

ECE 445
SENIOR DESIGN LABORATORY
PROJECT PROPOSAL

SoftReach Arm

JUNYI CHEN (junyi10@illinois.edu)
JINWEN WANG
(jinwenw3@illinois.edu)
RUXI DENG (ruxid2@illinois.edu)
ZHIAN XIE (zhianx2@illinois.edu)

Professor: Shi Ye

TA name: Jiangshan Zhuo

March 24, 2026

Contents

1	Introduction	1
1.1	Problem Statement	1
1.2	Proposed Solution	1
1.3	Visual Aid	2
1.4	High-Level Requirements	3
2	Design	3
2.1	Block Diagram	3
2.2	Subsystem Overview	4
2.3	Subsystem Requirements	5
2.3.1	Vision Subsystem	5
2.3.2	Control Subsystem	5
2.3.3	Pneumatic Actuation Subsystem	6
2.3.4	Soft Manipulation Subsystem	6
2.3.5	Power Subsystem	7
2.4	Tolerance Analysis	7
3	Ethics and Safety	9
3.1	Ethical Considerations	9
3.2	Safety Considerations	9
3.3	Risk Mitigation and Compliance	10
	References	12

1 Introduction

1.1 Problem Statement

Robotic grasping remains difficult in practical environments because real objects rarely appear in perfectly known poses or have perfectly known shapes. Conventional rigid manipulators and rigid grippers generally perform best when the target geometry, pose, and contact conditions are well modeled in advance. However, even small uncertainties in object placement, orientation, or surface shape can lead to failed grasps, unstable contact, or the need for highly precise sensing and control. This challenge becomes more significant in tasks that involve varied or partially unknown objects, where a purely rigid system may require complex planning and tight positioning tolerances to succeed consistently. Prior work in robotic grasping under uncertain information and vision-based grasping highlights that uncertainty in object pose and object geometry is a central difficulty in manipulation systems.

Soft robotic manipulation offers a promising alternative because compliance can passively absorb positioning errors and adapt contact geometry during grasping. In particular, soft grippers are attractive for handling objects with variable shapes or fragile surfaces, while pneumatic soft actuators are widely studied because they can produce large deformations with relatively simple structures and hardware. Despite these advantages, there remains a practical need for integrated systems that combine visual target detection with a compliant soft arm and soft gripper in a form that can be fabricated, controlled, and demonstrated within a capstone-scale project. The motivating problem for this project is therefore to determine whether a vision-guided pneumatic soft manipulator can improve grasp robustness when object pose and geometry are uncertain, while still remaining simple enough to build and test in a senior design setting.

1.2 Proposed Solution

Our proposed solution is SoftReach Arm, a vision-guided robotic manipulation system that combines a compliant pneumatic soft arm with a soft two-finger gripper for adaptive object grasping. At a high level, the system first uses camera-based perception to detect a target object and estimate its location in the workspace. The manipulator then bends toward the detected target using a three-chamber soft arm, and once the end effector is positioned near the object, a separately actuated soft gripper closes around it. By combining visual perception with mechanical compliance, the system is designed to tolerate moderate error in object position and shape while still achieving reliable grasping. This design directly addresses the uncertainty problem described above: the vision module provides coarse localization, and the soft arm and gripper provide passive adaptation during final contact.

The planned implementation is explicit and modular. The lower portion of the device is a soft pneumatic arm composed of three parallel air chambers that are independently pressurized. By varying the pressure applied to each chamber, the arm can bend in different directions and achieve continuous pointing motion in the workspace. Mounted above it is

a two-finger soft gripper, where each finger contains a biased internal chamber that causes inward curling when inflated. The arm and gripper are controlled separately: three pneumatic channels determine the arm bending direction, while an additional pneumatic line drives gripper opening and closing. This separation simplifies the manipulation sequence into two stages: first, orient the arm toward the target; second, close the gripper to grasp it. Pneumatic actuation was selected because it enables fast and large deformation while preserving a relatively simple mechanical structure, making it well suited to a short-term capstone implementation of soft robotic manipulation.

