

ECE 445
SENIOR DESIGN LABORATORY
DESIGN DOCUMENT

SoftReach Arm

Team #4

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1 Introduction

1.1 Problem and Solution

1.1.1 Problem

Underwater object retrieval remains difficult because target objects are often located at uncertain positions on the seafloor and are difficult to access using conventional rigid manipulators. In submerged environments, the robot must operate with limited tolerance for alignment error while reaching outward from a fixed mounting point. Even moderate uncertainty in object location can lead to failed retrieval attempts if the manipulator requires highly precise positioning or cannot adapt during final contact. This challenge becomes more significant when the target is not directly adjacent to the base and must be reached through an extended structure.

Conventional rigid retrieval mechanisms generally perform best when the target location and contact geometry are accurately known in advance. In underwater settings, however, rigid systems often require tighter alignment, more complex positioning control, and greater structural complexity to reach and grasp an object successfully. As a result, retrieval performance degrades when the target object is located at an uncertain position or when compliant contact is needed during the final grasping stage.

The central engineering problem of this project is therefore to develop an underwater robotic grasping system that can extend from a compact base, reach a target object at an uncertain location, and grasp it reliably while remaining practical to fabricate, control, and demonstrate within a senior design setting.

1.1.2 Solution

Our proposed solution is *SoftReach Arm*, an underwater robotic retrieval system that combines a retractable support structure with a compliant soft arm and a soft two-finger gripper. The system is mounted on a base and deploys outward into the underwater workspace toward a nearby target object. Once the arm has extended to the required position, the soft two-finger gripper approaches the object and closes around it to complete the grasp.

This design directly addresses the retrieval problem by combining deployable reach with compliant grasping. The retractable structure allows the system to extend from a compact base toward objects that are not immediately adjacent to the mounting point, while the soft gripper provides tolerance during final contact and reduces the need for perfect alignment. In contrast to a purely rigid mechanism, the compliant grasping structure can better accommodate moderate uncertainty in object position during the final retrieval step.

The implementation is modular and practical for a capstone-scale prototype. The extendable portion uses a retractable structure similar to a tape measure, based on a curved C-shaped carbon fiber strip. When deployed, the carbon fiber strip provides sufficient

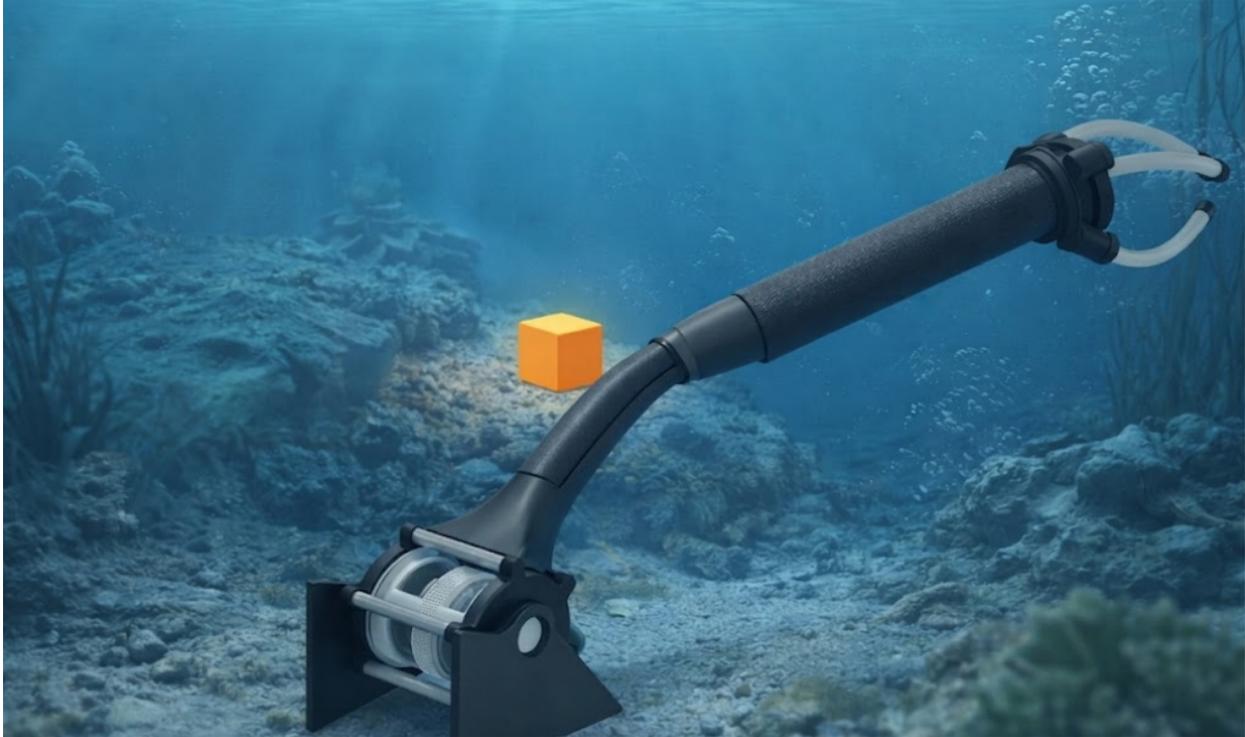


Figure 1: Contextual visual aid for the underwater SoftReach Arm. The retractable soft robotic arm is deployed from its base on the seafloor and extends toward a target object in the underwater workspace, illustrating how the final system is used for underwater grasping under object-location uncertainty.

stiffness to support the distal arm and gripper. When retracted, it can bend and roll back onto the drum in the base, enabling compact storage and repeated use. At the distal end, a soft two-finger gripper performs the final grasping action. Pneumatic actuation was selected because it enables large deformation, fast response, and a relatively simple mechanical structure, making it well suited for the intended underwater prototype.

1.2 Visual Aid

Figure 1 shows the main functional behavior of the final solution rather than only its isolated mechanical structure. The lower base contains the retractable deployment mechanism, which supports and extends the arm away from the mounting point. The long compliant arm then reaches into the workspace while maintaining sufficient structural support, and the soft two-finger gripper at the distal end approaches the target object for grasping. This configuration is appropriate for underwater use because it allows the system to access objects that are not positioned directly next to the base while still providing a compliant end effector for adaptive contact. By showing the deployed arm reaching toward the object in the underwater environment, the figure demonstrates how the final solution combines reach, compliance, and grasping capability in a realistic use case.

