ECE 445

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

Project Proposal for ECE 445: Terrain-adaptive bipedal service robot

---

Team #2

YUAN ZHOU
(yuanz15@illinois.edu)
ZIHAO YE
(zihaoye5@illinois.edu)
BINHAO WANG
(binhaow2@illinois.edu)
GAOKAI ZHANG
(gaokaiz2@illinois.edu)

TA: Xinlei Chang

March 14, 2025

Abstract

This project describes the design and creation of a service robot that is bipedal and capable of navigating across uneven and complex surfaces. The robotic vehicle is intended to enhance mobility in environments that traditional wheeled robots have a hard time dealing with, such as stairs, slopes, and rough outdoor areas. Using feedback from realtime sensors, modular mechanical components, and a reinforcement learning-based motion controller, the robot guarantees consistent and efficient movement. Key attributes include obstacle detection, dynamic balancing, and a user-friendly interface that is designed to be integrated with human intelligence. The project focuses on safety and ethical concerns, including the protection of privacy, the security of data, and environmentally responsible design decisions. By providing dependable, autonomous assistance in both domestic and professional settings, this dual-legged robot provides novel solutions to service problems in human-oriented environments.

Contents

List of Figures

List of Tables

1 Introduction

Our project is focusing on developing a **terrain-adaptive bipedal service robot** which is designed to operate reliably on uneven and even changing surfaces. This introduction will be outlining the main goals of the project, the robot's intended functions, the benefits being offered to users, its key features, and the high-level requirements that truly will define its success.

1.1 Goals

The goal of this project is building a bipedal service robot that can relatively easily traverse a variety of terrains and environments which are challenging for traditional wheeled robots. Specifically, if successful, we target at enhancing mobility in areas with uneven ground like stairs and ramps, by empowering the robot with the dynamic adjustment of its gait and balance. Overall, the robot should be improved in both accessibility and efficiency in service tasks, which would be verified in reliably navigating areas that rather require human mobility or specialized equipment.

1.2 Functions

The robot will have several core functions. First and foremost, it will be able to walk with good balance on uneven terrain with its adaptive gait control and real-time feedback from sensors. Furthermore, it can navigate around obstacles and also climbing stairs or slopes. Additionally, a user interface function will enable users to direct the robot while monitoring the robot's status. These combined functions enable the robot to act as a flexible helper in both structured and unstructured environments.

1.3 Benefits

This terrain-adaptive robot offers several benefits for users, increasing convenience and safety by, without much human effort, handling tasks in environments that would otherwise be difficult or risky for people – for example, traversing rough outdoor ground to carry supplies. By utilize bipedal locomotion, the robot can operate in spaces designed for humans (doorways, staircases, narrow passages), providing services in places where wheeled robots cannot easily reach, which would be able to save users time and effort and also assist in taking on the physical strain of moving items across challenging terrain. Overall, the robot will bring the advantage of automated assistance to a wider range of household and workplace scenarios.

1.4 Features

Key features of our bipedal service robot include:

- **All-Terrain Mobility**: Advanced leg manipulation and terrain sensing enabling it to walk on uneven floors, carpets, inclines, or outdoor ground (like gravel or grass) without losing balance.

- **Dynamic Stability**: A real-time control system actively keeping its balance, making sure that the robot will be able to recover from small pushes or stumbles and remain upright.
- **Safe Human Interaction**: Obstacle detection avoiding collisions with other objects, ensuring the safety to operate around users.
- **User-Friendly Interface**: Advanced intreaction interface allowing users to command the robot and monitoring the robot.
- **Modular Expandability**: Attachments or upgrades easy to implement, extending its functionality for various service needs.

1.5 High-Level Requirements

To ensure the robot effectively addresses the mobility problem, it must meet several high-level requirements quantitatively:

1. **Terrain Adaptability:** The robot shall be able to climb steps up to 10 cm in height and walk on slopes up to 15° inclination.
2. **Latency Tolerance:** The Master Board must process sensor inputs and send control signals within 10ms latency. It should achieve a 0.2ms latency communication with our PC.
3. **Operational Endurance:** The robot should remain balanced without tipping when its legs subjected to dynamic impact forces up to 10 N.

