ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

SoftReach Arm: Telescopic Three-Finger Soft Robotic Gripper

Team #4

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Abstract

SoftReach Arm is a bench-top robotic manipulation prototype that combines a 500 mm lead-screw telescopic stage with a pneumatically actuated three-finger soft gripper. The system addresses the need for a compact manipulator that can extend from a fixed base and grasp lightweight objects while tolerating moderate object-position and contact-geometry uncertainty. The final design uses stepper-motor-driven linear motion for reach, pneumatic inflation for compliant grasping, and an electronic control path for coordinated extension, gripping, release, and retraction. Final verification evaluated telescopic travel, end-position repeatability, gripper response, grasp reliability, and full-cycle operation. The prototype achieved a 500 mm commanded extension stroke, 9/10 successful grasps, and an 11.8 s mean full-cycle time, satisfying the high-level requirements.

Contents

1 Introduction

1.1 Problem Statement

Many small robotic manipulation tasks require an end effector to reach outward from a compact base and grasp an object whose exact position and geometry are not perfectly controlled. A rigid gripper can perform well when the object location, object size, and approach direction are known accurately, but it is less tolerant of placement error and irregular contact geometry. Soft robotic systems use compliant materials to reduce the dependence on perfectly rigid alignment, which motivates the use of a soft end effector for this project [1, 2].

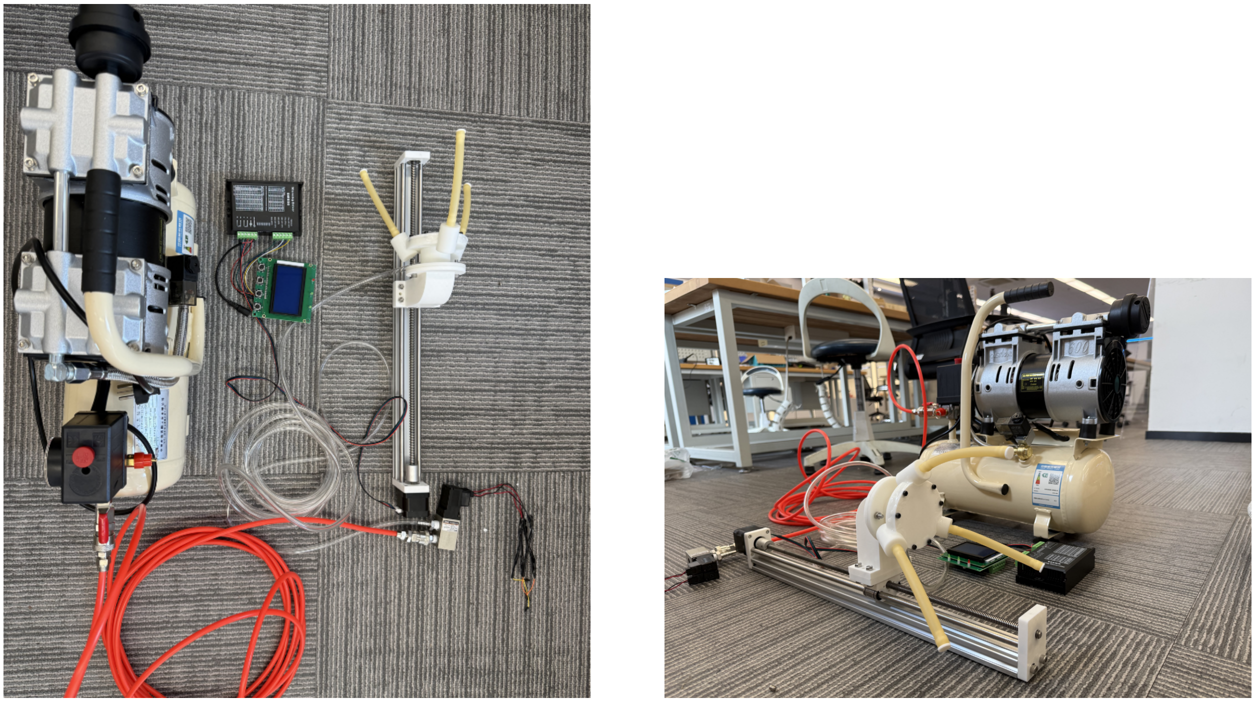
The engineering problem addressed by *SoftReach Arm* is to design and verify a compact robotic arm that can extend linearly from a fixed base and grasp lightweight objects using a compliant end effector. The system must be practical to fabricate, safe to test in a laboratory setting, and repeatable enough for final demonstration. The project scope is a bench-top prototype; it is not designed for human contact, medical use, industrial deployment, or operation around hazardous objects.

1.2 Solution Overview

The final design combines a lead-screw telescopic stage with a pneumatic soft gripper. The telescopic stage uses a stepper motor, lead screw, linear guide rail, sliding block, motor driver, and single-axis stepper controller to convert motor rotation into controlled linear displacement. This stage moves the gripper away from the fixed base and provides the required 500 mm extension.

The end effector is a three-finger soft gripper driven by a compressed-air source. When pressurized air enters the gripper chamber and soft tubular fingers, the fingers bend inward and conform around the target object. Pneumatic soft actuators can generate large deformations through fluidic pressurization, which is suitable for compliant grasping with simple control hardware [3]. The complete manipulation cycle is therefore: extend, stop, pressurize the gripper, hold the object, release pressure, and retract.

Figure 1 shows the final bench-top prototype in the context of the target manipulation task. The object is placed within the reachable workspace of the lead-screw stage, and the gripper is extended toward the object before pneumatic closure. This setup reflects the intended use case of the project: a compact base remains fixed while the end effector reaches outward and performs compliant grasping on a lightweight object.



(a) Overall layout of the integrated prototype (b) Side view of the final assembled system

Figure 1: Final bench-top prototype in the target manipulation context, showing the three-finger soft gripper mounted on the lead-screw telescopic stage and connected to the pneumatic and control hardware.

1.3 System Architecture

Figure 2 shows the system-level architecture of *SoftReach Arm*. The design is divided into four main subsystems: power, control, telescopic mechanical actuation, and pneumatic gripper actuation. The power subsystem supplies the stepper motor driver, compressed-air source, solenoid valve, and low-voltage control electronics. The control subsystem sends pulse and direction signals to the stepper driver and switching commands to the pneumatic valve-control path. The telescopic mechanical subsystem provides linear reach, while the pneumatic gripper subsystem provides compliant object capture.