1.3 High-level Requirements

- SoftReach Arm shall successfully grasp, lift, and hold each object in the defined underwater test object set for at least 3 seconds with a success rate of at least 80% over 10 trials per object under the specified test conditions.
- SoftReach Arm shall be able to reach and grasp target objects located within a horizontal distance of at least 8 cm from the base mounting point in the defined underwater workspace.
- SoftReach Arm shall complete one full retrieval cycle, including arm deployment, arm positioning, gripper closure, and object lift, in no more than 15 seconds per trial, measured from the start of actuation to successful object lift.

2 Design

2.1 Overall System Architecture and Block Diagram

2.1.1 Block Diagram

Figure 2 shows the overall architecture of the hybrid-actuated soft robotic system, which consists of three main modules: the Power Module, Control Module, and Actuation Module.

The Power Module provides a 12V DC supply to the entire system. A buck converter is used to step down the voltage to 5V for the Arduino microcontroller, ensuring stable operation of the control electronics. The Control Module is centered around the Arduino, which serves as the main processing unit. It generates control signals for both the motor driver and the solenoid valve. The motor driver regulates the direction and speed of the motor for linear extension and retraction, while a MOSFET is used to switch the solenoid valve for pneumatic control of the gripper.

The Actuation Module consists of two subsystems: a motor-driven extension mechanism and a pneumatic soft gripper. The motor enables controlled linear motion of the main body, while the solenoid valve controls the airflow from the air pump to actuate the soft gripper for grasping. Power flow and signal flow are clearly distinguished in the diagram. The power flow supplies energy to all components, while the signal flow represents control commands from the microcontroller to the actuators.

This modular design allows independent control of extension and grasping, improving system flexibility, reliability, and ease of integration. In addition to the overall system-level block diagram, the detailed design of the soft gripper and the retractable arm structure is further illustrated in the following subsections.

2.1.2 Gripper Design

This design adopts a three-finger soft robotic gripper configuration. Each finger is constructed from a flexible tubular structure and achieves bending through asymmetric de-

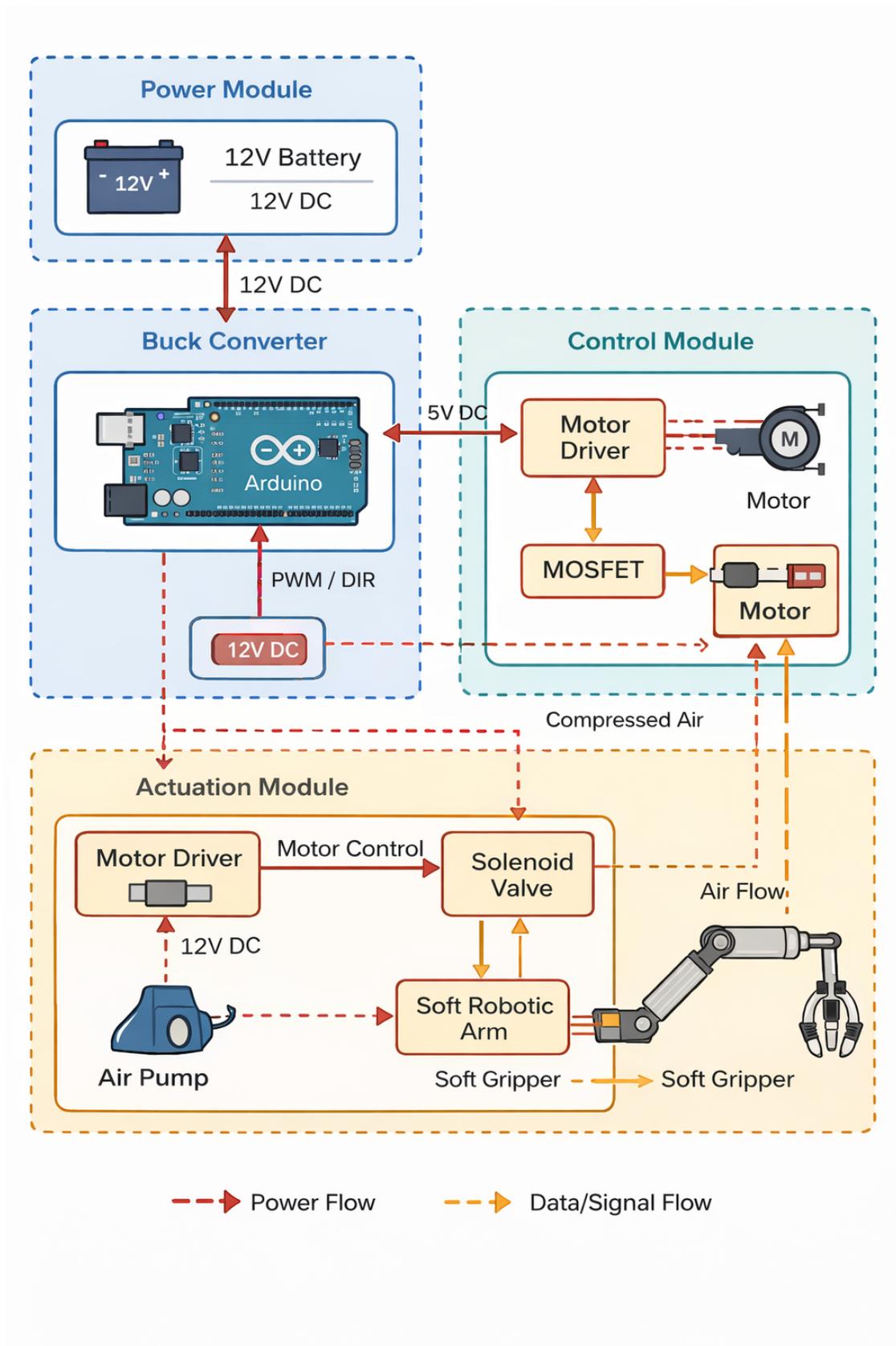


Figure 2: Block diagram of the hybrid-actuated soft robotic system

formation induced by a fiber constraint layer attached along one side. In addition, an outer latex coating is applied to enhance the overall compliance and mechanical performance of the structure.

The gripper is driven by a single air source. When pressurized air is supplied to the internal chamber, all three fingers inflate simultaneously and bend toward the center, enabling the gripper to envelop and grasp target objects. This actuation principle allows the gripper to conform to object geometry while maintaining a relatively simple pneumatic architecture.