2 Design & Requirements

2.1 Block Diagram & Physical Diagram

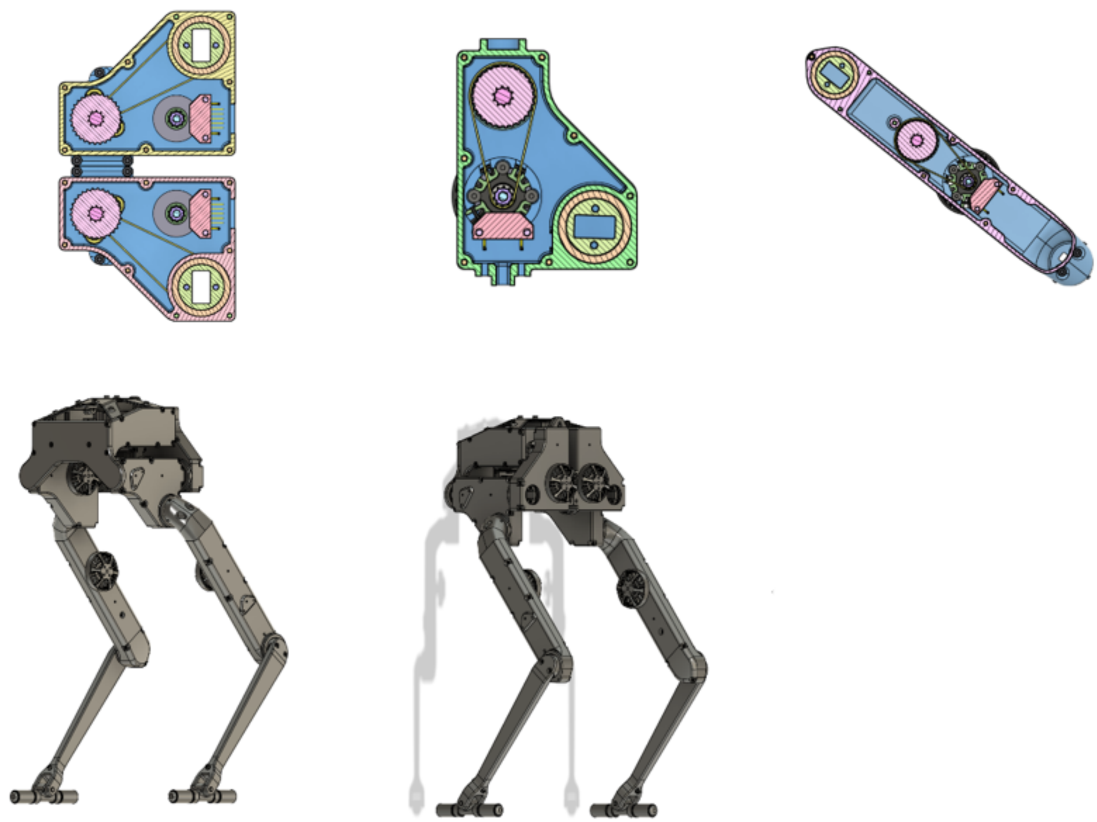

Figure 1: The Fusion CAD model and cross-sectional view of our bipedal robot.