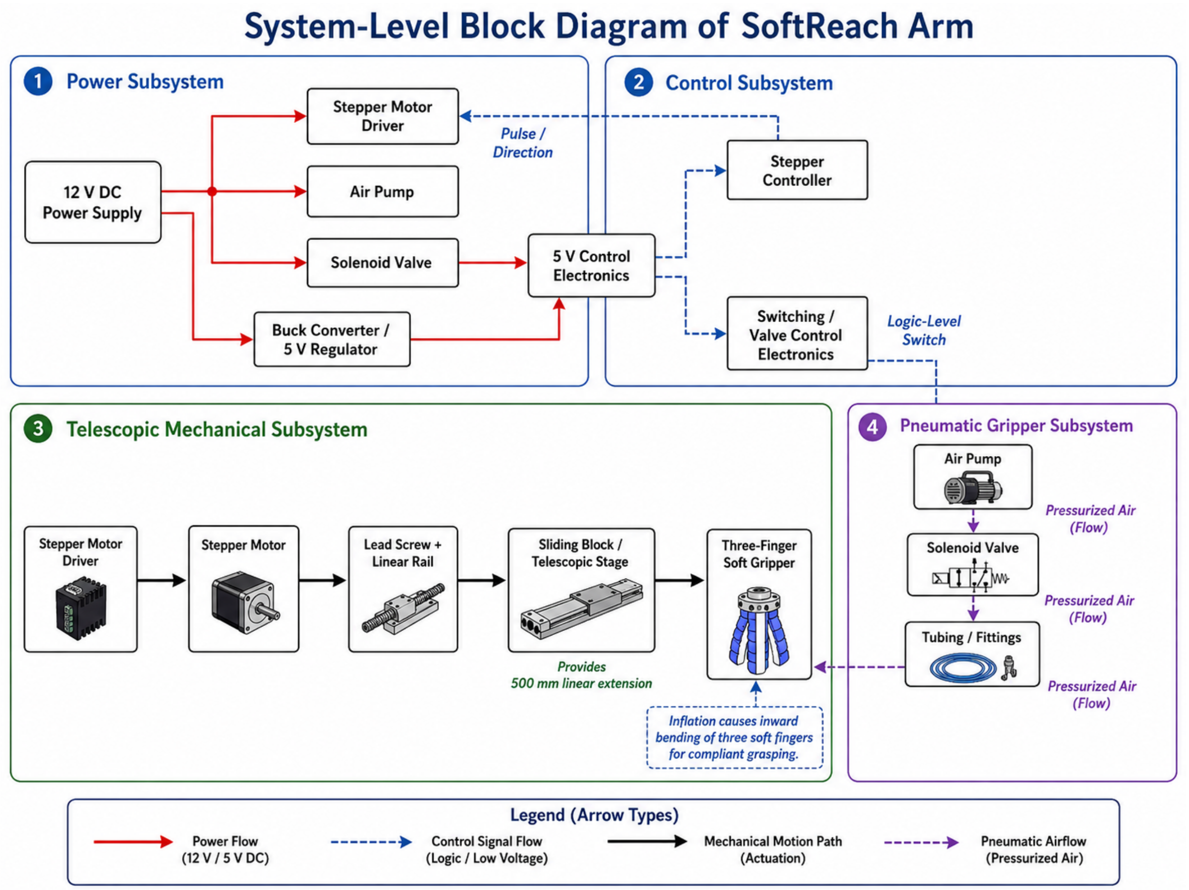


Figure 2: System-level block diagram of *SoftReach Arm*. The design separates power distribution, control electronics, lead-screw telescopic actuation, and pneumatic gripper actuation.

The system uses separate actuation mechanisms because reaching and grasping impose different engineering requirements. Linear extension requires repeatable one-dimensional motion, so a lead-screw linear rail mechanism is used. Grasping requires compliance and tolerance to imperfect object placement, so a pneumatic soft gripper is used. Combining these mechanisms gives the prototype both controlled reach and compliant contact.

1.4 High-Level Requirements

The following high-level requirements define successful project completion:

H1. **Grasping reliability:** The system shall grasp, lift, and hold the selected lightweight test object for at least 3 s with a success rate of at least 80% over 10 trials.

H2. **Telescopic reach:** The telescopic mechanism shall provide a commanded linear extension of 500 mm from the retracted reference position, with end-position variation no greater than ±5 mm across 10 trials.

H3. **Cycle time:** The system shall complete one full manipulation cycle, including extension, gripper closure, object hold, release, and retraction, in no more than 15 s under nominal test conditions.

1.5 Project Scope and Design Constraints

The final prototype was scoped as a laboratory demonstration platform rather than a field-deployable robot. This scope affected several design decisions. First, the design prioritized visible and repeatable mechanical behavior over full autonomy. Second, the system used direct command sequencing rather than a perception-based closed-loop controller. Third, the gripper was designed for lightweight bench-top objects, not heavy payloads or hazardous items.

The most important constraints were fabrication time, component availability, pneumatic sealing, alignment, and integration simplicity. The soft gripper improves tolerance to object-position uncertainty, but it also introduces sealing and pressure-delivery challenges. The lead-screw stage provides stable linear motion, but it introduces moving pinch points and requires careful alignment between the sliding block, gripper mount, and target object. The final system therefore uses simple mechanisms, visible operation, and a conservative open-loop control sequence.

2 Design

2.1 Design Procedure and Alternative Approaches

The design procedure began by separating the project into two physical functions: reaching and grasping. Reaching required controlled linear motion from a fixed base, while grasping required compliant contact with the object. Treating these functions independently reduced integration risk because the telescopic stage, pneumatic gripper, and control path could be tested before the final full-cycle experiment.

Several alternatives were considered for each function. Table 1 summarizes the main design alternatives and the reason for selecting the final approach.

Table 1: Design alternatives considered during final prototype development.

Function	**Alternatives**	**Selected Approach**	**Reason for Selection**
Linear extension	Belt drive, rack-and-pinion, tape-spring arm, lead screw	Lead-screw linear rail	Provides stable linear travel, simple mounting, and sufficient repeatability without custom drivetrain tuning.
End-effector closure	Rigid servo claw, two-finger soft gripper, three-finger soft gripper	Three-finger pneumatic soft gripper	Provides symmetric object enclosure and better tolerance to imperfect object centering.
Gripper actuation	Servo linkage, cable drive, pneumatic inflation	Pneumatic inflation	Produces large finger deformation with a simple structure and compliant material contact.
Motion control	Fully manual switching, microcontroller timing, LCD stepper controller with driver	Stepper controller and driver for the telescopic axis; switched pneumatic path for gripping	Reduces software burden and allows repeatable stroke and speed settings during verification.
Feedback	Open-loop timing, limit switches, encoder, pressure sensor	Open-loop timing with measured verification	Sufficient for the bench-top prototype; closed-loop position or pressure feedback is reserved for future improvement.