1.3 Visual Aid

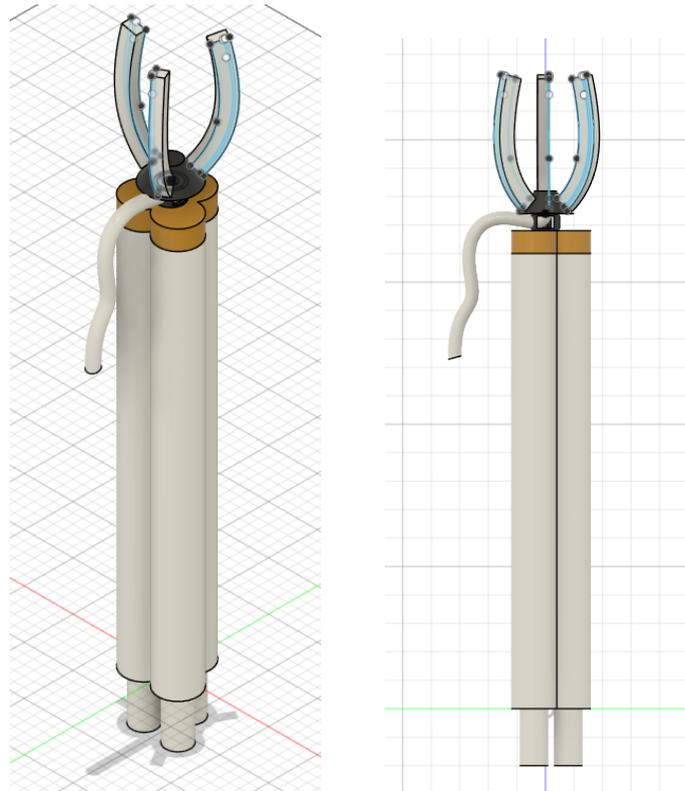


Figure 1: CAD views of SoftReach Arm showing the overall physical structure of the three-chamber soft arm and the two-finger soft gripper.

The figures illustrate the physical form and intended use context of SoftReach Arm. The device consists of a vertically mounted three-chamber pneumatic soft arm with a two-finger soft gripper at the top. In operation, SoftReach Arm is positioned above or next to a tabletop workspace containing target objects. A vision system identifies the approximate location of the object, after which the soft arm bends toward the target and the gripper closes to grasp it. The air tubing connected to the actuator represents the external pneumatic supply required to drive both the arm and the gripper.

These figures are intended to show how the system is used rather than to break down its internal components. The lower section of the device provides the compliant positioning

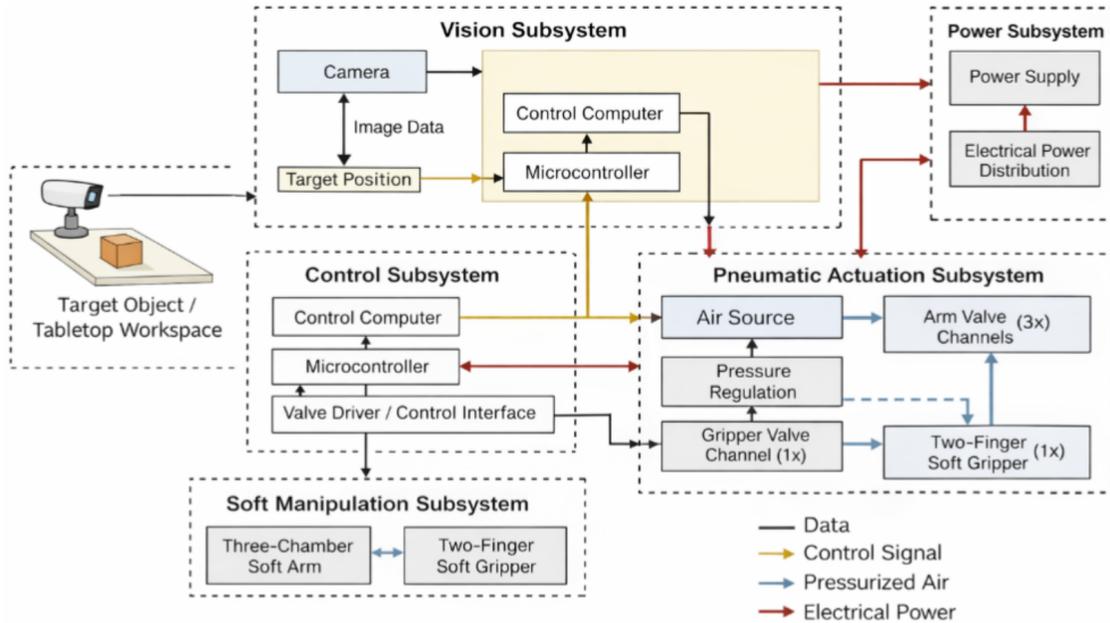


Figure 2: SoftReach Arm's Block Diagram

motion, while the upper gripper performs the final grasp. In the complete system context, SoftReach Arm will also interface with an external camera and a control unit that processes visual input and commands the pneumatic actuation sequence. Together, these elements place the proposed solution in its practical operating environment and illustrate how visual perception and soft manipulation are combined during grasping.