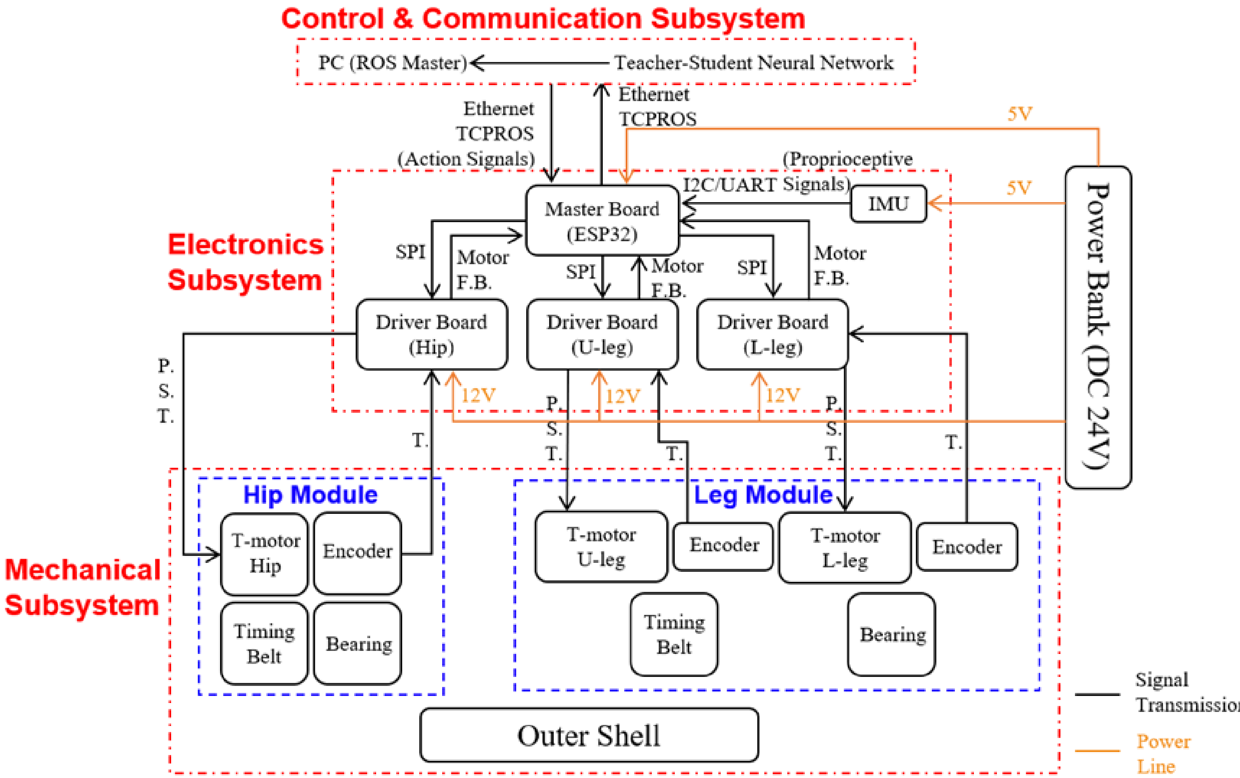

Figure 2: The block diagram of our bipedal robot.

2.2 Diagram Descriptions – Functionality and Requirements of each Component

2.2.1 Physical Diagram Description

The Physical Diagram of our bipedal robot system illustrates its modular mechanical design, highlighting the structural framework, actuation mechanisms, and power transmission components.

The full-body views depict a lightweight 3D-printed outer shell, with potential upgrades to carbon fiber, and a symmetrical leg structure ensuring stability and balance. The section views provide insight into the internal arrangement of key modules. Each of the hip actuation parts houses a T-Motor that drives the hip joint through a timing belt and pulley system, with an encoder for real-time position feedback and bearings to minimize friction. Similarly, the upper leg module features a T-Motor-driven transmission, supported by precisely positioned bearings for smooth operation and structural integrity, which drives the motion of the upper leg. The lower leg module, responsible for the final stage of motion transmission, is the same as the aforementioned parts, and it drives the motion of the lower leg.

The modular design enables easy maintenance and component replacement, making the robot efficient, adaptable, and scalable for real-world applications such as transportation and autonomous navigation.

2.2.2 System Overview

The Biped Robot System consists of four modular interconnected subsystems: Mechanical Subsystem, Electronics Subsystem, Control & Communication Subsystem, and Power Supply Subsystem. Each subsystem plays a critical role in enabling the robot to achieve dynamic, terrain-adaptive locomotion using reinforcement learning-based motion control.

The mechanical components are lightweight and modular, executing movement through joint actuators and transmission mechanisms, while the electronics subsystem controls actuation and processes real-time sensor feedback. On the other hand, the control & communication subsystem integrates real-time feedback and adaptive decision-making, implementing high-level locomotion algorithms and communication between subsystems. The power supply system, which provides stable energy for motors, controllers, and sensors, is responsible for ensuring stable and efficient energy distribution across all components.

Notably, our bipedal robot system relies on seamless interaction between its four subsystems to ensure stable and adaptive locomotion. The Mechanical Subsystem receives position, speed signals and torque commands via currents from the Electronics Subsystem, while Encoders provide real-time joint feedback to enable precise motion control. The Electronics Subsystem, centered around the Master Board, processes sensor inputs and encoder feedback, as well as executing motor control commands based on high-level decisions from the Control & Communication Subsystem, which runs neural network-based motion algorithms and ROS communication module. Meanwhile, the Power Supply Subsystem provides regulated 24V power, ensuring stable operation for all components. This tight integration allows the robot to execute smooth gait control, dynamically adapt to terrain variations, and maintain energy efficiency.

