ECE 445

Design Document

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Table Cleaning Robot: Autonomous Elevated Surface Cleaner

Team No. 33

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1. Introduction

1.1 Problem

In homes, workplaces, and restaurants, cleaning tables is a repetitive and time-consuming chore that must be completed on a regular basis. Spills, food particles, and dust can quickly build up, requiring frequent cleaning. While floor-cleaning robots have made floor cleaning easier, there aren't many automated options for cleaning tables. Without a table-cleaning robot, people must physically clean surfaces, which takes time and effort. In places like cafes and restaurants, where tables need to be cleaned frequently, an automated solution could reduce labor costs and improve efficiency.

Unlike floor-cleaning robots, designing a table-cleaning robot has its own set of difficulties. The robot must be able to move around objects like plates and cups, identify table edges to avoid falling, and clean efficiently without pushing stuff off the surface. Current cleaning robots focus on flat and large floor areas, but a table-cleaning robot needs more accurate control and obstacle interaction.

1.2 Solution

Our solution is a small, self-operating table-cleaning robot that can effectively clean flat surfaces while avoiding falls and obstacles. This robot is designed for elevated surfaces, ensuring safe and reliable operation. The robot will navigate around objects like plates and cups, detect edges to prevent falls, move around objects like plates and cups, and use a small vacuum system or rotating brushes to collect dust and crumbs.

To achieve these functions, the robot will include several key components. Depth-detecting cameras will recognize the table's borders, ensuring the robot stops or turns before reaching an edge. It will also help the robot navigate around objects without knocking them over. Debris will be collected by a vacuum and placed in a collection bin for cleaning. Additionally, the robot may clean beneath objects without tipping them over. The table-cleaning robot will provide a dependable and automated solution for maintaining clean tabletops by combining these elements.

1.3 Visual Aid

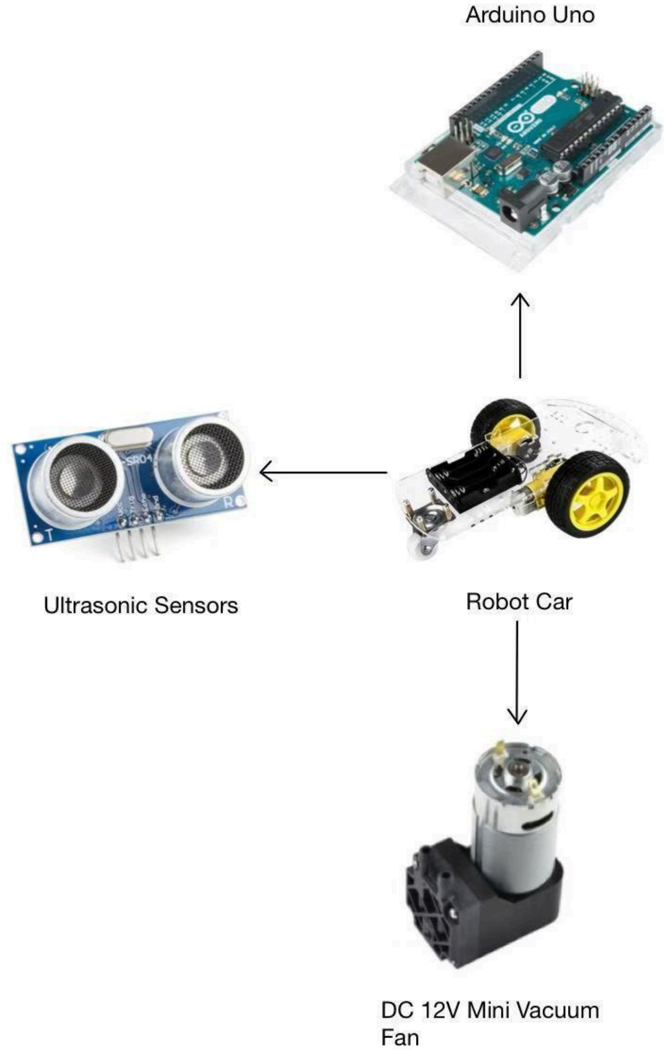

Figure 1. Visual Aid of the Automated Table Cleaning Robot

The Arduino Uno [1] functions as the microcontroller, the ultrasonic sensors [2] detect edges and obstacles, and the mini vacuum fan provides suction for dust. Each of these components corresponds to a core functionality within our subsystems.

