPIO pulse will measure the time from leader-side sampling to the follower target position update. Paper-cup trials will use fixed start and end markers 200 mm apart and will record successful transport, drops, visible tears, permanent creases, and wall collapse over ten trials. The force limiter will be tested by confirming that additional gripper closure is prevented within 100 ms after the configured force limit is reached. Haptic recognition will be evaluated using 24 randomized blind trials, with eight trials each for no contact, light grip, and strong grip. Subsystem tests listed in Section 2 will be completed before the corresponding integrated tests so that failures can be localized. Automatic compliance classification will be evaluated separately as an additional design goal rather than as a high-level acceptance requirement.

3 Cost and Schedule

3.1 Cost

The total cost for parts as seen below in table 2 before shipping is \$185.32 shipping cost adds another \$8.49 and \$3.48 tax and a \$9.31 cost in tariffs. We also paid about \$115 for the 3D print with a rough \$15 in shipping. We can expect a cost of \$112.2 per team member. We were told that each student in the group gets around 50\$ roughly to use on this project that the ECE department will pay for so we plan to split the rest of the cost left over equally between us all to afford the rest of the project. With this project we can expect a salary of $\$37.5/\text{per hour} \times 2.5\text{hr} \times 60 = \5625 . We then can multiply this by 3 members to get \$16,875.

Description	Manufacturer	Quantity	Unit Price	Extended Price
STEMMA QT AS5600 MAGNETIC ANGLE	Adafruit Industries LLC	6	5.95000	\$35.70
EVAL BOARD FOR TCA9548A	Adafruit Industries LLC	1	6.95	6.95
EVAL BOARD FOR PCA9685	Adafruit Industries LLC	1	14.95000	14.95
SENSOR RESISTIVE 3US ANALOG	Interlink Electronics	3	7.12000 (+1.81126 tariff)	21.36 (+ 5.43 tariff)
MAGNET 0.315"D X 0.098"THICK CYL	Radial Magnets, Inc.	8	0.77800 (+0.20423)	\$6.22 (+\$1.63)
POT 10K OHM 1/4W PLASTIC LINEAR	Bourns Inc.	6	5.51000 (+ 0.37468)	\$33.06 (+\$2.25)
PRE-CUT MULTI-COLORED HEAT SHRIN	Adafruit Industries LLC	1	9.95000	\$9.95
SERVO EXTENSION CBL 30CM	Adafruit Industries LLC	10	1.95000	\$19.50
Nema 17 Stepper Motor	Amazon	1	11.99	11.99
6-Pack MG996R	Amazon	1	25.64	25.64

Table 2 Part costs from [Digikey](#) and [Amazon](#)

3.2 Schedule

Week of	Task	Person
October 5th	Design Review	Everyone
	Connect 3D printed components	Junghyun
	Complete follower PCB	Godrein
	Start motor implementation	Junseo
October 12th	Continue Board Assembly	Everyone
	Use development board to test code and signals	Junseo & Godrein
	Continue to connect 3D printed components together	Junghyun
October 19th	Solder leader PCB (1st round) with components together	Godrein/Junghyun
	Continue motor/sensor implementation	Junseo & Godrein
	Test leader if PCB works after soldering	Everyone
October 26th	Continue leader and follower code implementation	Junseo & Godrein
	Connect motors and base together	Junghyun
	Make final changes for last PCB order (*if needed)	Everyone
	Solder follower PCB together	Junghyun
November 2nd	Progress Report	Everyone
	Work on ECE 398 Project	Junghyun & Godrein
	Work on allowing for both the leader and follower to communicate	Everyone
November 9th	Finalize Assembly	Everyone
	Practice Mock Presentation	Everyone
	Work on ECE 398 Project	Junghyun & Godrein

November 16th	Mock Demo	Everyone
	Finish minor bugs	Everyone
November 23th	FALL BREAK	Everyone
	Finalize final presentation by practicing	Everyone
November 30th	Final Demo	Everyone

4 Ethics Safety and Societal Impact

4.1 Ethical Responsibilities

The IEEE Code of Ethics places public safety and welfare first and requires engineers to disclose factors that might endanger people or the environment, avoid deceptive acts, and make claims based on available evidence [6]. For this project, that means the team will report failed trials and uncertainty rather than describing a prototype as ready for medical, explosive-ordnance, or hazardous-material work. Demonstrations will use benign objects in a controlled area, and any video or report will identify the device as an instructional proof of concept. The team will also document calibration conditions because changing the finger pad, object geometry, or FSR mounting can invalidate the force thresholds. Reused mechanical files and ideas will be attributed to their original creators, and the team will confirm and follow the applicable file licenses before fabrication.