To ensure airtight connections, a protruded fitting geometry is designed at both ends of the soft tubes. The tubes are then secured using zip ties, providing reliable sealing through external compression. Representative design illustrations and implementation details of the gripper are shown in Figure 3.

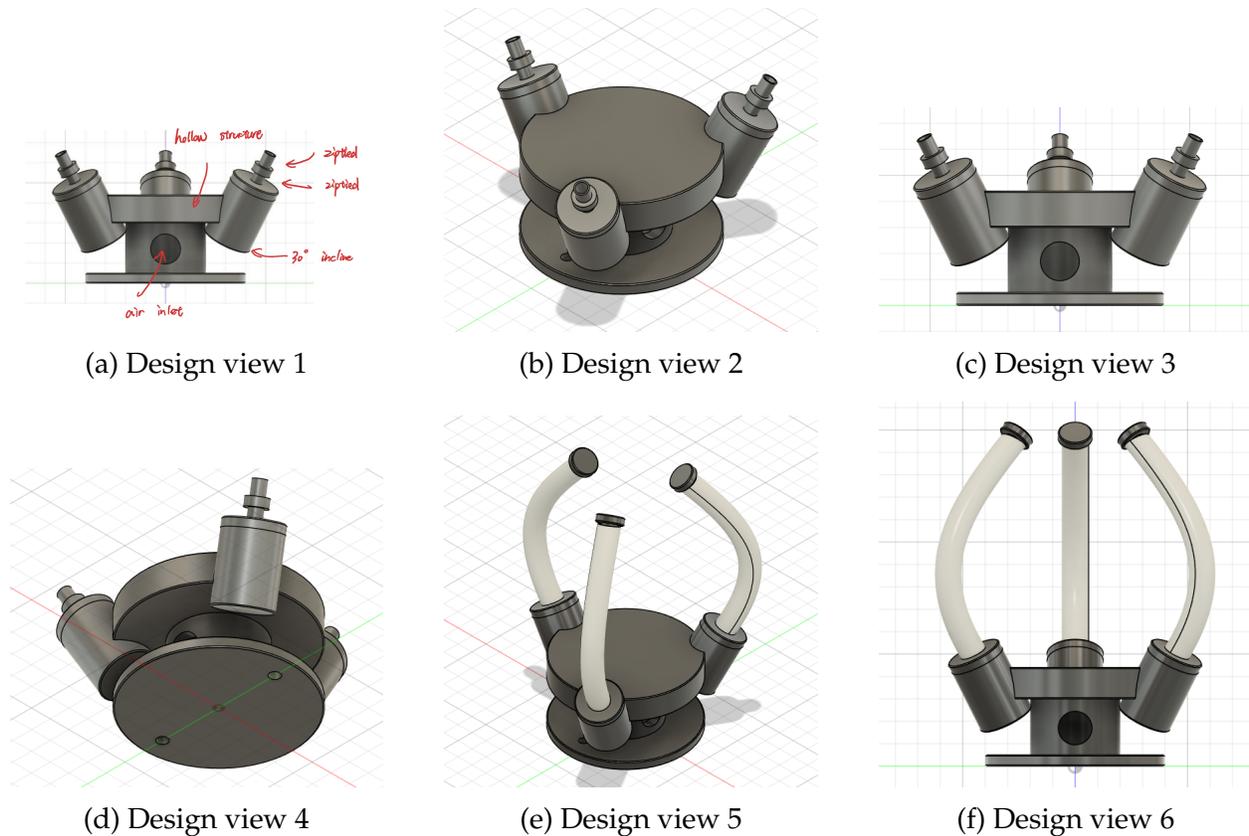


Figure 3: Representative images of the three-finger soft robotic gripper design

2.1.3 Retractable Arm Design

This design uses a retractable structure similar to a tape measure. The extendable part is made of a curved, C-shaped carbon fiber strip. When extended, the curved carbon fiber provides sufficient stiffness, allowing it to support the claw section at the front and maintain stability during operation.

When retracted, the carbon fiber strip can bend and roll back like a tape measure, winding around the drum located below. This retractable mechanism enables compact storage while preserving structural support during extension. By combining lightweight properties, structural rigidity, and retractability, this design is suitable for mechanical systems that require an extendable supporting structure.

Representative design illustrations of the retractable arm are shown in Figure 8. These images further demonstrate the structural concept and the physical arrangement of the extension mechanism.



Figure 4: Representative images of the retractable arm design

2.2 Power Subsystem

2.2.1 Subsystem Description

The power subsystem is responsible for supplying regulated electrical power to the entire SoftReach Arm system. As shown in Figure 2, a 12V DC battery serves as the primary power source for the system. This 12V supply is distributed to the actuation hardware,

including the motor-driving circuitry, motor, air pump, and solenoid valve. A buck converter is used to step the 12V supply down to 5V for the Arduino and other low-voltage control electronics.

This architecture separates the high-power actuator supply from the regulated low-voltage control supply. Such separation improves reliability by reducing the risk that transient load changes from the motor, pump, or valve will disturb the controller power rail. The power subsystem therefore interacts directly with both major downstream subsystems: it powers the Control Subsystem through the regulated 5V output and powers the Actuation Subsystem through the 12V output. In this way, the subsystem supports stable command generation, actuator operation, and integrated system functionality during deployment and grasping.

2.2.2 Subsystem Requirements

The power subsystem shall satisfy the following requirements:

- The subsystem shall provide a regulated 12.0V DC actuator supply of 12.0 ± 0.5 V during normal system operation.
- The subsystem shall provide a regulated 5.0V DC control supply of 5.0 ± 0.1 V to the Arduino and control electronics during normal system operation.
- The subsystem shall supply at least 2.0 A total current to the combined control and actuation loads without causing controller reset, loss of actuation, or unacceptable voltage droop.
- The subsystem shall maintain both the 12V and 5V outputs within their specified voltage ranges during a complete system operating cycle, including arm deployment, gripper actuation, and reset.
- The subsystem shall support at least 15 minutes of continuous benchtop operation without requiring battery replacement, manual reconnection, or system restart.

2.2.3 Subsystem Verification

The power subsystem will be verified using electrical measurements and integrated load testing.