1.4 High-level Requirements List

- Edge Detection and Fall Prevention: The robot must detect table edges using ultrasonic sensors and respond by stopping or changing direction within 2 cm of the edge to prevent falling.

- Debris Collection Efficiency: The cleaning system must remove at least 90% of dust, crumbs, and small debris from a 60 cm x 60 cm table surface in a single cleaning cycle and store the collected debris in a removable bin that holds dirt for at least three full cleaning cycles.

- Obstacle Avoidance and Object Interaction: The robot must detect and navigate around objects as small as 5 cm in diameter and as large as 20 cm in diameter with at least 95% success. It must avoid collisions and prevent pushing objects off the table.

2. Design

2.1 Block Diagram

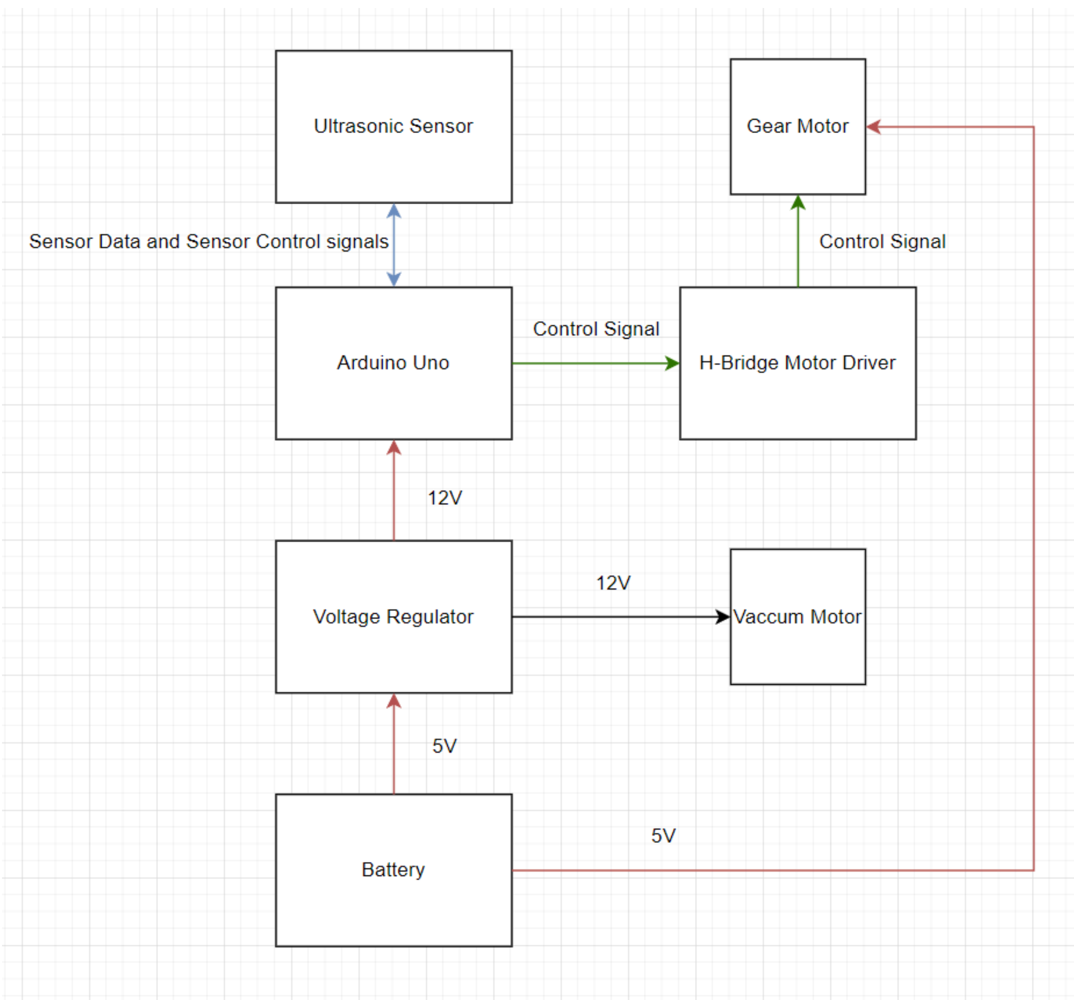

Figure 2. Block Diagram of the Automated Cleaning Robot

2.2 Subsystem Overview

2.2.1 Edge Detection Subsystem

The edge detection and fall prevention subsystem is a critical safety component that ensures the robot does not fall off the table by detecting edges in real time. Failure to accurately detect edges could result in the robot falling and becoming damaged. This subsystem interacts directly with the motion control system, adjusting the robot's movement based on its proximity to table edges.