The final system uses electromechanical actuation for positioning and pneumatic actuation for compliant grasping. This division is important because the extension stage must move predictably along one axis, while the gripper must tolerate lateral and angular placement errors at the object. A single rigid mechanism would have difficulty satisfying both requirements without additional sensing and feedback control.

2.2 Subsystem Requirements and Verification Summary

Table 2 summarizes the main subsystem-level requirements and verification methods. The requirements focus on team-designed functions rather than only off-the-shelf component ratings. Detailed pass/fail records are provided in Appendix 8.

Table 2: Subsystem-level requirements and verification summary.

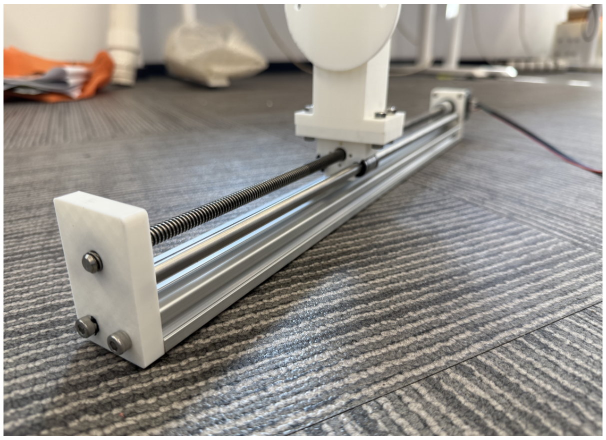
Subsystem	**Requirement**	**Verification Method**	**Result**
Telescopic stage	Provide a commanded 500 mm extension with endpoint variation no greater than ±5 mm.	Run 10 extension-retraction trials and measure the final slider position relative to the retracted reference.	500 mm mean stroke, ±3 mm variation.
Soft gripper	Close visibly within 2.0 s and hold the selected lightweight object for at least 3 s.	Pressurize the gripper, record closure time, and run 10 grasp-hold trials.	1.6 s closure, 9/10 successful grasps.
Pneumatic path	Deliver pressure without leakage that prevents successful grasping.	Pressurize the gripper for 10 s and inspect tubing, fittings, and gripper ports for audible or visible leakage.	No leakage preventing grasping.
Control path	Execute extension, stop, pressurization, release, and retraction in the intended order.	Run 10 full cycles and observe command order, missed commands, and resets.	10/10 correct command sequence.
Power path	Complete 10 full cycles without controller reset, missed motor command, or actuator dropout during motor motion and pneumatic switching.	Observe full-cycle operation during extension, valve switching, pneumatic actuation, and retraction.	10/10 full cycles completed without reset or actuator dropout.

2.3 Telescopic Mechanical Subsystem

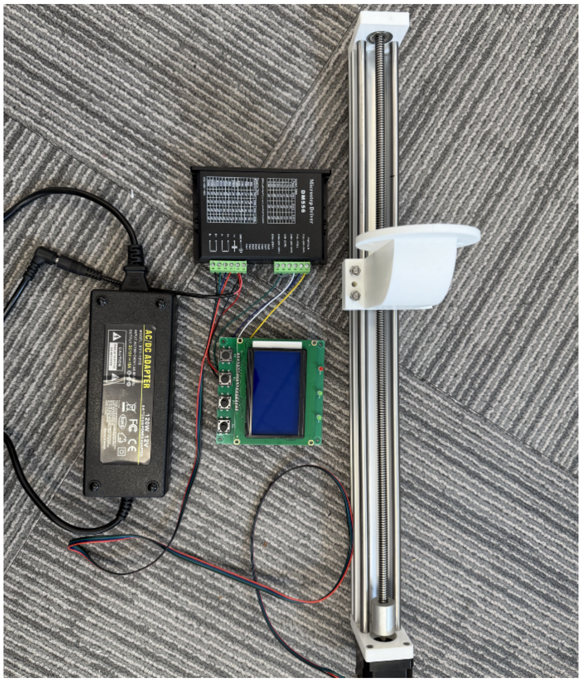
The telescopic subsystem is the extension and retraction module of the arm. It consists of a stepper motor, lead screw, linear rail, sliding block, stepper motor driver, and YF-27 single-axis LCD stepper controller. The stepper motor rotates the lead screw, and the nut interface in the sliding block converts this rotation into linear displacement along the rail. The guide rail supports the sliding block and reduces lateral motion, which improves stability during extension and retraction.

Figure 3 shows the fabricated telescopic stage and its integration with the controller and motor driver. The lead-screw architecture was selected because it provides controlled linear travel, mechanical stiffness, and simple mounting. The extension distance is adjusted by changing the commanded pulse count, while the extension speed is adjusted through the controller speed setting.

(a) Lead-screw rail and sliding block



(b) Side view of the telescopic stage



(c) Integrated stage with controller and driver

Figure 3: Lead-screw linear rail telescopic mechanism used for extension and retraction. The stepper motor rotates the lead screw, and the sliding block carries the mounted gripper along the rail.

For a lead screw with pitch p, motor step angle θ_s, and microstepping factor m, the ideal linear displacement per commanded step is