2.2.3 Specific Components in the Block & Their Functionality and Connections

1. Mechanical Subsystem
Body Module (represented as outer shell in the block diagram)

Function: Provides a structural framework for mounting actuators, electronics, and sensors while maintaining a lightweight and durable design.

Components: 3D-printed outer shell (preliminary decision), potential carbon fiber upgrade for enhanced strength.

Connections: Houses electronics (master board, IMU, power unit), interfaces with leg modules via joint actuators and motor control cables.

Leg & Hip Modules *Function:* Enable controlled movement via torque-controlled brushless motors, ensuring smooth gait execution.

Components: Each leg & hip consists of:

- T-Motors (brushless DC motors): Provides precise torque control for stable movement (T-motors for upper leg modules are written as T-motor U-leg, and the T-motors for lower leg modules are written as T-motor L-leg).
- Encoders: Measure the actual torque exists in the T-motor for real-time feedback control.
- Timing Belts & Bearings: Ensures smooth torque transmission while minimizing mechanical losses.

Connections:

T-motors receive position, speed, and torque command signals from corresponding driver board (position, speed, torque are written as P., S., T.).

Encoders send real-time torque signal feedback through currents to driver boards (torque is written as T.).

2. Electronics Subsystem
Master Board (ESP32)

Function: Acts as the central processing unit, coordinating motor control, sensor data processing, and high-level decision-making.

Connections:

- Transports the proprioceptive information from IMU to PC (ROS Master) via Ethernet TCPROS.
- Receives action signals proceeded by TSNN (Teacher-Student Neural Network) through Ethernet TCPROS.
- Receives real-time IMU feedback via I2C/UART (proprioceptive signals).
- Sends motor control commands to driver boards via SPI.
- Receives motor feedback from driver board via SPI (feedback is written as F.B.)

Driver Boards (Hip, Upper Leg, Lower Leg, which are written as U-leg and L-leg.)

Function: Manages motor actuation and sensor feedback processing for each leg and hip segment.

Connections:

- Communicate with Master Board via SPI.
- Controls T-Motors using current signals.

- Processes encoder feedback via current signals to ensure precise motor actuation.

IMU (Inertial Measurement Unit)

Function: Measures real-time orientation, acceleration, and angular velocity to maintain balance and terrain adaptability.

Connections:

- Sends series of proprioceptive signals to Master Board via I2C/UART.

3. Control & Communication Subsystem
PC (ROS Master)

Function: Runs high-level motion control algorithms, including reinforcement learning-based locomotion and trajectory tracking (planned feature).

Connections:

- Communicates with Master Board via Ethernet TCPROS.
- Receives motion feedback and sensor data to refine locomotion control.

Motion Control Algorithms (TSNN)

Function: Implements deep reinforcement learning-based walking control using a teacher-student neural network, which can provide a reliable "student" for terrain-adaptive walking.

Connections:

- Processes IMU data sent from Master Board and encoder feedback to output action commands in real-time.
- Sends adaptive control signals to PC (ROS Master).

4. Power Supply Subsystem
Power Bank (DC 24V)

Function: Supplies stable voltage levels for the entire system, and each component specifically.

Connections:

- DC-DC Converter:
- Converts 24V $\rightarrow$ 12V for motor drivers.
- Converts 24V $\rightarrow$ 5V for Master Board, IMU, and sensors.
- Current Protection Circuitry: Prevents voltage fluctuations and ensures operational stability.

2.2.4 Subsystem Requirements

Each subsystem must meet the following requirements to ensure functionality, reliability, and performance.

1. Mechanical Subsystem Requirements

- The body module must support all electronic components and actuators while keeping the overall weight below 2 kg.
- Each T-Motor in Hip or Leg modules must provide continuous torque output of at least 1.5 Nm for stable gait execution.
- The timing belts and bearings must minimize friction to maintain motion efficiency $\geq$90%.
- The leg modules must withstand dynamic impact forces up to 10 N during walking.
- Encoders must provide 0.1° resolution for real-time control precision.

2. Electronics Subsystem

- The Master Board must process sensor inputs and send control signals within 10ms latency. It should achieve a 0.2ms latency communication with our PC.
- Driver Boards must handle SPI communication at 1 kHz for real-time motion updates.
- IMU must deliver ±0.5° orientation accuracy.