To achieve reliable edge detection, we use ultrasonic sensors, which detect edges and help control the robot's movement by stopping or changing its direction when necessary. Ultrasonic sensors were chosen over other options because they are not affected by ambient light, making them reliable in both bright and dark environments. They also provide fast and accurate distance measurements, allowing the robot to quickly detect changes in surface height and identify edges effectively.

We will mount four ultrasonic sensors on the front, back, and sides of the robot to ensure full coverage, even when the robot is changing direction or moving backward. Each sensor will be positioned slightly downward to improve edge detection, but the angle must remain within 15 degrees due to the sensor's effectual angle—beyond this limit, accuracy decreases significantly. Each sensor has a ranging distance of 2 cm to 400 cm with a resolution of 0.3 cm [3].

The system classifies an edge when an ultrasonic sensor detects a sudden increase in distance from less than 5 cm to greater than 20 cm within two consecutive sensor readings, which prevents false triggers. The ultrasonic sensors will continuously send distance measurements to the Arduino Uno microcontroller, which processes the data in real time. Once an edge is confirmed, the microcontroller will send PWM signals to the motor driver (L298N) to either stop or turn when an edge is detected, allowing the robot to stop or change direction.

Requirements	Verification
The ultrasonic sensors must detect a	Allow the robot to move at a controlled

table edge when the distance reading suddenly increases within two consecutive sensor readings	speed from different distances toward the table edge. Use a logic analyzer to measure sensor readings and confirm that the edge is correctly detected.
The system must send a STOP or TURN command within 100ms of detecting an edge.	Use an oscilloscope to measure the time delay between edge detection and the execution of the STOP or TURN command. Verify that the command is issued within 100ms to ensure proper functionality.
The robot must avoid falling off the table in at least 95% of test cases.	Conduct at least 50 trials. Record the number of successful edge detections and confirm that the robot avoids falling in at least 95% of cases.
The ultrasonic sensors must function correctly under different lighting conditions.	Test the robot in various lighting environments, including bright daylight and complete darkness, to ensure edge detection remains unaffected by ambient light.
The robot must be able to detect edges at different approach angles and movement directions.	Position the robot at various angles and movement directions. Verify that the robot successfully detects the edge and stops or changes direction accordingly.

Table 1. R&V Table for Edge Detection Subsystem

2.2.2 Power Supply Subsystem

The power supply subsystem is responsible for delivering stable, regulated power to all components of the table-cleaning robot, including the microcontroller, sensors, motors, and vacuum pump. It manages energies from the battery using components such as the 18650 rechargeable battery, which is the power supply of the gear motor, and the XL6009 DC-DC Step-Up Converter[4], and converts it to 12V, which is used as the voltage supply of vacuum and Arduino Uno. This subsystem also incorporates necessary protection features to ensure safe operation under normal and fault conditions.

Requirements	Verification
The subsystem must supply a regulated voltage in the range of 4.5–5.5 V to the input of the voltage regulator and the gear motor, and the voltage regulator must supply 10.8-12.4 V to the Arduino Uno and the vacuum.	Connect the digital multimeter to the power supply output and verify that the voltage of the battery remains within 4.5–5.5 V, and that of the voltage regulator remains 10.8-12.4V, under no-load conditions. Intentionally simulate fault conditions and verify that the protection mechanisms activate by either shutting down or regulating the output appropriately. Place the power supply in a temperature-controlled environment and verify that it operates within the specified temperature and humidity ranges.
The power supply should automatically regulate or shut down if the output exceeds 12.4 V. A low-voltage warning or shutdown must be triggered if the battery voltage drops below a safe threshold, which is 3.2V for the battery we used.	Connect the shape generator to the voltage input. Start from normal operating voltage, and gradually increase the voltage until the output exceeds 12.4V, and observe with an oscilloscope if the power supply shuts down automatically. Repeat the process, but gradually turn the input voltage down until it's below 3.2V to observe if it shuts down automatically.