Haptic-recognition tests will involve only consenting adult participants, will collect no identifying or sensitive information, and will begin only after the team confirms with course staff whether formal IRB review is required. During blindfolded trials, participants will interact only with the wearable haptic device and will remain outside the robot's guarded operating area. Participants may stop the test at any time.

The platform is dual use: the same affordability that benefits education could encourage unsafe deployment or remote manipulation without adequate oversight. We will reduce that risk through visible limitations, supervised operation, published safe operating ranges, and a design that requires deliberate local power-up. We will not present adaptive force limiting as a substitute for certified guarding, redundant safety controls, or trained operators.

4.2 Safety Hazards and Controls

The principal development hazards are finger pinching, unexpected arm movement, a snagged wearable frame, and overheating caused by actuator current or wiring faults. Risk reduction follows the hierarchy in ISO 12100: first constrain energy and motion through low speed, limited force, fixed unused axes, and mechanical stops; then add protective functions such as the emergency stop and communication timeout; finally provide warnings and operating procedures [7]. The emergency stop is designed as a hardware interruption of actuator power, consistent with the design principles of ISO 13850, rather than as a normal software stop [8]. ISO 10218-1 is written for industrial robots, so this prototype will not claim compliance, but its emphasis on controlled motion, limits, and risk reduction is relevant design guidance [9].

Hazard	Possible consequence	Planned control
Pinch or impact from the moving arm	Finger injury or damaged object	Low speed; guarded test zone; software and mechanical limits; accessible E-stop; supervised operation
Communication failure or corrupted command	Uncontrolled continuation of motion	CRC-16 rejection; sequence checking; 100 ms timeout; no further closing command after timeout
Servo overcurrent or wiring fault	Hot wiring, reset, or component damage	Current-rated conductors/connectors; input fuse; separated rails; bulk and local decoupling; pre-power inspection
Wearable snag or misalignment	Discomfort or restricted motion	Passive low-force frame; rounded edges; adjustable straps; quick removal; calibration within comfortable range
Intentional misuse or exaggerated capability claims	Use in unsafe medical, explosive, or hazardous settings	Proof-of-concept labeling; documented limits; no unsupervised or safety-critical use; honest reporting of test results

Table 2 Project specific hazards and planned controls

Before each powered test, the team will inspect connectors and reused printed parts, confirm that fixed wrist axes and fasteners are secure, clear the work area, test the emergency stop at low speed, and begin with no object in the gripper. The wearable will be removed before mechanical adjustment. Power will be disconnected before rewiring. The system uses only low-voltage DC outside the enclosed wall adapter, and exposed conductors will be insulated. These controls supplement the ECE 445 laboratory safety rules [10].

4.3 Societal Economic Environmental and Global Context

A successful low-cost platform can make bilateral teleoperation experiments accessible to more students and smaller laboratories. Potential long-term applications include inspection of contaminated or structurally unsafe areas, remote maintenance, disaster response, assistive manipulation, and research toward remote medical systems. The immediate project does not establish the reliability, sterilization, cybersecurity, precision, or regulatory evidence required by those applications, so they are future contexts rather than promised uses.

The design's economic benefit comes from modular replacement of sensors, servos, printed parts, and PCBs instead of replacing an integrated commercial system. That same modularity reduces environmental impact by making damaged parts repairable. The project will minimize unnecessary printed iterations, reuse development boards during bring-up, label wiring and PCB revisions, and separate electronic waste for appropriate campus disposal. Globally, common components and open documentation may improve reproducibility, but supply availability and local safety practices vary; therefore the final documentation will state component-independent interface requirements rather than assuming one vendor or region.

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