$$\Delta x = \frac{p\theta_s}{360m} \tag{1}$$

The commanded travel distance is

$$x_{cmd} = N\Delta x \tag{2}$$

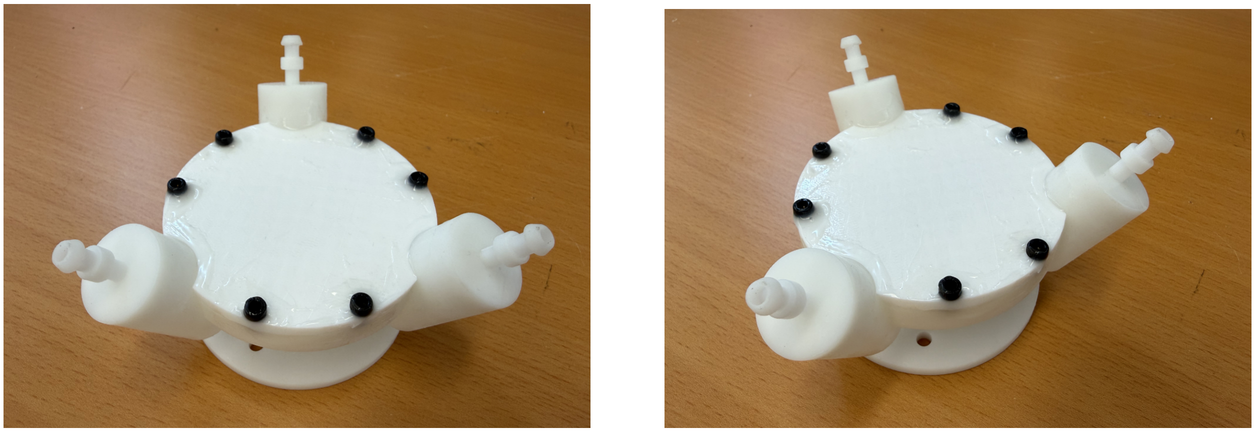
where N is the number of commanded steps. Equations (1) and (2) relate the controller pulse setting to the ideal travel distance. The final 500 mm stroke and end-position repeatability are verified in Section 4.

2.4 Three-Finger Soft Gripper Subsystem

The end effector is a pneumatically actuated three-finger soft gripper. Each finger is made from a flexible tubular structure. A constraint layer is attached along one side of the finger so that pressurization produces asymmetric deformation. Because one side expands less than the other, the finger bends inward rather than expanding uniformly. This inward bending allows the fingers to wrap around the object and provide compliant contact, which is consistent with the general use of soft robotic grippers for adaptive grasping [2].

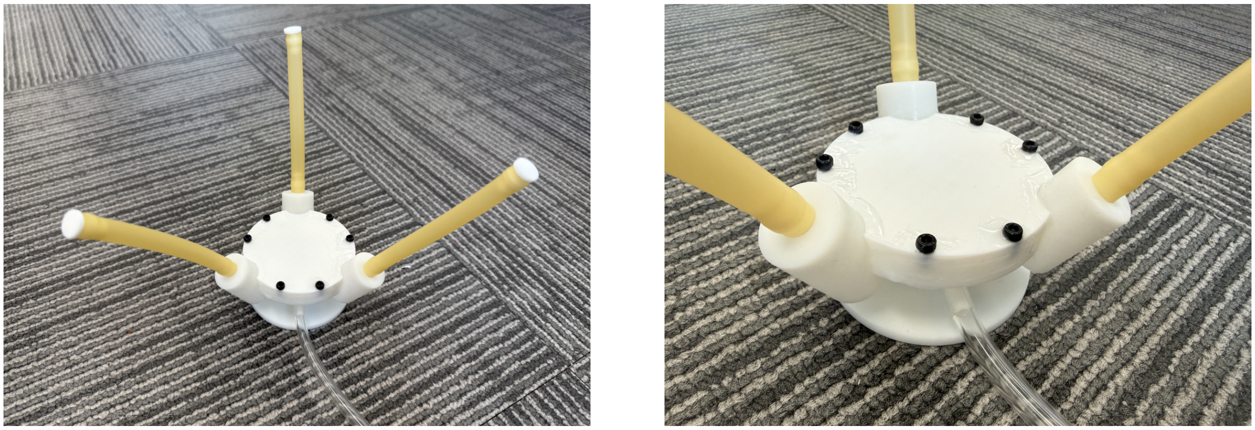
The gripper is driven by a single compressed-air path. When the pneumatic path is pressurized, all three fingers inflate simultaneously and bend toward the center of the gripper. This allows the end effector to envelope the target object rather than depending on point contact at a fixed rigid jaw position. The gripper body uses a central pneumatic chamber, tube fittings, and mechanical fastening to distribute air to the soft fingers and reduce leakage at the connection points.

Figure 4 shows the fabricated gripper body, air-inlet ports, tube fittings, three-finger layout, and pressurized grasping configuration.



(a) Gripper body and air-inlet ports

(b) Sealed central chamber and tube fittings



(c) Three-finger layout with soft tubular fingers

(d) Pressurized gripper closing around a lightweight object

Figure 4: Fabricated three-finger soft gripper. The gripper uses a sealed central chamber, tube fittings, and three soft tubular fingers to distribute pressurized air; under pressure, the fingers bend inward and close around the target object.

The first fabrication issue was that the initial tubing and inlet geometry did not provide a reliable fit for the gripper body. The design was revised by using more elastic latex tubing and a more secure inlet geometry. This change improved mechanical fit and reduced leakage risk at the tube connections.

2.5 Pneumatic Subsystem

The pneumatic subsystem consists of a compressed-air source, tubing, fittings, and a solenoid valve. The compressed-air source provides the pressure needed to actuate the soft fingers, while the solenoid valve controls whether the gripper path is pressurized or released. Inflation-based pneumatic soft actuators are commonly used because fluidic pressurization can produce large bending motions using simple control inputs [3]. When the valve routes air into the gripper, the fingers bend inward and close around the object.

When the valve switches to the release path or pressure is removed, the internal pressure decreases and the soft fingers return toward their unactuated shape.

The key design requirement for this subsystem is repeatable pressure delivery. If the pressure is too low, the fingers may not close far enough to hold the object. If the pressure is too high, the tubing connections and soft material may experience excessive stress. For this reason, verification focuses on closure response, leakage, release behavior, and object-holding reliability rather than pressure alone.

2.6 Mechanical Integration and Operating Envelope

Figure 1 shows the integrated prototype used to connect the telescopic stage and the soft gripper. The gripper is mounted on the sliding block of the lead-screw stage so that its closing direction is aligned with the target object when the telescopic stage reaches the commanded grasping position. If the gripper is mounted too high, too low, or with excessive angular offset, the fingers may contact only the edge of the object or push the object away before a stable grasp is formed.

The effective operating envelope is defined by the 500 mm telescopic stroke and the closing volume of the gripper. During testing, the target object must be placed within the overlap between these two regions. The telescopic stage determines the approach distance, while the gripper determines the acceptable lateral placement error. Because the prototype is open-loop, the starting position and object placement must be reset consistently between trials.

The interface between the telescopic slider and gripper mount is a critical mechanical detail. The mount must resist bending when the gripper is pressurized and when the object is held. Excessive bending reduces the effective reach and changes the approach angle. Therefore, the mounting plate, rail alignment, and fasteners were checked before repeated verification trials.