Table 2. R&V Table for the Power Supply Subsystem

2.2.3 Debris Collection Subsystem

The debris collection subsystem is responsible for cleaning the table by vacuuming dust and crumbs into a collection bin. It consists of a mini vacuum motor and a collection bin. When the robot is moving, the vacuum will stay on. The motion control subsystem will control the speed and direction of the robot to ensure proper table coverage.

The ROB-10398 vacuum pump is an excellent choice for our table cleaning robot due to its compact design, efficient suction capabilities, and low power consumption. It operates at 12V DC, making it compatible with our power system, while delivering a strong airflow of 1.2 L/min, ensuring effective debris collection. Additionally, its lightweight structure minimizes the load on the robot, improving maneuverability and battery efficiency. The pump's reliable operation and ease of integration make it well-suited for continuous cleaning while the robot is in motion.

The Debris Collection Subsystem receives a 12V input from the voltage regulator, as the vacuum pump operates at 12V while the system's battery voltage is 5V. The voltage regulator ensures that the pump receives a stable supply for consistent suction performance. The only electrical input to the vacuum pump is the regulated 12V. There are no outputs from the subsystem, and all debris collected by the vacuum pump will be stored inside the collection bin. The bin will be cleaned after the cleaning process.

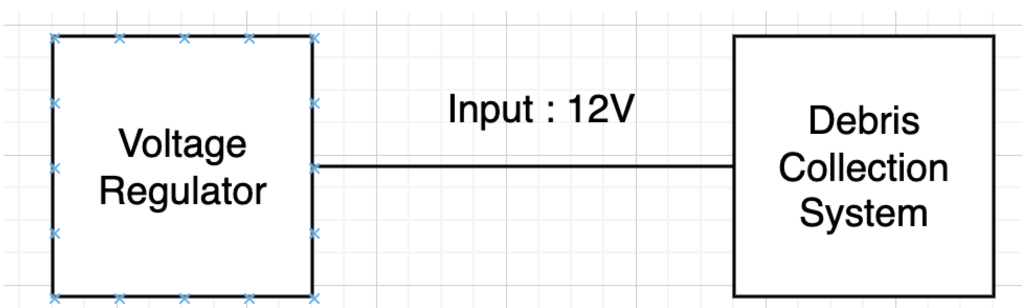

Figure 3. Input to Debris Collection Subsystem

Requirement	Verification
The debris collection subsystem must vacuum at least 90% of debris in a given area.	Measure before and after debris mass to confirm 90% collection efficiency.

The input voltage to the Debris Collection System should be 12V (±0.4V).	Measure input voltage using a multimeter and an oscilloscope.

Table 3. R&V Table for the Debris Collection Subsystem

2.2.4 Obstacle Avoidance Subsystem

The obstacle avoidance subsystem identifies objects on the table using ultrasonic sensors. It measures distances and sends processed signals to the central control module to prevent collisions. The system determines how to move around or interact with objects to clean area near them.

To achieve reliable obstables detection, we use ultrasonic sensors, which detect edges and help control the robot's movement by stopping or changing its direction when necessary. Ultrasonic sensors are able to function in both bright and dark environments. They also provide fast and accurate distance measurements, allowing the robot to quickly detect the obstacles and make interaction with them effectively.

To ensure precise measurement, four ultrasonic sensors will be mounted on the front and back of the robot for both edge detection and obstacle detection. Each sensor has a ranging distance of 2 cm to 400 cm with a resolution of 0.3 cm.

The system classifies an obstacle when an ultrasonic sensor detects a sudden decrease in distance within two consecutive sensor readings. It will send signals to the Arduino Uno microcontroller, which processes the data in real time. Once an obstacle is confirmed, the microcontroller sends a corresponding command to the motor driver, allowing the robot to stop or change direction.

Requirements	Verification
The ultrasonic sensor needs to detect	Place testing obstacles and set the input

the obstacle and let the Arduino Uno to stop the gear motor.	voltage to 3.2V and 5.5V respectively to test if the robot can detect and stop before hitting the obstacle under minimum and maximum power.
To ensure its stability, the robot must avoid hitting obstacles in at least 95% of the test cases	Repeat tests for 50 times under the regular operating voltage, and record the outcome, including cases of changing angles between the robot and the testing obstacles, and airs with various humidity and temperature.