1.4 High-Level Requirements

- SoftReach Arm shall successfully grasp and lift target objects with a success rate of at least 80% over 10 consecutive trials for each object under the defined test conditions.
- SoftReach Arm shall be able to reach and grasp objects whose initial position is within a horizontal workspace radius of at least 8 cm from the arm centerline.
- SoftReach Arm shall complete one full grasping cycle, including target detection, arm positioning, gripper closure, and object lift, in no more than 15 seconds per trial.

2 Design

2.1 Block Diagram

The diagram is shown as figure 2.

2.2 Subsystem Overview

The **Vision Subsystem** is responsible for observing the tabletop workspace and extracting the information needed for grasping. As shown in the block diagram, it includes the camera and the target position output derived from the captured image data. The camera observes the target object in the workspace, and the resulting image data is processed to determine the object position. This target position information is then passed to the control subsystem so that the robot can decide how to bend the soft arm toward the object before grasping.

The **Control Subsystem** serves as the central decision-making unit of SoftReach Arm. It includes the control computer, microcontroller, and valve driver/control interface shown in the diagram. This subsystem receives target position information from the vision subsystem, interprets the grasping task, and generates the control signals required for pneumatic actuation. It connects directly to the pneumatic actuation subsystem by sending control commands that determine when and how each pneumatic channel is activated. In this way, the control subsystem coordinates the overall sequence of object detection, arm positioning, and gripper closure.

The **Pneumatic Actuation Subsystem** converts the electrical control commands into physical air-driven motion. According to the block diagram, it consists of the air source, pressure regulation stage, arm valve channels, and gripper valve channel. The subsystem receives control signals from the control subsystem and routes pressurized air to the appropriate actuator channels. Three valve channels are assigned to the soft arm to control directional bending, while one separate channel drives the soft gripper. This subsystem therefore acts as the interface between electronic control and the soft robotic hardware.

The **Soft Manipulation Subsystem** is the part of the robot that physically interacts with the object. In the diagram, it contains the three-chamber soft arm and the two-finger soft gripper. The soft arm bends in different directions depending on how the pneumatic channels are actuated, allowing the end effector to move toward the target location. The soft gripper then closes around the object to complete the grasp. This subsystem is connected to the pneumatic actuation subsystem through the pressurized air lines and represents the mechanical output stage of the entire system.

The **Power Subsystem** provides the electrical energy required for the system to operate. As shown in the block diagram, it contains the power supply and electrical power distribution blocks. This subsystem supplies electrical power to the control electronics and the pneumatic actuation electronics, ensuring that sensing, processing, and valve control can all function reliably. Although it does not directly perform sensing or grasping, it is essential because all other active subsystems depend on stable electrical power during operation.

2.3 Subsystem Requirements

2.3.1 Vision Subsystem

The **Vision Subsystem** consists of the camera and the object position estimation stage shown in the block diagram. Its role is to observe the tabletop workspace and provide the control subsystem with the location of the target object before actuation begins. This subsystem contributes directly to the overall design because SoftReach Arm relies on vision to avoid requiring the object to be placed at a perfectly known location. Without this subsystem, the robot would lose the ability to perform vision-guided grasping and would no longer satisfy the high-level requirement of reliable grasping under pose uncertainty. The interface between the vision subsystem and the control subsystem is a target position output, which should be updated at a fixed rate and provided with bounded spatial error so that the controller can generate appropriate bending commands for the soft arm.

- The vision subsystem shall detect the target object and output an estimated target position at a rate of at least 5 updates per second.
- The estimated target position supplied to the control subsystem shall have a planar localization error of no more than ± 1.5 cm within the defined tabletop workspace.
- The vision subsystem shall provide target position data to the control subsystem with a latency of no more than 500 ms from image capture to usable output.
- The camera shall continuously observe a workspace area of at least $20 \text{ cm} \times 20 \text{ cm}$ so that all intended test objects can be detected during operation.