1. **12V output verification:** Using a digital multimeter, measure the battery output at the actuator supply terminals under nominal operating load. The subsystem passes this test if the measured voltage remains within 12.0 ± 0.5 V.
2. **5V output verification:** Using a digital multimeter, measure the buck converter output at the Arduino supply terminals while the controller is powered and active. The subsystem passes this test if the measured voltage remains within 5.0 ± 0.1 V.
3. **Load capability verification:** Operate the Arduino, motor-driving circuitry, motor, air pump, and solenoid valve together in an integrated test condition representing

the maximum expected operating load. The subsystem passes this test if the controller does not reset, all commanded actuators respond correctly, and the measured 12V and 5V rails remain within their specified limits throughout the test.

4. **Cycle stability verification:** Run the system through repeated deployment, grasping, and reset cycles for 10 consecutive trials. The subsystem passes this test if no loss of power, controller reset, or voltage excursion outside the specified ranges occurs during any trial.
5. **Continuous operation verification:** Operate the complete system continuously for 15 minutes under normal demonstration conditions. The subsystem passes this test if power is maintained for the full duration without manual intervention, restart, or failure of the control or actuation hardware.

2.3 Control Subsystem

2.3.1 Subsystem Description

The control subsystem is responsible for generating and coordinating the electrical control signals required for both arm deployment and pneumatic grasping. As shown in Figure 5, the subsystem is centered around the Arduino microcontroller, which serves as the main command-generation unit of the SoftReach Arm system. The Arduino receives regulated low-voltage power from the power subsystem and produces control outputs for the deployment and grasping paths.

For arm deployment, the control subsystem sends PWM and direction signals to the motor-driving interface, which then drives the extension motor used to extend or retract the main body. For pneumatic grasping, the Arduino sends a digital switching signal to a MOSFET-based interface, which energizes or de-energizes the solenoid valve controlling airflow to the soft gripper. In this way, the control subsystem interfaces directly with the actuation subsystem by converting low-power logic commands into signals that control higher-power electrical and pneumatic actuators.

The control subsystem therefore performs three main functions: command generation, timing coordination, and independent actuator control. It ensures that extension and grasping can be executed separately or in sequence, allowing the system to deploy toward a target, stop at the required position, actuate the gripper, and then retract if needed. By separating the deployment control path from the pneumatic control path while coordinating both through one controller, the subsystem improves modularity, simplifies integration, and supports reliable overall system operation.

2.3.2 Subsystem Requirements

The control subsystem shall satisfy the following requirements:

- The subsystem shall generate logic-level control outputs of 0–5.0 V for both the motor-control path and the solenoid-valve control path, with logic-high voltage not less than 4.5 V and logic-low voltage not greater than 0.5 V.

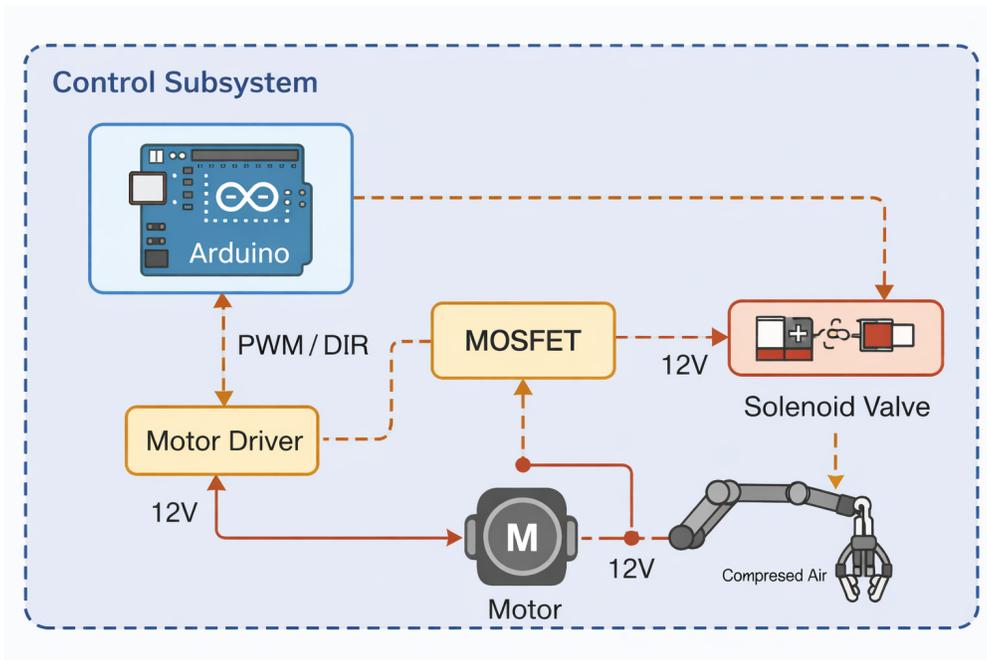


Figure 5: Control subsystem diagram of the hybrid-actuated soft robotic system.

- The subsystem shall provide PWM and direction commands to the motor-driving interface at an update rate of at least 20 Hz during active arm deployment and retraction.
- The subsystem shall command the solenoid-valve control path with an electrical response time of no more than 100 ms from the controller command to MOSFET gate switching.
- The subsystem shall support independent control of the deployment mechanism and the pneumatic gripper such that commanding one path does not unintentionally trigger motion or switching in the other path.
- The subsystem shall execute a complete command sequence consisting of deploy, stop, grip, release, and retract for 10 consecutive trials without controller reset, missed command output, or unintended actuator activation.

2.3.3 Subsystem Verification

The control subsystem will be verified through signal measurement and integrated functional testing.

1. **Logic-level output verification:** Measure the Arduino output pins used for the motor-control path and the MOSFET control path using a multimeter or oscilloscope. The subsystem passes this test if logic-high output is at least 4.5 V and logic-low output is at most 0.5 V on all required control lines.
2. **Motor-command verification:** Command the controller to issue extend, retract, and

stop signals while observing the motor-driving interface and deployment motor response. The subsystem passes this test if the correct PWM and direction signals are produced and the deployment motor responds correctly to all three commands in 10 consecutive trials.

3. **Solenoid-control verification:** Command the controller to switch the gripper control path on and off while monitoring the MOSFET gate signal and the solenoid-valve response. The subsystem passes this test if MOSFET switching occurs within 100 ms of the controller command and the solenoid valve actuates correctly in 10 consecutive trials.
4. **Independent-path verification:** Command the deployment path and pneumatic path separately while observing the inactive path for unintended behavior. The subsystem passes this test if commanding the motor path does not unintentionally switch the solenoid valve, and commanding the solenoid-valve path does not unintentionally drive the deployment motor.
5. **Integrated sequence verification:** Run the controller through a full sequence of deploy, stop, grip, release, and retract for 10 consecutive cycles. The subsystem passes this test if all command outputs occur in the intended order, no controller reset occurs, no command is missed, and no unintended actuator activation is observed during any cycle.