2.7 Power and Control Subsystem

The power and control subsystem supplies the energy and command signals required by the lead-screw stage and pneumatic gripper. A 12 V supply powers the stepper motor driver, compressed-air source, and solenoid valve path. A regulated 5 V rail powers the low-voltage control electronics where needed. The telescopic axis is controlled through the stepper controller and motor driver, while the pneumatic path is controlled through the valve-switching electronics.

Table 3 summarizes the main electrical and pneumatic interfaces.

Table 3: Electrical and pneumatic interfaces of the integrated prototype.

Interface	**Nominal Value**	**Function**
Main actuator supply	12 V DC	Powers the stepper motor driver, compressed-air source, and solenoid valve path.
Control supply	5 V DC	Powers low-voltage control and switching electronics where required.
Stepper control	Pulse / direction	Commands extension and retraction of the lead-screw stage.
Valve control	Logic-level switch	Switches the solenoid valve to pressurize or release the gripper path.
Air output	Pressurized air	Supplies airflow to the soft gripper through tubing and fittings.

The implemented control sequence is intentionally simple. First, the telescopic stage extends to the commanded 500 mm position. Second, the motor stops and the valve-control path pressurizes the gripper. Third, the system holds the object for the required duration. Finally, the gripper releases pressure and the stage retracts. This sequence avoids simultaneous extension and grasping, which makes failure modes easier to diagnose.

2.8 Control Sequence and Timing Budget

The control sequence was designed as a deterministic state sequence rather than as a continuous feedback controller. This choice made the final demonstration easier to repeat and verify. Table 4 lists the operating states and the quantities recorded during full-cycle testing.

Table 4: Full-cycle operating sequence and timing quantities.

State	Action	Measured Quantity	Expected Observation
Reset	Place the stage at the retracted reference and leave the gripper unpressurized.	Initial position	Slider and gripper start from the same reference condition for each trial.
Extend	Command the stepper controller to move the slider outward.	Extension time and stroke	Stage reaches the 500 mm position without binding or visible stall.
Close	Switch the pneumatic path to pressurize the gripper.	Closure time	Three fingers bend inward and contact the object.
Hold	Keep the object captured for the specified hold interval.	Hold duration and slip	Object remains held for at least 3 s.
Release	Remove pressure or open the release path.	Release time	Fingers relax enough for the object to be released.
Retract	Command the stage back to the retracted reference position.	Retraction time	Slider returns to the reference position without interference.

The total cycle time is estimated as

$$t_{cycle} = t_{extend} + t_{close} + t_{hold} + t_{release} + t_{retract} \tag{3}$$

where the required hold time is 3 s. Equation (3) was used to identify which stage dominated the full-cycle time. If the measured cycle time exceeds 15 s, the most direct corrective actions are increasing the extension speed within safe limits, reducing pneumatic filling time, or improving the release path so the fingers return faster.

3 Design Revisions Based on Professor Lee's Feedback

The team appreciates the valuable and constructive feedback provided by Professor Timothy Lee during the design stage. His comments helped the team reconsider the project from the perspective of manufacturability, demonstration feasibility, and clear engineering scope. Instead of only describing a broad soft-robotic manipulation idea, the team revised the project toward a concrete bench-top prototype with specific mechanical, pneumatic, and control components that could be fabricated, assembled, and verified within the course schedule.

The following subsections summarize Professor Lee's comments and explain how the final design was revised in response.

3.1 Clarifying What Would Actually Be Built

Professor Lee's first comment was:

> "Pay more attention to what will actually be made."

This comment directly affected the overall project scope. In the early design stage, the project was framed as a soft manipulator capable of reaching, grasping, and potentially repositioning objects. However, this concept was too broad for the available fabrication time and did not clearly specify which physical mechanisms would actually be built. After considering this feedback, the team narrowed the project into a bench-top prototype with two concrete and verifiable functions: linear extension and compliant grasping.

The final design therefore uses a lead-screw telescopic stage as the main reaching mechanism and a three-finger pneumatic soft gripper as the end effector. The lead-screw stage is composed of a stepper motor, lead screw, linear rail, sliding block, stepper motor driver, and single-axis stepper controller. This mechanism converts motor rotation into controlled linear displacement and provides the required 500 mm commanded extension. The soft gripper is mounted on the sliding block so that the gripper can be carried forward from the fixed base toward the target object.

This revision made the project substantially more realistic. The team no longer needed to build a fully dexterous soft arm with multiple bending sections, closed-loop pose control, or complex object manipulation. Instead, the final prototype consists of components that could be physically assembled and tested: the lead-screw rail, gripper mount, pneumatic tubing, solenoid valve, compressed-air source, controller, motor driver, and three-finger soft gripper. The resulting system is simpler, but it is also much more concrete, inspectable, and suitable for engineering verification.

This change also improved the verification plan. Because the final design has a clearly defined telescopic axis and a clearly defined gripper function, the team could measure stroke, endpoint repeatability, gripper closure time, grasp success rate, and full-cycle time. These measurable quantities made the final report more consistent with the ECE 445 requirement that the design be evaluated using quantitative tests rather than only qualitative demonstration.

3.2 Manufacturing the Shape of the Gripper

Professor Lee's second question was:

> "How do you plan on making a shape for the gripper?"

This question led the team to revise the gripper from a conceptual soft end effector into a specific manufacturable structure. The final gripper uses a three-finger pneumatic layout. The fingers are arranged symmetrically around a central gripper body so that, when pressurized, they bend inward toward the center and surround the target object. This geometry was selected because a three-finger layout provides more symmetric enclosure than a two-finger gripper and is more tolerant of small object-centering errors than a rigid claw.

The shape of each finger is produced using a flexible tubular structure. A constraint layer is attached along one side of the soft finger. When pressurized air enters the finger, the unconstrained side expands more than the constrained side. This asymmetric deformation causes the finger to bend inward instead of expanding uniformly. In this way, the gripper shape is not only a static geometry but also a pressure-actuated bending structure. The final gripper body includes a central pneumatic chamber, air-inlet ports, tube fittings, and mechanical fastening points so that air can be distributed to the three fingers.

The fabrication process was also revised after initial testing. The first tubing and inlet geometry did not provide a sufficiently reliable connection for repeated pressurization. The tubing fit was not secure enough, and the inlet geometry was too short to maintain a robust seal. In response, the team changed to more elastic latex tubing and improved the inlet connection so that the tubing could be secured more consistently. External compression and tighter tube fitting were used to reduce leakage risk at the connection points.