2.3.2 Control Subsystem

The **Control Subsystem** contains the control computer, microcontroller, and valve driver/control interface. It receives the estimated target position from the vision subsystem, determines the required bending and grasping sequence, and sends actuation commands to the pneumatic actuation subsystem. This subsystem contributes directly to the overall design because it coordinates the two-stage manipulation process: first positioning the three-chamber soft arm and then closing the two-finger soft gripper. Without this subsystem, the system would have no means to convert visual information into a timed actuation sequence and would therefore fail to satisfy the high-level requirements on grasp success and cycle completion time. Its upstream interface is the target position data from the vision subsystem, and its downstream interface is a set of control signals to the pneumatic actuation subsystem that independently address the arm channels and the gripper channel.

- The control subsystem shall accept target position updates from the vision subsystem and compute an actuation command sequence within 200 ms of receiving a new target position.
- The control subsystem shall provide at least four independently addressable output control channels: three for the arm valve channels and one for the gripper valve channel.

- The control subsystem shall update valve command states at a rate of at least 10 Hz during active grasping.
- The control subsystem shall support a full grasping sequence, including arm positioning and gripper closure, without requiring manual intervention during a trial.

2.3.3 Pneumatic Actuation Subsystem

The **Pneumatic Actuation Subsystem** includes the air source, pressure regulation stage, three arm valve channels, and one gripper valve channel. Its purpose is to convert electrical control signals into controlled air delivery for the soft arm and gripper. This subsystem contributes directly to the overall design because the compliance and motion of the robot are generated entirely through pneumatic actuation. Without this subsystem, the soft actuators would not receive pressurized air and the robot would be unable to bend, position itself, or grasp any object. The subsystem interfaces electrically with the control subsystem through four control channels and mechanically with the soft manipulation subsystem through pneumatic lines delivering regulated air pressure.

- The pneumatic actuation subsystem shall provide four independently controlled pneumatic outputs: three for the three-chamber soft arm and one for the two-finger soft gripper.
- The pneumatic actuation subsystem shall supply regulated air pressure over a controllable range of at least 0 to 15 psi to each output channel.
- Each pneumatic channel shall be capable of switching between commanded states within 300 ms of receiving a control signal from the control subsystem.
- The pressure regulation stage shall maintain delivered pressure within ± 1 psi of the commanded set value during steady operation.

2.3.4 Soft Manipulation Subsystem

The **Soft Manipulation Subsystem** consists of the three-chamber soft arm and the two-finger soft gripper. The three-chamber arm provides compliant directional bending, while the gripper provides adaptive object capture through inward curling during inflation. This subsystem contributes directly to the overall design because it is the physical mechanism that interacts with the target object and realizes the compliance advantage being studied in the project. Without this subsystem, the robot would have no compliant manipulator and no grasping element, making object pickup impossible. Its interface to the pneumatic actuation subsystem is the set of regulated air lines feeding the arm and gripper, and its interface to the environment is direct mechanical contact with the target object.

- The three-chamber soft arm shall bend sufficiently to position the gripper over any target whose center lies within a horizontal radius of at least 8 cm from the arm centerline.

- The two-finger soft gripper shall be capable of grasping at least three objects of different geometries, including one cylindrical object, one box-shaped object, and one irregularly shaped object.
- The soft manipulation subsystem shall lift and hold a target object with a mass of at least 100 g for a minimum of 3 seconds without dropping it.
- The soft manipulation subsystem shall complete the mechanical grasping portion of a trial, including arm positioning and gripper closure, in no more than 10 seconds after receiving the actuation sequence.

2.3.5 Power Subsystem

The **Power Subsystem** contains the power supply and electrical power distribution blocks. Its function is to provide stable electrical power to the camera, control electronics, and pneumatic actuation electronics. This subsystem contributes directly to the overall design because every active block in the system depends on electrical power for sensing, computation, valve control, and pneumatic operation. Without this subsystem, no other subsystem can function, and the robot would fail to operate entirely. Its interfaces include electrical power delivery to the vision subsystem, control subsystem, and pneumatic actuation subsystem, each of which requires continuous and stable supply during a grasping trial.

- The power subsystem shall provide a regulated electrical output of $5.0\text{ V} \pm 0.1\text{ V}$ to the control electronics during normal operation.
- The power subsystem shall continuously supply at least 1.0 A total current to the powered electronics without shutdown or unacceptable voltage droop.
- The power subsystem shall distribute electrical power simultaneously to the vision subsystem, control subsystem, and pneumatic actuation subsystem during a full grasping cycle.
- The power subsystem shall support at least 15 minutes of continuous benchtop operation without requiring a power reset or manual reconnection.