3. Control & Communication Subsystem Requirements

- The ROS Master (PC) must process motion planning and reinforcement learning updates at a rate of 10Hz.
- The deep reinforcement learning-based motion control must enable adaptive walking on terrain of different heights with fast and generalized output.

4. Power Supply Subsystem

- 24V Power Bank must supply continuous 100W power to sustain motor operations.
- DC-DC converters must achieve $\geq$90% efficiency in power conversion to minimize thermal losses.
- The current protection circuitry must prevent voltage drops exceeding 10% under peak loads.

2.2.5 Risk and Tolerance Analysis

The most challenging subsystem to implement is the motion control subsystem, specifically the reinforcement learning-based gait generation and torque distribution across the six actuated joints. This poses the greatest difficulty due to the nonlinear dynamics of legged locomotion, real-time adaptation to terrain variations, and uncertainties in contact forces when interacting with different surfaces.

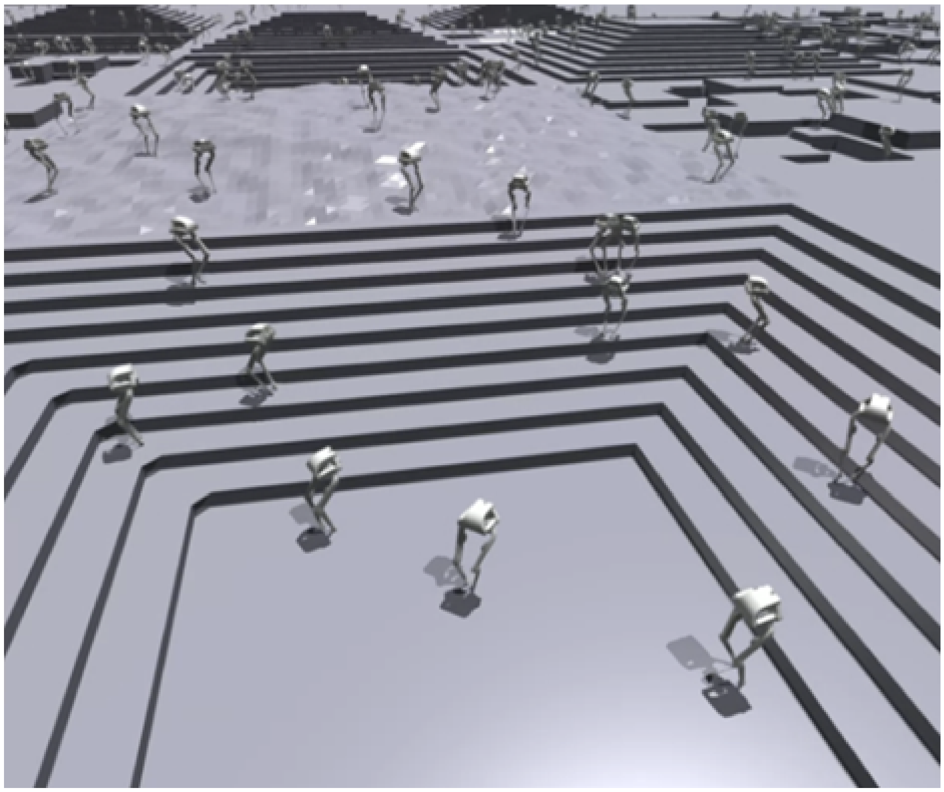

Figure 3: Simulation of our bipedal robot in Issac Gym.

To validate its feasibility, we conducted simulations using Isaac Gym, where the robot's URDF model, generated from STL files with accurate physical parameters (center of mass, inertia, etc.), was tested across various terrains, including flat surfaces, slopes, and stairs. The results confirmed that the robot can continuously walk without falling, and the joint actuators provide sufficient torque to support the body under different conditions.

The acceptable tolerances for this subsystem include:

- Maximum trajectory deviation: ±5 cm
- Body orientation stability: ±3°
- Joint torque execution variance: ±10%

These tolerances align with the high-level requirement that the robot must maintain stable locomotion while adapting to different terrains. The Isaac Gym simulation results provide simulation validation that our control framework can generate generalized and stable gait patterns, significantly reducing the risk of real-world deployment failure and ensuring reliable operation.