This revision directly addressed the concern about how the gripper would actually be made. The final gripper is not an abstract soft-robotic concept; it is a physical assembly consisting of soft tubular fingers, a central gripper body, pneumatic ports, tubing, and sealing features. The structure can be fabricated, mounted to the telescopic stage, pressurized repeatedly, and evaluated through closure and grasping tests.

3.3 Clarifying Object Posing and Final Demonstration Scope

Professor Lee's third question was:

> "How is the soft manipulator going to pose objects? Eventually your robot may need to demonstrate some precise stacking. What will you be showing at the final demonstration?"

This question helped the team clarify the difference between compliant grasping and precise object posing. A soft gripper is useful for adapting to object-position uncertainty and irregular contact geometry, but it does not automatically provide precise control over object orientation. Precise stacking would require additional capabilities beyond the final prototype, such as closed-loop object pose sensing, repeatable end-effector orientation control, and feedback-based placement correction. These features would add substantial mechanical and control complexity.

After evaluating the project scope, the team decided not to claim precise stacking as the final demonstration objective. Instead, the final demonstration was defined as a repeatable extend-grip-hold-release-retract manipulation sequence. In this task, the object is placed at a marked location within the reachable workspace of the telescopic stage. The stage extends the gripper toward the object, the pneumatic path pressurizes the gripper, the three soft fingers close around the object, the object is held for at least 3 s, the gripper releases pressure, and the stage retracts to the initial position.

This final demonstration is more appropriate for the actual hardware. It tests the core engineering contribution of the project: combining controlled linear reach with compliant pneumatic grasping. The lead-screw stage demonstrates that the system can move the gripper from a fixed base to a target location over a 500 mm stroke. The soft gripper demonstrates that the end effector can tolerate moderate object-position uncertainty and hold a lightweight object without requiring precise rigid-jaw alignment. The full-cycle test demonstrates that the mechanical, pneumatic, electrical, and control subsystems can operate together in the intended order.

The team therefore treated precise stacking as a possible future extension rather than a required final demonstration. A future stacking-capable version would need additional sensing and control, such as object pose estimation, gripper orientation control, pressure sensing, and feedback-based release positioning. The final version of *SoftReach Arm* focuses on the more realistic and measurable task of reach-and-grasp manipulation.

3.4 Resulting Improvements to the Final Prototype

Professor Lee's feedback changed the project in three important ways. First, it forced the team to define the final prototype around hardware that could actually be built: a lead-screw telescopic stage, a sliding gripper mount, pneumatic tubing, a solenoid valve, a compressed-air source, and a three-finger soft end effector. This made the project physically realizable and easier to verify.

Second, it led to a more specific gripper fabrication plan. The final gripper shape was implemented using soft tubular fingers, a central pneumatic chamber, tube fittings, and a constraint-based bending mechanism. The gripper design was revised after early fabrication issues, especially at the tubing and air-inlet interfaces. This made the final gripper more robust for repeated pressurization and demonstration.

Third, it clarified the final demonstration. Instead of claiming a broad manipulation or stacking capability, the final system demonstrates a complete and repeatable extend-grip-hold-release-retract cycle. This demonstration is aligned with the actual capabilities of the prototype and with the quantitative verification metrics used in the final report.

Overall, Professor Lee's feedback helped the team move from an ambitious but underdefined soft-manipulation concept to a manufacturable and testable engineering prototype. The final design is narrower in scope than the earliest concept, but it is more concrete, more reliable, and more consistent with what the team physically built and verified.

4 Design Verification

4.1 Verification Strategy

Verification was performed at two levels. First, each major subsystem was tested independently to confirm basic operation. The telescopic mechanism was tested for commanded stroke, end-position repeatability, extension time, and retraction time. The pneumatic gripper was tested for visible closure, leakage, release behavior, and object-holding reliability. The electrical and pneumatic integration was tested for stable switching, correct command order, and full-cycle operation.

Second, the complete prototype was tested through repeated manipulation cycles. This two-level strategy made it possible to separate subsystem-level failures from integration-level failures. For example, a failed grasp could be caused by insufficient gripper closure, poor object centering, pneumatic leakage, or misalignment between the gripper and the telescopic stage. Testing the subsystems separately before full-cycle trials reduced this ambiguity.

4.2 Detailed Test Procedure and Data Reduction

Each full trial began with the telescopic stage at the retracted reference position, the gripper unpressurized, and the test object placed at a marked target location. The operator then commanded the extension stage, allowed the gripper to close around the object, held the object for the required interval, released the gripper, and retracted the stage. After each trial, the object and slider were reset to the same starting conditions.

For the telescopic mechanism, the primary measured quantities were extension distance, end-position variation, extension time, and retraction time. The stroke was measured from the retracted reference position to the final slider position after extension. The mean stroke was computed from 10 trials. End-position repeatability was reported as the maximum deviation from the mean because this value describes the worst-case placement error observed during testing.

For the gripper, the primary measured quantities were closure response, grasp success count, hold success, and qualitative failure mode. A grasp was counted as successful only if the gripper captured the object and held it for at least 3 s without dropping it. For the full-cycle test, timing started at the first extension command and stopped when the stage returned to the retracted reference position after release. Both mean and maximum cycle times were recorded because a single slow release or stalled extension can cause failure even when the average time is acceptable.

4.3 High-Level Requirement Results

Table 5 summarizes the high-level verification results from repeated bench-top trials. The prototype passed all three high-level requirements.

Table 5: High-level requirement verification summary.

Req.	Metric	Target	Measured Result	Status
H1	Grasp, lift, and hold success rate	$\geq$ 80% over 10 trials	9/10 = 90%	Pass
H2	Linear extension stroke	500 mm commanded stroke	500 mm mean stroke	Pass
H2-R	End-position repeatability	$\leq \pm 5$ mm	±3 mm	Pass
H3	Full-cycle time	≤ 15 s	11.8 s mean, 13.2 s max	Pass

4.4 Telescopic Mechanism Verification

The telescopic mechanism was verified by commanding 10 extension-retraction trials and measuring the final slider position relative to the retracted reference. The target extension stroke was 500 mm. A measuring tape was used to check final position, and video timing was used to estimate extension and retraction time.

The measured mean extension stroke was 500 mm, with a maximum end-position deviation of ±3 mm from the mean. The maximum measured extension time was 4.1 s, and the maximum measured retraction time was 3.9 s. These results show that the lead-screw mechanism provides the required reach and remains within the ±5 mm repeatability tolerance.