2.4 Tolerance Analysis

A major design risk in SoftReach Arm is whether the three-chamber soft arm can generate enough lateral bending to place the gripper over the target object while still maintaining a stable grasping posture. This is a design-level risk because the entire system depends on the arm reaching the object before the gripper can close. If the arm cannot bend far enough, then even a perfectly functioning camera, controller, and gripper would still fail to complete the grasp. Since one of the high-level requirements is that SoftReach Arm must reach objects within a horizontal workspace radius of at least 8 cm from the arm centerline, the feasibility of this bending motion must be demonstrated quantitatively.

A first-order geometric analysis can be used to estimate the required bending angle. If the

active length of the soft arm is modeled as a bending segment of length L , then the horizontal reach x of the gripper relative to the arm centerline can be approximated by

$$x = L \sin \theta$$

where θ is the effective bending angle of the arm. Based on the current CAD concept, the active arm length is approximately

$$L \approx 18 \text{ cm.}$$

To satisfy the workspace requirement,

$$x \geq 8 \text{ cm.}$$

Substituting into the geometric model gives

$$8 \leq 18 \sin \theta$$

which implies

$$\sin \theta \geq \frac{8}{18} = 0.444.$$

Therefore, the required bending angle is

$$\theta \geq \sin^{-1}(0.444) \approx 26.4^\circ.$$

This required angle is moderate rather than extreme, which supports the feasibility of the design. A three-chamber pneumatic soft arm is specifically intended to generate directional bending through unequal chamber pressurization, and the required motion is only about 26.4° . Even if manufacturing variation or pneumatic loss reduces the achievable bend somewhat, the design still has useful margin. For example, if the arm reaches

$$\theta = 30^\circ,$$

then the horizontal displacement becomes

$$x = 18 \sin 30^\circ = 9.0 \text{ cm,}$$

which exceeds the 8 cm requirement by 1 cm. Similarly, if the final active arm length is slightly shorter, such as

$$L = 16 \text{ cm,}$$

the required bending angle becomes

$$\theta \geq \sin^{-1}\left(\frac{8}{16}\right) = 30^\circ,$$

which remains within a practical target range for a compliant pneumatic arm. This analysis indicates that the required workspace is achievable as long as the fabricated arm can reliably generate bending in the range of approximately 30° .

For the final implementation, this analysis will be validated experimentally by measuring the tip displacement of the fabricated arm under different pressure combinations in the three chambers. However, the present geometric model already shows that the required reach is feasible with the proposed arm length and bending strategy. Therefore, the bending capability of the soft arm, while still a critical design risk, appears achievable within the intended project scope.

3 Ethics and Safety

3.1 Ethical Considerations

SoftReach Arm raises ethical concerns related to user safety, honest performance reporting, and responsible use of camera-based sensing. The IEEE Code of Ethics emphasizes making engineering decisions consistent with the safety, health, and welfare of the public, while the ACM Code of Ethics states that the public good is the primary consideration and that computing professionals should avoid harm and be honest and trustworthy. These principles are directly relevant because SoftReach Arm combines perception, actuation, and physical interaction with real objects in a shared workspace. [1], [2] :contentReference[oaicite:0]index=0

One important ethical issue is the risk of overstating the system’s precision or reliability. SoftReach Arm is designed as a compliant tabletop manipulation system, not as a high-precision industrial robot. Its performance may vary with object geometry, lighting, pneumatic response, and fabrication quality. To avoid misleading users or evaluators, all claims about grasp success, workspace, and task timing should be based on measured experimental results under clearly stated test conditions rather than selective demonstrations. This approach is consistent with the IEEE and ACM emphasis on honesty, responsible disclosure, and avoidance of harm caused by misleading technical claims. [1], [2] :contentReference[oaicite:1]index=1

A second ethical issue is privacy and responsible sensing. Although the intended use of the camera is object detection in a tabletop workspace, the camera may still capture nearby people or unrelated personal items if it is not positioned carefully. To reduce unnecessary data collection, the camera should be aimed only at the workspace, image storage should be minimized, and any saved development data should be limited to what is needed for debugging and evaluation. This is aligned with the ACM Code’s guidance on avoiding harm and considering the broader impact of computing systems. [2] :contentReference[oaicite:2]index=2