2.4 Actuation Subsystem

2.4.1 Subsystem Description

The actuation subsystem is responsible for converting electrical control commands into the physical motions required for deployment and grasping in the SoftReach Arm system. As shown in Figure 2, this subsystem contains two coordinated but functionally distinct actuation paths: a motor-driven deployment path and a pneumatic grasping path.

The motor-driven deployment path is responsible for extension and retraction of the main body. It includes the motor, motor-driving interface, and retractable mechanical structure. When the control subsystem issues deployment commands, this path converts electrical power and control signals into controlled mechanical motion so that the arm can extend outward from the base, stop at the required position, and retract when needed. This path therefore provides the reach function of the overall system.

The pneumatic grasping path is responsible for actuating the soft gripper. It includes the air pump, solenoid valve, pneumatic tubing, and soft gripper. The air pump provides compressed air, and the solenoid valve regulates when airflow is delivered to the gripper. When commanded by the control subsystem, this path inflates the soft gripper so that the gripper can close around the target object and perform the final grasping action. This path therefore provides the compliant end-effector function of the system.

The actuation subsystem interacts directly with both the power subsystem and the control subsystem. It receives electrical power from the power subsystem for operation of

the motor, air pump, and valve-driving hardware, and it receives low-power control commands from the control subsystem for deployment and grasping. In response, it produces the physical extension, retraction, and gripping actions required by the overall robot. By separating deployment from grasping while integrating both into one subsystem, the design improves modularity, simplifies debugging, and allows the robot to reach and grasp using two independently controlled actuation mechanisms.

2.4.2 Subsystem Requirements

The actuation subsystem shall satisfy the following requirements:

- The motor-driven deployment path shall provide an extension stroke of at least 8.0 cm from the base mounting point, with end-position repeatability within ± 0.5 cm over 10 consecutive trials.
- The motor-driven deployment path shall complete a full commanded extension or full commanded retraction in no more than 10.0 s per motion.
- The pneumatic grasping path shall actuate the soft gripper within 1.0 s of the control command to the solenoid valve.
- The soft gripper shall be capable of grasping, lifting, and holding a target object with mass up to 100 g for at least 3.0 s without dropping the object.
- The deployment path and the pneumatic grasping path shall operate independently such that commanding one path does not unintentionally actuate the other path.
- The complete actuation subsystem shall execute 10 consecutive deploy–grip–release–retract cycles without actuator stall, pneumatic leakage that prevents grasping, or unintended motion.

2.4.3 Subsystem Verification

The actuation subsystem will be verified through separate path-level tests followed by integrated system testing.

1. **Deployment stroke verification:** Command the system to fully extend from its initial position and measure the horizontal displacement of the deployed arm relative to the base mounting point using a ruler or caliper. Repeat for 10 trials. The subsystem passes this test if the measured stroke is at least 8.0 cm and the final position is repeatable within ± 0.5 cm across the 10 trials.
2. **Deployment timing verification:** Measure the time required for one full commanded extension and one full commanded retraction using a stopwatch or video timing analysis. Repeat for 10 trials. The subsystem passes this test if each full extension and each full retraction is completed in no more than 10.0 s.
3. **Gripper response verification:** Command the pneumatic path to actuate the gripper while measuring the time from the electrical valve command to visible gripper

closure. Repeat for 10 trials. The subsystem passes this test if the gripper closes within 1.0 s in all 10 trials.

4. **Load-holding verification:** Place a 100 g test object in the gripper, actuate the gripper, lift the object clear of the support surface, and hold for 3.0 s. Repeat for 10 trials. The subsystem passes this test if the object is successfully grasped, lifted, and held for at least 3.0 s without dropping in at least 8 of the 10 trials.
5. **Independent-path verification:** Command deployment without gripper actuation and then command gripper actuation without deployment. Observe both paths during each test. The subsystem passes this test if no unintended gripper actuation occurs during deployment-only commands and no unintended deployment motion occurs during gripper-only commands.
6. **Integrated cycle verification:** Run the full actuation sequence of deploy, grip, release, and retract for 10 consecutive cycles under normal operating conditions. The subsystem passes this test if all cycles are completed in the intended order with no actuator stall, no failure of gripper actuation due to pneumatic leakage, and no unintended motion in any trial.

2.5 Supporting Material

To supplement the subsystem descriptions, representative reference figures of key components are provided in this section. These materials are not intended to redefine the system architecture, but to clarify the physical meaning of several major components already introduced in the block diagram.

Figure 6 shows a representative Arduino development board corresponding to the microcontroller platform used in the control subsystem. In the current system architecture, the Arduino serves as the main processing unit and generates the control signals for both the motor driver and the solenoid valve control path.



Figure 6: Representative Arduino development board used as the controller reference

Figure 7 illustrates the operating principle of a solenoid valve. In the hybrid-actuated soft robotic system, the solenoid valve is the key switching element in the pneumatic path. It controls the airflow from the air pump to the soft gripper, allowing the system to perform pneumatic grasping under electrical control.

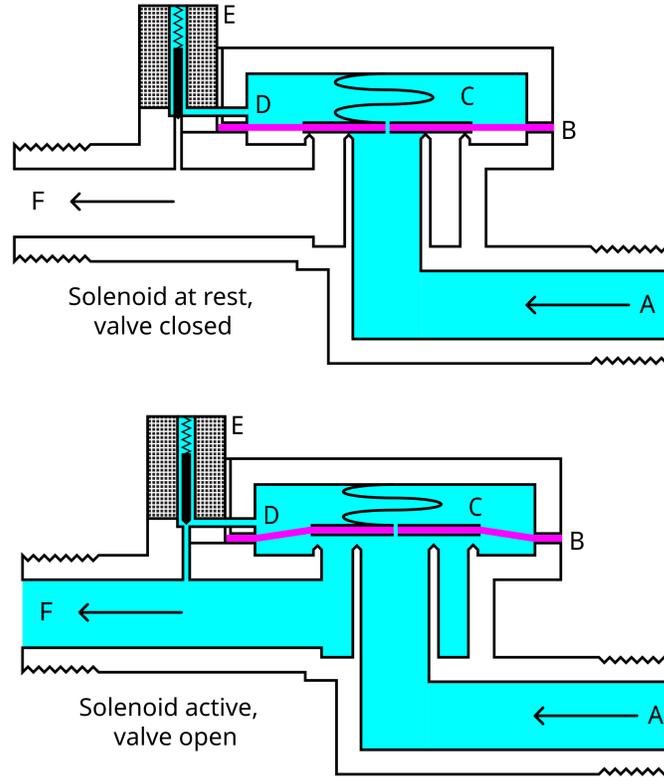


Figure 7: Illustrative operating principle of a solenoid valve

These supporting materials help connect the abstract block diagram to the actual physical implementation. In particular, they clarify the two major actuation paths of the system: the electrically driven motion path and the pneumatically driven grasping path.