4.5 Soft Gripper Verification

The gripper was verified by pressurizing the pneumatic path and observing finger closure, leakage, release behavior, and object-holding reliability. A trial was counted as successful only if the fingers closed around the object and the object remained captured for at least 3 s. The test was repeated 10 times using the selected lightweight test object.

The gripper achieved 9 successful grasps over 10 trials. The primary observed failure mode was object slip when the object was not centered within the three-finger closing region. This result indicates that the gripper met the required 80% success target, while also showing that consistent object placement remains important for reliable operation.

4.6 Electrical and Pneumatic Integration Verification

The integrated system was verified by running complete extend-grip-hold-release-retract cycles. During these tests, the system was observed for missed commands, controller reset, unintended valve activation, motor stall, excessive leakage, tubing disconnection, and mechanical interference between the gripper and telescopic stage.

Across 10 full-cycle trials, the prototype completed all 10 cycles without manual intervention. The measured mean cycle time was 11.8 s, and the maximum measured cycle time was 13.2 s. Both values are below the 15 s requirement. The main integration issue was occasional object slip after incomplete centering. The corrective action was to reset the object position more consistently and allow sufficient gripper closure time before lifting or holding the object.

4.7 Observed Failure Modes and Corrective Actions

The main observed or anticipated failure modes were tubing leakage, object slip, slider binding, slow gripper release, and electrical dropout during actuator switching. Tubing leakage was reduced by using more elastic tubing and securing the air inlets with external compression. Object slip occurred mainly when the object was not centered under the gripper or when the closure interval was too short. Slider binding can occur if the gripper mount applies off-axis load to the sliding block, so rail alignment and fastener tightness were checked before repeated trials.

Electrical dropout was treated as a power-distribution issue rather than a control-sequence issue. During integration testing, the actuator supply and low-voltage control path were checked for resets or unexpected behavior during motor motion and valve switching. No repeated controller reset was observed during the final full-cycle trials.

4.8 Tolerance Analysis

The critical tolerance for the prototype is the endpoint accuracy of the telescopic stage, because the soft gripper can only compensate for object-position error within its closing volume. If the extension endpoint varies too much, the gripper may contact only the edge of the object or push the object away before closure. The design requirement therefore limits endpoint variation to ±5 mm over repeated 500 mm extension trials.

For each trial, the endpoint error is defined as

$$e_x = x_{measured} - x_{cmd} \tag{4}$$

where $x_{cmd} = 500$ mm is the commanded extension distance and $x_{measured}$ is the final measured slider position. The repeatability requirement is

$$|e_x| \leq 5 \text{ mm} \tag{5}$$

The measured maximum endpoint deviation was 3 mm. Therefore, the available repeatability margin is

$$M = 5 \text{ mm} - 3 \text{ mm} = 2 \text{ mm} \tag{6}$$

The ±5 mm endpoint tolerance was selected because the gripper closes over a finite capture region rather than a single point. During testing, the object was placed near the center of the three-finger closing region, and the soft fingers could tolerate small lateral placement errors through material compliance. Therefore, the telescopic stage does not need submillimeter positioning accuracy; it only needs to place the gripper within the effective closing volume of the soft fingers. The measured 3 mm endpoint deviation is smaller than this allowable positioning error, so the extension mechanism is sufficiently accurate for the intended grasping task.

This positive margin shows that the lead-screw stage provides sufficient endpoint repeatability for the selected bench-top grasping task. The remaining endpoint error is attributed primarily to mechanical backlash, manual reset uncertainty, and small compliance in the gripper mounting structure. Because the measured error is smaller than the allowable tolerance, the telescopic subsystem can place the gripper inside the intended grasping region during repeated trials.

5 Costs

Table 6 lists estimated prototype-scale costs for the major components used in the final system. All costs are reported in RMB because the parts were purchased or estimated from local suppliers. The table reports retail or replacement cost where appropriate. Lab-owned equipment is listed with an estimated replacement cost for transparency, even when it did not directly increase the team's out-of-pocket expense.

Table 6: Prototype cost summary.

Item	**Qty.**	**Unit Cost**	**Total Cost**	**Purpose**
Lead-screw linear rail module	1	220 RMB	220 RMB	Telescopic extension and retraction.
Stepper motor driver	1	80 RMB	80 RMB	Drives the stepper motor.
YF-27 stepper controller	1	120 RMB	120 RMB	Pulse, direction, speed, and travel control.
Compressed-air source	1	300 RMB	300 RMB	Supplies pressurized air for gripper actuation; listed as estimated replacement cost if lab-owned during testing.
Solenoid valve	1	45 RMB	45 RMB	Switches the pneumatic path for pressurization and release.
Tubing, fittings, and zip ties	1 set	40 RMB	40 RMB	Pneumatic connection and sealing.
Latex tubing / soft finger material	1 set	35 RMB	35 RMB	Three-finger soft gripper fabrication.
Constraint material	1 set	20 RMB	20 RMB	Produces asymmetric bending in the soft fingers.
Power supply / adapter	1	100 RMB	100 RMB	Main actuator power.
Buck converter / regulator	1	15 RMB	15 RMB	Low-voltage electronics supply where required.
Switching electronics and wiring	1 set	35 RMB	35 RMB	Valve control and electrical integration.
3D-printed / fabricated mounts	1 set	60 RMB	60 RMB	Mechanical connection between gripper and telescopic stage.
		Estimated material total	1070 RMB	One complete prototype.

Following the ECE 445 cost-estimation convention, labor cost was estimated as ideal hourly salary multiplied by actual hours and then multiplied by a factor of 2.5. Using a nominal 40 RMB/h engineering labor rate and approximately 60 h per team member, the labor estimate is

$$4 \times 60 \times 40 \times 2.5 = 24{,}000 \text{ RMB} \tag{7}$$

This value is an accounting estimate rather than a direct project expense. The estimated total including labor is therefore 25,070 RMB.

6 Schedule

Table 7 summarizes the final project schedule and division of labor. The schedule is organized by project phase and week, with the main responsible members listed for each task.

Table 7: Final project schedule and division of labor.