Table 4. R&V Table for the Obstacle Avoidance Subsystem

2.4 Tolerance Analysis

-The robot runs Edge Detection checks at a certain sampling frequency (In this case 40Hz)

-The Ultrasonic sensor can detect a drop-off at nominal d_s = 2 cm from the edge with a typical uncertainty of measurement e = ±3mm.

-The robot moves at v = 5.65 cm/s (0.0565 m/s)

-Reaction time t_r = 0.2s (at 5Hz)

-Deceleration rate a = 0.5 m/s^2

With such parameters, the numerical calculation is below:

The distance during reaction time:

$$d_r = v * t_r = 0.0565m/s * 0.025s = 0.0014125m$$

The braking distance:

$$d_b = v^2/2a = (0.0565)^2/(2 * 0.5) = 0.00319225m$$

The distance needed to stop:

$$d_{stop} = d_r + d_b = 0.0014125 + 0.00319225 = 0.00460475m$$

Distance of effectiveness:

$$d_{effective} = d_s - e = 0.02 - 0.003 = 0.017m$$

Since 0. 00460475m<< 0.017m, theoretically, the parameter of parts allows the robot to detect the edge of the table or obstacles and stop to avoid any accidents.

3. Cost and Schedule

3.1 Cost Analysis

Team Member	Hourly Rate	Hours	Total
Ann Luo	$38	77	$7315
Bolin Pan	$38	77	$7315
Yening Liu	$38	77	$7315
Total			$21945

Table 5. Salary Assumption

Part Name	Part Number	Manufacturer	Quantity	Cost
Arduino Uno	EL-CB-001	ELEGOO	1	$14.99
L293D DC Motor Drive	3-01-0506	HiLetgo	1	$7.49
HC-05 Wireless Bluetooth RF Transceiver	8541554474	HiLetgo	1	$10.39
HC-SR04 Ultrasonic Module Distance Sensor	3-01-0008-A	HiLetgo	1	$9.19
TT Gear Motor	B07DDC3ZBK	Guangzhou Openfind Electronic Commerce CO., LTD	4	$11.99
Plastic Tire Wheel	JC3176X2	S-snail	4	$13.99
Battery Storage Case	4350280812	Ltvystore	1	$9.99
ROB-10398	1568-ROB-10398-ND	SparkFun Electronics	1	$18.95

18650 Rechargeable Battery	B0CS2M2VJR	jiukekeji	2	$11.99
XL6009 DC-DC Step-Up Converter	3-01-0101	HiLetgo	1	$5.99
Total				$114.96

Table 6. Parts Costs

We assume each team member's salary to be $7,315, based on an hourly rate of $38. The total labor cost amounts to $21,945. Additionally, the total cost of parts is $96.98. Combining both, the overall project cost comes to $22,059.96.

3.2 Schedule

Date	Task	Team Member
Feb. 24-Mar. 2	Order components	Ann
	Work on schematics of PCB	Bolin
Mar.3 - Mar.9	Schematic design	Ann
	Work on PCB wiring, breadboard	Bolin
	Write design document	All
Mar.10 - Mar.16	Finish PCB before 2nd round due	Bolin
	Breadboard Demo	All
	Write code	Ann
	Update design document	Yening
Mar.17 - Mar.23	Spring Break	All
Mar.24 - Mar.30	Write code	Ann
	Debug PCB	Bolin

	Update design document	Yening
Mar.31 - April 6	Individual Progress Report	All
	Order 3rd PCB if necessary	Bolin
	Test functionality	Ann, Yening
April 7- April 13	Finalize the project	All
April 14-April 20	Team Contract Assessment	All
	Finalize the project	All
April 21-April 27	Mock Demo	All
April 28 - May 4	Final Demo	All
	Final Papers	All
	Project Video	All
May 5 - May 9	Final Presentation	All
	Final Papers	All

Table 7. Team Schedule

4. Ethics and Safety

The design, development, and deployment of the Table Cleaning Robot must adhere to ethical principles to ensure safety, reliability, and responsible engineering practices. This section assesses ethical issues and safety concerns, drawing guidance from the IEEE Code of Ethics.