Together, these supporting figures and data communicate the most important technical details of the design: the physical arrangement of the robot, the separation of the deployment and grasping control paths, and the quantitative performance targets that define successful system operation. As a result, this supporting material complements the block diagram and subsystem descriptions by providing both physical and numerical context for the proposed design.

Figure 8 demonstrates the structural concept and the physical arrangement of the extension mechanism.

Parameter	Design Target	Purpose
Deployment stroke	≥ 8.0 cm	Enables the system to reach target objects away from the base
End-position repeatability	± 0.5 cm	Supports consistent positioning over repeated trials
Extension / retraction time	≤ 10.0 s	Keeps deployment motion within practical operating time
Gripper actuation response time	≤ 1.0 s	Enables timely grasping after command input
Object mass capacity	≥ 100 g	Ensures the gripper can lift the defined test object
Object hold duration	≥ 3.0 s	Verifies stable grasping after lift
Actuator supply voltage	12.0 ± 0.5 V	Provides power for the deployment and pneumatic hardware
Controller supply voltage	5.0 ± 0.1 V	Provides regulated power for the Arduino and control electronics

Table 1: Representative technical design targets for the SoftReach Arm prototype.

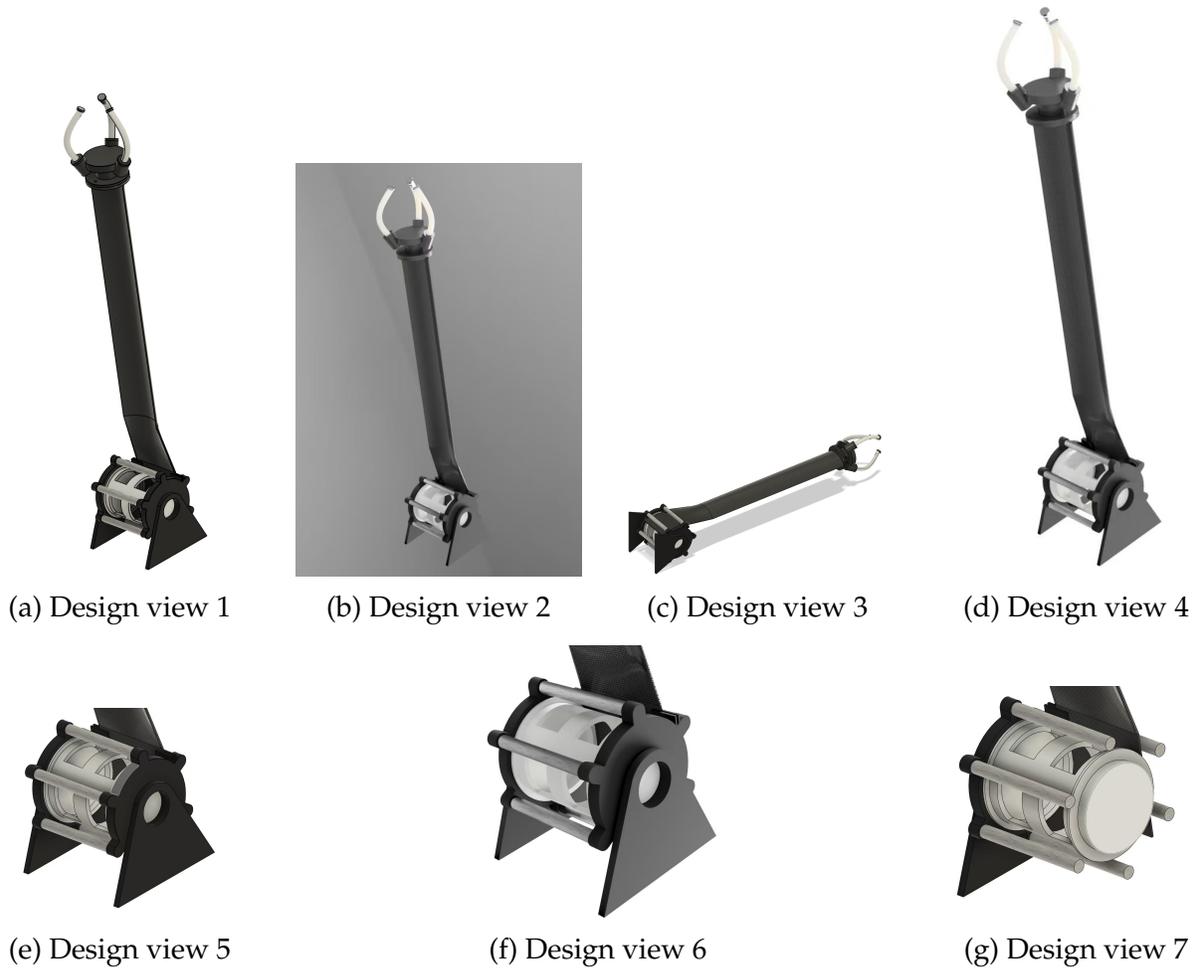


Figure 8: Representative images of the retractable arm design

2.6 Tolerance Analysis

The most critical subsystem function in the current design is the deployment mechanism's ability to extend the gripper far enough from the base to reach an underwater target object. This function is critical because even if the soft gripper operates correctly, the system will fail to retrieve the object if the deployment path cannot position the end effector within the required workspace. One of the high-level requirements of the project is that the system must be able to reach objects located at least 8.0 cm away from the base mounting point. The feasibility of this function can therefore be evaluated through a tolerance analysis of the deployment stroke.

Let the effective deployment distance of the end effector be

$$x_{\text{eff}} = x_{\text{nom}} - \Delta x_{\text{motor}} - \Delta x_{\text{backlash}} - \Delta x_{\text{structure}} - \Delta x_{\text{assembly}}, \quad (1)$$

where x_{nom} is the nominal designed deployment stroke, Δx_{motor} is the positioning error associated with motor actuation, $\Delta x_{\text{backlash}}$ is the error due to mechanical backlash in the deployment mechanism, $\Delta x_{\text{structure}}$ is the displacement loss caused by structural compliance of the deployable member, and $\Delta x_{\text{assembly}}$ is the error introduced by mounting and assembly tolerances.