Week	**Primary Task**	**Responsible Member(s)**	**Final Status**
Week 1	Define system architecture, high-level requirements, and main subsystem interfaces.	All members	Completed.
Week 2	Select telescopic mechanism, gripper concept, pneumatic components, and control approach.	Junyi Chen, Jinwen Wang	Completed.
Week 3	Fabricate gripper body, prepare soft fingers, and revise air-inlet geometry after fit issues.	Jinwen Wang, Zhian Xie	Completed.
Week 4	Assemble lead-screw stage, sliding mount, stepper driver, and controller wiring.	Junyi Chen, Ruxi Deng	Completed.
Week 5	Integrate pneumatic path, solenoid valve, tubing, fittings, and gripper mount.	Jinwen Wang, Zhian Xie	Completed.
Week 6	Run subsystem tests for 500 mm extension, gripper closure, leakage, and command sequence.	Ruxi Deng, Junyi Chen	Completed.
Week 7	Run full-cycle tests, record grasp success, cycle time, and observed failure modes.	All members	Completed.
Week 8	Prepare final report, figures, requirement table, cost table, and safety analysis.	All members	Completed.

7 Ethics and Safety

7.1 Ethical Considerations

The main ethical responsibility of this project is to report the prototype's capabilities honestly. *SoftReach Arm* is a course project prototype, not a certified industrial robot. Therefore, the report states the test conditions, number of trials, success count, measured cycle time, and observed failure modes. Selective reporting would overstate the robustness of the system and could mislead future users of the design. This is consistent with the IEEE Code of Ethics, which emphasizes public safety and honest technical claims, and the ACM Code of Ethics, which emphasizes avoiding harm and being trustworthy [4, 5].

The system also has clear limits on intended use. It should only be used for lightweight object manipulation in a controlled laboratory or demonstration setting. It should not be used on people, animals, fragile biological samples, medical objects, hazardous materials, or high-value equipment. Any future extension beyond this scope would require additional safety validation, mechanical guarding, pressure regulation, and reliability testing.

7.2 Broader Impacts

The broader impact of this project is the demonstration of a low-cost compliant manipulation architecture that can be built and tested by a small student team. Soft robotic grippers are useful because they reduce the need for precise object modeling and rigid contact planning [2]. In educational and prototyping contexts, this can make manipulation experiments more accessible and safer to test at small scale.

The environmental impact of the prototype is modest but not zero. The design uses plastic tubing, latex material, electronic components, and fabricated mounts. Future versions should reduce disposable pneumatic fittings, improve repairability, and use replaceable soft fingers to reduce material waste.

7.3 Safety Considerations

The primary safety risks are pinch points, unexpected telescopic motion, pneumatic tube release, air leakage, electrical shorts, and overheated switching components. The lead screw and sliding block can pinch fingers during extension or retraction. The gripper can also pinch skin if actuated while a user is adjusting the end effector. Pneumatic tubing can disconnect if fittings are not secured or if pressure exceeds the connection strength.

To reduce these risks, the system should be powered off before mechanical adjustment, and the pneumatic path should be depressurized before tubing is removed. Users should keep hands outside the moving range during commanded operation. Early pneumatic tests should be performed at low pressure. Wiring should be checked before power is applied, and a current-limited supply should be used during debugging when possible. These practices are consistent with general laboratory safety expectations and compressed-air safety precautions [6, 7].

These safety considerations also affected the design choices. The prototype uses a visible open-loop sequence rather than automatic high-speed motion, and the gripper is limited to lightweight objects to reduce contact risk. The pneumatic system is tested at low pressure before full operation, and the moving range of the lead-screw stage is kept clear during commanded motion.

8 Conclusion

SoftReach Arm demonstrates a bench-top manipulation system that combines 500 mm lead-screw extension with pneumatic three-finger compliant grasping. The lead-screw linear rail mechanism provides controlled reach from the base, while the soft gripper improves tolerance to object shape and placement uncertainty. The final prototype integrated mechanical, pneumatic, electrical, and control components into a complete extend-grip-hold-release-retract sequence.

Final verification showed that the prototype met the major high-level requirements. The system achieved a 500 mm commanded extension stroke with ±3 mm end-position repeatability, 90% grasp success over 10 trials, and an 11.8 s mean full-cycle time. The main remaining limitations are sensitivity to object centering, possible pneumatic leakage at tubing interfaces, and the absence of closed-loop position or pressure feedback. Future revisions should improve pressure regulation, add position or pressure sensing, and package the wiring and tubing more robustly.

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A Requirement and Verification Table

Table 8 gives the detailed requirement and verification record for the prototype. The main text summarizes the high-level results, while this appendix preserves the detailed pass/fail criteria.

Table 8: Detailed requirement and verification table.

ID	Requirement	Verification Procedure	Result
H1	The system shall grasp, lift, and hold the selected lightweight test object for at least 3 s with at least 80% success over 10 trials.	Run 10 grasp trials. A trial passes only if the object is captured and held for at least 3 s without falling.	9/10, Pass.
H2	The telescopic mechanism shall provide a commanded linear extension of 500 mm from the retracted reference position.	Command full extension and measure the displacement from the retracted reference position over 10 trials.	500 mm mean stroke, Pass.
H2-R	The extension endpoint shall vary by no more than ±5 mm across 10 trials.	Record the final position after each extension trial and calculate the maximum deviation from the mean.	±3 mm, Pass.
H3	The system shall complete a full extend-grip-hold-release-retract cycle in no more than 15 s.	Time 10 full manipulation cycles using a stopwatch or recorded video.	11.8 s mean, 13.2 s max, Pass.
P1	The power subsystem shall complete 10 full cycles without controller reset, missed motor command, or actuator dropout during motor motion and pneumatic switching.	Observe full-cycle operation during extension, valve switching, pneumatic actuation, and retraction.	10/10 full cycles completed without reset or actuator dropout, Pass.
C1	The control subsystem shall issue extension, stop, gripper actuation, release, and retraction commands in the intended order.	Run the full sequence for 10 trials and observe whether each command occurs in the intended order.	10/10, Pass.
M1	The lead-screw stage shall extend and retract without mechanical stall under the mounted gripper load.	Run 10 extension and retraction cycles with the gripper installed and observe for stall, binding, or missed travel.	10/10, Pass.
G1	The soft gripper shall close visibly within 2.0 s after pneumatic actuation.	Command the valve and measure the time from command to visible finger closure using video timing.	1.6 s, Pass.
G2	The pneumatic connections shall not show leakage that prevents successful grasping.	Pressurize the gripper, hold for 10 s, and inspect tubing and interfaces for audible or visible leakage.	No leakage preventing grasping, Pass.
S1	The system shall remain safe to test under normal laboratory use.	Verify that moving parts are kept clear of hands, tubing is secured, and power is removed before adjustment.	Pass.