3.2 Safety Considerations

The most significant safety risks in SoftReach Arm arise from pneumatic actuation, unintended motion, pinch points at the gripper, and electrical faults in the controller and valve-driving hardware. Pressurized air can cause sudden motion if a valve opens unexpectedly or if tubing disconnects under pressure. The soft gripper can also pinch fingers during testing if inflation occurs while a user is manually adjusting the mechanism. These hazards are especially relevant during development, when the system may be repeatedly assembled, modified, and retested. [3], [4] :contentReference[oaicite:3]index=3

If an external compressed-gas source or regulated air supply is used, the project must also follow applicable safety guidance for compressed gas handling. OSHA states that compressed air used for cleaning must be reduced below 30 psi except under limited protected conditions, reflecting the broader risk posed by uncontrolled compressed air

exposure. At UIUC, the Division of Research Safety provides compressed gas cylinder safety guidance and maintains laboratory safety requirements through the Laboratory Safety Plan and laboratory safety training process. These sources are relevant because the project involves pneumatic hardware, tubing, fittings, and pressurized actuation components that must be handled safely in a laboratory environment. [3], [4], [5], [6] :contentReference[oaicite:4]index=4

The electrical subsystem also presents safety concerns. Solenoid valves, pumps, and control electronics can fail if wiring is incorrect or if excessive current is drawn through logic-level components. Short circuits, overheating, or improper grounding could damage the system or create burn hazards. During prototyping, electrical power should therefore be treated as a separate safety concern from the pneumatic system, especially because an electrical fault could also trigger unintended actuation. This interaction between electrical and pneumatic hazards makes careful integration important for safe development and testing. [5], [6] :contentReference[oaicite:5]index=5

SoftReach Arm could also be misused intentionally or accidentally. It is not designed for contact with humans, animals, medical materials, or hazardous objects, and it should not be treated as safe for assistive or industrial deployment without much more validation. Because the system is optimized for lightweight tabletop objects in a controlled environment, using it outside that operating envelope could create both safety and ethical problems. [1], [2] :contentReference[oaicite:6]index=6

3.3 Risk Mitigation and Compliance

To reduce ethical risk, the team will document the intended use of SoftReach Arm clearly and report only measured results. The robot will be presented as a capstone-scale demonstration of vision-guided soft grasping under uncertainty, not as a certified precision manipulator. Camera use will be restricted to the tabletop workspace, and any stored images will be limited to development and evaluation needs. These practices help avoid misleading claims and unnecessary collection of visual data, which is consistent with the responsibilities described by IEEE and ACM. [1], [2] :contentReference[oaicite:7]index=7

To reduce safety risk during development, subsystem testing should be incremental. Electrical verification should be completed before pressurizing the actuators, and early pneumatic tests should be performed at reduced pressure. The robot should only be adjusted by hand when the air supply is disabled and the system is depressurized. A clearly marked keep-out area should be maintained around the manipulator during active testing, and the controller should default to a safe state that closes valves or removes actuation commands when power is lost or software stops responding. These measures reduce the likelihood of accidental motion, hose release, or gripper pinch during use. [3], [5], [6] :contentReference[oaicite:8]index=8

To support compliance with relevant safety expectations, the project will follow UIUC laboratory safety procedures, including the laboratory safety plan and training framework maintained by the Division of Research Safety. If compressed gas cylinders or external regulated air sources are used, they will be handled in accordance with campus

compressed gas safety guidance. In addition, tubing, fittings, and pressure regulation will be selected so that the pneumatic subsystem operates within its intended pressure range during demonstration. Together, these steps reduce the likelihood of both safety incidents and ethical breaches while keeping the project aligned with professional and institutional expectations. [4], [5], [6] :contentReference[oaicite:9]index=9

References

- [1] Institute of Electrical and Electronics Engineers, *Ieee code of ethics*, PDF, Accessed 2026-03-24.
- [2] Association for Computing Machinery, *Acm code of ethics and professional conduct*, ACM, Accessed 2026-03-24, 2018.
- [3] Occupational Safety and Health Administration, *29 cfr 1910.242(b): Compressed air used for cleaning*, OSHA, Accessed 2026-03-24.
- [4] University of Illinois Urbana-Champaign Division of Research Safety, *Compressed gas cylinder safety*, DRS Safety Library, Accessed 2026-03-24.
- [5] University of Illinois Urbana-Champaign Division of Research Safety, *Laboratory safety plan overview*, DRS, Accessed 2026-03-24.
- [6] University of Illinois Urbana-Champaign Division of Research Safety, *Laboratory safety training*, DRS, Accessed 2026-03-24.