For the current design, a nominal deployment stroke of

$$x_{\text{nom}} = 10.0 \text{ cm} \quad (2)$$

is selected in order to provide margin beyond the 8.0 cm minimum workspace requirement. A conservative tolerance budget is assigned as follows:

$$\Delta x_{\text{motor}} \leq 0.3 \text{ cm}, \quad (3)$$

$$\Delta x_{\text{backlash}} \leq 0.2 \text{ cm}, \quad (4)$$

$$\Delta x_{\text{structure}} \leq 0.3 \text{ cm}, \quad (5)$$

$$\Delta x_{\text{assembly}} \leq 0.2 \text{ cm}. \quad (6)$$

Under worst-case conditions, the minimum effective deployment distance is therefore

$$x_{\text{eff},\text{min}} = 10.0 - (0.3 + 0.2 + 0.3 + 0.2) = 9.0 \text{ cm}. \quad (7)$$

Since

$$x_{\text{eff},\text{min}} = 9.0 \text{ cm} > 8.0 \text{ cm}, \quad (8)$$

the design still satisfies the required workspace even under the full worst-case accumulation of deployment tolerances. This provides a margin of

$$9.0 - 8.0 = 1.0 \text{ cm}. \quad (9)$$

In addition to worst-case reach, repeatability can be estimated using a root-sum-square (RSS) combination of independent error sources:

$$\Delta x_{\text{RSS}} = \sqrt{(0.3)^2 + (0.2)^2 + (0.3)^2 + (0.2)^2} = 0.51 \text{ cm}. \quad (10)$$

This result is approximately consistent with a repeatability target of ± 0.5 cm for the deployment path, indicating that the design is also feasible from a positioning-consistency standpoint.

This analysis shows that the deployment subsystem can meet the critical reach requirement with positive tolerance margin, provided that the motor, mechanical interface, deployable structure, and assembly are manufactured and integrated within the stated tolerance budget. Therefore, the most critical subsystem function—placing the gripper within the required underwater workspace—is feasible by mathematical analysis.

3 Cost & Schedule

3.1 Cost

Table 2 summarizes the estimated cost of the SoftReach Arm prototype. The table includes the major power, control, deployment, pneumatic, structural, and fabrication components required to build and test the system. General laboratory items that are already available, such as a laptop, basic hand tools, and shared benchtop equipment, are not included in the total.

The estimated total cost of the prototype is 1415 RMB. This cost includes the major power, control, deployment, pneumatic, structural, and fabrication components required for one complete prototype build and test.

3.2 Schedule

Table 3 shows the week-by-week project schedule from April 6 to May 11. Each team member is assigned one primary task per week so that mechanical fabrication, control electronics, pneumatic integration, subsystem testing, and final documentation can proceed in parallel.

The schedule is structured so that subsystem design is completed first, followed by fabrication, integration, verification testing, and final documentation. This parallel plan reduces the risk that fabrication delays or integration issues will accumulate near the mock demo and final report deadlines.

4 Ethics & Safety

4.1 Ethics

SoftReach Arm is an underwater robotic retrieval prototype that combines electrical control, mechanical deployment, and pneumatic grasping in a shared experimental environment. As a result, the primary ethical responsibilities of the project are to avoid foreseeable harm, report system performance honestly, and limit the prototype to uses that are consistent with its validated capabilities. These responsibilities are consistent with the

Item	Qty.	Unit Cost (RMB)	Total Cost (RMB)	Purpose / Notes
12V battery pack	1	160	160	Primary power source for the complete system.
Buck converter	1	30	30	Steps the 12V supply down to 5V for the Arduino and low-voltage control electronics.
Arduino microcontroller board	1	85	85	Main control unit for deployment and gripper actuation.
DC motor	1	100	100	Drives extension and retraction of the deployable structure.
Motor driver module	1	60	60	Interfaces the Arduino with the deployment motor.
Solenoid valve	1	55	55	Controls airflow to the soft gripper.
MOSFET valve driver electronics	1	35	35	Switches the solenoid valve from the controller output.
Air pump	1	160	160	Provides pressurized air for pneumatic gripper actuation.
Pressure regulator and gauge	1	100	100	Regulates the pneumatic pressure delivered to the soft gripper.
Pneumatic tubing and fittings set	1	80	80	Connects the air pump, regulator, valve, and gripper.
C-shaped carbon fiber strip	1	100	100	Serves as the retractable deployable support structure.
Spool / retractable mechanism parts	1	80	80	Supports rolling, storage, and guided deployment of the carbon-fiber strip.
Silicone / elastomer material	2	80	160	Used to fabricate the soft two-finger gripper.
3D-printed base and structural parts	1	100	100	Includes base housing, mounting fixtures, and actuator support parts.
Wires, connectors, and prototyping materials	1	60	60	Electrical interconnects, terminals, and assembly accessories.
Fasteners, adhesive, and sealing materials	1	50	50	Mechanical assembly and basic sealing for integrated prototype construction.
Estimated Total			1415	Prototype cost estimate for one complete system build.

Table 2: Estimated cost breakdown for the SoftReach Arm prototype.