4.1 Ethical Considerations

1. Public Safety and Welfare
   According to IEEE code #1 [5]: "Hold paramount the safety, health, and welfare of the public", public safety and welfare must be ensured. The Table Cleaning Robot must operate safely without causing harm to users, pets, or property. It must be designed to prevent falls and avoid pushing objects off the table so that no one will get hurt during the cleaning process. Therefore, rigorous testing for edge detection, fall prevention, and obstacle detection is required.

2. Honesty and Transparency in Design
   According to IEEE code #5: “Be honest and realistic in stating claims or estimates based on available data”, honesty and transparency in design are required. The capabilities of the robot should be accurately presented. If the robots have limitations, the limitations must be clearly disclosed.
3. Privacy Protection
   According to IEEE code #4: “Avoid unlawful conduct in professional activities”, we as designers should notice the importance of privacy protection. When we use visual sensors, we must ensure that data is encrypted, avoid storing unnecessary information, and comply with privacy regulations.
4. Fairness and Non-Discrimination
   The project must not create biased or discriminatory outcomes. We will conduct bias testing and ensure inclusivity in design and deployment.

4.2 Safety Considerations

1. Mechanical and Electrical Hazards
   The robot has moving parts that could cause injury if mishandled. Electrical components, particularly lithium-ion batteries, pose risks of overheating or short-circuiting. Implementation of protective casing around moving parts can mitigate the hazards.
2. Fall Prevention and Object Handling Risks
   The robot must reliably detect table edges to avoid falling and prevent damage to itself and surrounding objects. If the robot attempts to move objects, it could accidentally push items off the table. Therefore, high-precision edge detection systems and object detection systems should be strictly tested. Also, implementing redundant safety measures will mitigate risks of failure in mission-critical applications.
3. Safe Charging and Energy Efficiency
   The charging station must be designed to prevent overheating and electrical fires. Therefore, auto-shutoff is recommended.

4.3 Regulatory Compliance

1. Battery Safety

   If the robot uses a lithium-ion battery, it must meet UN/DOT 38.3 certification to ensure safe transport and usage.

2. Campus and Lab Safety Policies

   If deployed in university environments, the robot must follow campus safety protocols, especially concerning fire hazards, electrical devices, and laboratory usage.

4.4 Mitigation Strategies

To avoid ethical and safety breaches, the following strategies will be implemented:

1. **Regular Ethical Audits**: Conduct periodic reviews of the project's compliance with ethical guidelines.
2. **Risk Assessments**: Identify and mitigate potential hazards through systematic risk management frameworks.
3. **Stakeholder Involvement**: Engage with users, regulatory bodies, and ethicists to ensure accountability.
4. **Transparency and Documentation**: Maintain clear records of decisions, safety tests, and compliance measures to facilitate oversight.

By integrating these ethical principles, safety measures, and regulatory standards, the Table Cleaning Robot will be safe, reliable, and responsibly engineered. Compliance with the IEEE Code of Ethics ensures that the product prioritizes public welfare, environmental responsibility, honesty, and fairness

5. Citation

[1] *Arduino Uno R3*, Arduino. [Online].
Available:https://docs.arduino.cc/resources/datasheets/A000066-datasheet.pdf

[2] *Ultrasonic Distance Sensor - 5V (HC-SR04)*, Sparkfun Electronics. [Online].
Available: https://cdn.sparkfun.com/datasheets/Sensors/Proximity/HCSR04.pdf

[3] *HC-SR04 Ultrasonic Module Distance Sensor*, Sparkfun Electronics. [Online].
Available: https://cdn.sparkfun.com/datasheets/Sensors/Proximity/HCSR04.pdf

[4] XL6009 DC-DC Step-Up Converter, HiLetgo. [Online]. Available:
https://www.amazon.com/HiLetgo-Adjustable-DC3-0-30V-DC5-35V-Converter/dp/B00LP2LZ4M/ref=asc_df_B00LP2LZ4M?mcid=eca8452dbbee32959cfbbe10d3a10e46&hvocijid=12269984257663601826-B00LP2LZ4M-&hvexpln=73&tag=hyprod-20&linkCode=df0&hvadid=730432682330&hvpos=&hvnetw=g&hvrand=12269984257663601826&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9022185&hvtargid=pla-2281435178098&th=1

[5] *IEEE - IEEE Code of Ethics*. [Online]
www.ieee.org/about/corporate/governance/p7-8.html. Accessed 7 Mar. 2025.