3 Ethics and Safety

3.1 Ethics

3.1.1 Privacy and Data Security

Our terrain-adaptive bipedal service robot is equipped with multiple sensors, including cameras and IMUs, to navigate its environment effectively. Ensuring privacy and data security is paramount, as outlined in the IEEE Code of Ethics [1] and the ACM Code of Ethics [2]. We will implement strict data access controls, encryption protocols, and on-device processing to prevent unauthorized access. Collected data will only be used for operational purposes, and no personally identifiable information will be stored or transmitted beyond the necessary scope.

3.1.2 Environmental Stewardship

Our project aligns with the IEEE Code of Ethics, which requires engineers to strive for sustainable development and minimize environmental harm [1]. We aim to use energy-efficient brushless motors and lightweight, potentially recyclable materials such as 3D-printed biodegradable plastics or carbon fiber (pending structural testing). Moreover, battery management subsystems will be designed to optimize energy consumption and lifespan, reducing electronic waste. Compliance with e-waste disposal guidelines will be ensured for safe disposal and recycling of outdated components [3].

3.1.3 Scientific Integrity and Transparency

As engineering professionals, we follow the IEEE Code of Ethics, which requires honest and transparent scientific practices [1]. We will ensure that all claims about the robot's functionality are based on empirical data and thoroughly tested under realistic conditions. Our development process will be documented to allow for peer review and reproducibility. If any limitations or unexpected challenges arise, they will be transparently reported, and necessary modifications will be implemented.

3.1.4 Professional Ethics Compliance

Our team will observe IEEE and ACM ethical frameworks, ensuring that our project prioritizes safety, fairness, and accountability [1], [2]. Additionally, as mandated by ECE 445 Ethical Guidelines, we will go beyond compliance with professional ethics codes and reflect deeply on the broader societal impacts of our project [4]. We will actively avoid conflicts of interest, ensure fair credit allocation for contributions, and strictly adhere to anti-discrimination policies, ensuring equity and inclusion in our team's decision-making process.

3.2 Safety

3.2.1 Electrical Safety

The robot operates using high-current brushless DC motors and a 24V power supply, requiring strict compliance with laboratory electrical safety guidelines [3]. To prevent short circuits, overheating, and accidental electrocution, the following measures will be implemented:

- Insulation and shielding for all high-voltage components.
- Overcurrent and thermal protection circuits integrated into motor driver boards.
- Strict adherence to safe current limits to prevent accidental exposure to hazardous voltages.

3.2.2 Mechanical Safety

As a bipedal robot, mechanical safety is a major concern due to potential falls, impact forces, and pinch points. The robot will incorporate the following safety mechanisms:

- Physical stop limits on actuators to prevent excessive joint movement.
- Shock-absorbing materials in the feet to reduce impact forces when walking on uneven terrain.
- Fall detection algorithms that trigger an automatic shutdown or controlled descent in case of instability.
- Rounded edges and covered mechanical linkages to prevent user injuries during handling.

3.2.3 Electromagnetic Radiation Safety

The robot's onboard electronics and wireless communication modules will comply with IEEE electromagnetic compatibility standards [1]. Measures to mitigate unintended electromagnetic interference (EMI) include:

- Shielded cables and grounding techniques to minimize EMI generation.
- Use of certified wireless communication modules to prevent signal interference with other devices.

3.2.4 Environmental Hazards

The robot's battery system poses fire and chemical hazards if not properly managed. To mitigate these risks:

- Battery Management System will be integrated to prevent overcharging, deep discharging, and overheating.

- Thermal runaway protection will be included to minimize fire risks.
- Proper disposal protocols will be followed for end-of-life battery recycling [3].

References

[1] IEEE, *IEEE Code of Ethics*, Online, Available: https://www.ieee.org/about/corporate/governance/p7-8.html, 2020.

[2] Association for Computing Machinery (ACM), *ACM Code of Ethics and Professional Conduct*, Online, Available: https://www.acm.org/code-of-ethics, 2018.

[3] University of Illinois Urbana-Champaign, *ECE 445 Safety Guidelines*, Online, Available: https://courses.grainger.illinois.edu/ece445zjui/guidelines/safety.asp, 2023.

[4] University of Illinois Urbana-Champaign, *ECE 445 Ethical Guidelines*, Online, Available: https://courses.grainger.illinois.edu/ece445zjui/guidelines/ethical-guidelines.asp, 2023.