Week	Junyi Chen	Jinwen Wang	Ruxi Deng	Zhian Xie	Milestone / Deadline
4/6	Finalize the deployable structure design and define the target deployment stroke and base dimensions.	Finalize the control electronics design and complete the motor driver and solenoid-valve control interface.	Complete the Cost and Schedule sections and assemble the full design document for submission.	Finalize the gripper design description and complete the deployment-stroke tolerance analysis.	Design Document due; Teamwork Evaluation due; Weekly Project Update.
4/13	Fabricate the first retractable deployment structure and assemble the carbon-fiber support mechanism.	Bench-test the Arduino, motor driver, MOSFET, and solenoid-valve control path.	Order or organize remaining pneumatic and structural materials and prepare the bill of materials for subsystem assembly.	Fabricate the first soft two-finger gripper prototype using the selected silicone and mold process.	Weekly Project Update.
4/20	Assemble the deployment mechanism and measure preliminary extension and retraction performance.	Assemble the control and power hardware and verify correct electrical operation under repeated switching.	Assemble the pneumatic subsystem, including air pump, regulator, tubing, and fittings, and perform an initial leak test.	Characterize the first gripper prototype by measuring closure response and basic grasping behavior under controlled pressure input.	Individual Progress due; Weekly Project Update.
4/27	Integrate the deployable structure with the base and refine the extension/retraction mechanism for improved repeatability.	Implement the full control sequence, including deploy, stop, grip, release, and retract.	Refine the pneumatic layout to improve sealing, routing, and repeatability, and update the design revision materials.	Fabricate and assemble the revised soft gripper prototype based on the first round of experimental results.	Design Document Revision due; Weekly Project Update.
5/4	Run integrated underwater deployment and grasping trials and prepare the mechanical workflow for the mock demo.	Debug control timing and electrical reliability issues observed during repeated integrated testing.	Improve pressure stability and pneumatic repeatability for demonstration-ready system operation.	Collect verification data for deployment stroke, grasp success rate, and cycle time, and support the mock demo.	Mock Demo due; Weekly Project Update.
5/11	Write the final report draft sections describing the deployment mechanism and integrated system operation.	Write the final report draft sections describing the control subsystem, power subsystem, and electrical interface.	Finalize the cost table, supporting figures, and overall formatting of the final report draft.	Write the final report draft sections describing verification results, ethics, and safety considerations.	Final Report Draft due.

Table 3: Week-by-week project schedule for SoftReach Arm from April 6 to May 11. Each team member is assigned one primary task per week.

IEEE Code of Ethics, which emphasizes decisions that protect the safety, health, and welfare of the public, and with the ACM Code of Ethics, which emphasizes avoiding harm, being honest and trustworthy, and considering the broader impact of engineered systems. [1], [2]

One important ethical issue is the risk of overstating the capability of the system. SoftReach Arm is a capstone-scale prototype intended for controlled underwater retrieval of lightweight objects, not a certified industrial, medical, rescue, or human-interaction robot. Its performance may vary with object geometry, underwater drag, pressure losses, structural compliance, sealing quality, and fabrication tolerances. To avoid misleading users or evaluators, all claims about deployment stroke, grasp success, payload, and cycle time will be based on measured test results under clearly stated operating conditions, and failed trials will be reported alongside successful ones. This is an ethical design and reporting decision because it prevents claims that exceed the demonstrated performance of the prototype. [1], [2]

A second ethical issue is misuse outside the intended operating envelope. Because the system uses a retractable structure, pneumatic actuation, and a soft gripper, it is not designed for contact with people, animals, hazardous materials, fragile ecological environments, or high-value equipment. It is also not intended for open-water deployment without substantial additional waterproofing, environmental validation, and recovery safeguards. For this reason, the project explicitly limits intended use to lightweight object retrieval in a controlled test environment. This restricted use case is ethically appropriate because it matches the actual level of validation and reduces the risk of harm caused by inappropriate deployment. [1], [2]

A third ethical issue is environmental responsibility during testing. Because the device is intended for underwater operation, careless testing could introduce loose parts, leaked materials, or mechanical disturbance into the surrounding environment. To reduce this risk, the prototype will be tested only in controlled laboratory or benchtop water environments, with all components secured before operation and all materials inspected after testing. This design choice is ethically preferable because it minimizes environmental disturbance while still allowing the system to be evaluated for its intended function. [1], [2]

4.2 Safety

The primary safety risks in SoftReach Arm arise from compressed air, unintended deployment motion, pinch points at the gripper, electrical hazards associated with operating near water, and structural or sealing failure during underwater testing. Because the system combines electrical power, mechanical motion, and pneumatic actuation, failures in wiring, tubing, fittings, regulators, the deployment mechanism, or the sealed housing could lead to unsafe operating conditions. Safety must therefore be addressed through both operating procedure and deliberate design decisions. [3], [4], [5], [6]

The first major safety concern is pneumatic actuation. Pressurized air can cause sudden motion, hose release, fitting failure, or unexpected gripper actuation if it is not prop-

erly regulated and contained. To reduce this risk, the system will operate only within a limited pressure range appropriate for the soft gripper and tubing. Early testing will be performed at reduced pressure before full operation is attempted. Tubing, fittings, and the regulator will be selected for the expected operating pressure, checked for leakage before use, and routed to reduce snagging or accidental disconnection. If an external compressed-gas source is used, it will be handled according to applicable compressed-gas safety guidance. Although OSHA 29 CFR 1910.242(b) specifically addresses compressed air used for cleaning, it reinforces the broader principle that compressed air must be controlled so that it does not create unnecessary hazard. These considerations justify the decision to use regulated pneumatic actuation rather than any unregulated air source. [3], [4]

The second major safety concern is mechanical interaction with the robot. The retractable deployment mechanism can move unexpectedly if the motor is miscommanded or if the mechanism slips, and the soft gripper can still pinch fingers during closure even though it is compliant. To reduce this risk, testing will be conducted with a clearly defined keep-out area around the deployment path and gripper. Manual adjustment will be performed only when the motor is disabled, the pneumatic supply is turned off, and the system is depressurized. The prototype is also intentionally limited to moderate deployment stroke and lightweight target objects, which reduces stored energy and lowers the severity of accidental contact. This limited operating envelope is a deliberate safety-oriented design decision. [5], [6]

The third major safety concern is electrical operation near water. Water exposure can create short circuits, corrosion, loss of control, and possible shock hazards if the electrical hardware is not properly isolated from the test environment. To reduce this risk, the battery, controller, motor driver, and switching electronics will be placed in protected locations away from direct water exposure, and electrical connections near the test environment will be insulated and strain-relieved. Sealed interfaces and basic waterproof barriers will be used wherever wiring approaches the underwater portion of the setup. In addition, the system will be powered down immediately if leakage, condensation inside an enclosure, or unstable electrical behavior is observed. These precautions justify the design decision to separate the underwater mechanical and pneumatic components from the main electrical control hardware as much as possible. [5], [6]

Finally, all development and demonstration activities will follow applicable UIUC laboratory safety procedures and required safety training. Taken together, the use of regulated pneumatic pressure, protected electrical hardware, restricted operating conditions, staged validation, and a clearly limited intended use ensures that the project addresses both ethical and safety responsibilities in a manner appropriate for a capstone underwater robotic prototype. [1], [2], [4], [5], [6]

References

- [1] Institute of Electrical and Electronics Engineers, *Ieee code of ethics*, PDF, Accessed 2026-03-24.
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