ECE 445

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

Smart Assistive Walking Stick for the Visually Impaired

Team #16

YUCHENG ZHANG
(yz90@illinois.edu)
SANHE FU
(sanhefu2@illinois.edu)
YIHAN HUANG
(yihanh4@illinois.edu)
HAOYANG ZHOU
(hz74@illinois.edu)

Professor: Yushi Cheng
TA: Hongtai Lv

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1 Introduction

1.1 Objective and Background

More than 250 million people worldwide suffer from varying degrees of visual impairment, which has a profound impact on their physical health, mental well-being, and overall quality of life. Impaired vision can influence people's mobility, and thus impact their life quality [1] [2]. Individuals with impaired vision face three key challenges when navigating their surroundings: obstacle avoidance, indoor path planning, and key object localization. Therefore, it is important to have a tool to help blind people locate obstacles and plan routes. Especially in the intersections on the road, the road conditions in this area are complicated, and the blind cannot directly identify the traffic lights and traffic signals. In China, most city intersections do not have voice prompts like those in the United States, so blind people do not have the important information to cross an intersection in China. At the same time, the traffic flow at Chinese urban road intersections is very large with fast speed, so it is more dangerous to pass this section.

The most commonly used assistive tool for visually impaired individuals is the white cane, which provides users with tactile feedback. However, the standard white cane has a limited detection range, only sensing obstacles within its physical length, and cannot identify distant or elevated obstacles. But these situations are very common in the intersections. Moreover, the white cane provides only basic physical feedback and lacks the capability to convey detailed environmental information, such as road intersections and navigation directions. As a result, in unfamiliar or complex environments, relying solely on a white cane makes precise navigation difficult, forcing users to depend on external assistance or their memory of previously traveled routes.

Our solution to this problem is the development of an intelligent smart cane. [3] The smart cane can improve walking speed and safety both outdoors and indoors, and we have designed it with a focus on blind people crossing intersections. The sensors can be used to detect environmental information and help users address navigation problems [4]. Our smart cane will be equipped with LIDAR sensors to measure the distance to obstacles and estimate the user's position [5] [6]. A GPS system can be used for precise outdoor positioning [7]. And computer vision technology can be leveraged to capture detailed environmental information, such as traffic signs and other critical landmarks [8]. Additionally, the smart cane features motor-controlled omnidirectional wheels for directional guidance and provides real-time voice feedback to assist users in navigating their surroundings with greater ease, speed, and confidence. In outdoor environments, aid from GPS can not only help the user to walk in strange environments that are not similar but also help them to be more confident in their familiar environments. It will also show a great ability when navigating the users to walk in indoor environments, where the obstacles are usually many and unexpectable. When the user passes through the intersection area, GPS will help give the alert, the camera takes information about the surrounding environment, such as traffic lights and their duration, traffic signs, and whether there are vehicles around. This information is identified by computer vision algorithms and then prompted by voice to the user. And the strong detecting ability provided by the laser sensor of our smart cane can help to avoid crashing into obstacles, especially to avoid crashing into people and objects that are moving fast speed.

The smart assistive walking stick we designed is different from other existing products mainly in that it has mature obstacle location, route planning, and information acquisition functions. The guide sticks on the market are only equipped with voice prompts at most, and the blind need to obtain environmental information by themselves through touch. Most of the smart poles mentioned in the paper are equipped with sensors to detect obstacles or plan routes[9]. Their design works well to help blind people navigate roads, but they don't account for particularly dangerous sections. Our guide poles focus on the safety and efficiency of blind people when crossing dangerous sections such as intersections. To achieve this goal, our design not only integrates obstacle detection, path planning, and information acquisition, but also specifically enhances the application of computer vision algorithms to recognize the signal status of intersections, the direction of vehicle travel, and pedestrian priority rules. Through advanced image processing and deep learning algorithms, the guide stick can analyze the status of traffic lights and traffic flow density in real time to intelligently evaluate the best time to cross the road, thus improving the efficiency of walking for the blind under the premise of ensuring safety.

1.2 High Level Requirements List

High accuracy of computer vision algorithms

The Raspberry Pi camera must capture traffic lights and traffic signs within a 20-meter range and process images at a resolution of 3280 × 2464 pixels. The YOLOv3-based computer vision algorithm should achieve an accuracy of at least 90% in detecting and classifying these elements. The total processing time, from image capture to microcontroller feedback, must be within 1.5 seconds to ensure timely decision-making for the user.

The accuracy of the sensors to identify obstacles

The walking stick must detect both stationary and moving obstacles within a 12-meter range. The system should differentiate between moving and static objects with a detection accuracy of at least 90%. For immediate hazards such as the obstacles detected within 2 meters, the microcontroller should be able to trigger haptic feedback through a vibration motor with an intensity proportional to the obstacle's proximity.

The accuracy and real-time of GPS

The GPS Breakout module must achieve a positioning accuracy of 1.8 meters and update location data at a minimum rate of 10 Hz. The GPS data must be processed and transmitted to the microcontroller, which will compare the user's real-time location with the predefined route. Additionally, the GPS module must be able to detect when the user approaches major intersections, triggering an alert to indicate when it is safe to cross based on traffic signal recognition from the Raspberry Pi.

The energy efficiency of the entire system

The smart walking stick must operate on a battery-powered system with a minimum run-time of 6 hours per full charge under normal usage conditions. The microcontroller must regulate peripheral power dynamically, ensuring that non-essential modules enter low-power mode when not actively needed, reducing overall energy consumption by at least 30% compared to continuous operation. A battery level monitoring system must provide real-time alerts when battery life drops below 20%, ensuring the user is notified well in advance of power depletion.

2 Design and Requirement

2.1 Physical Diagram and Block Diagram

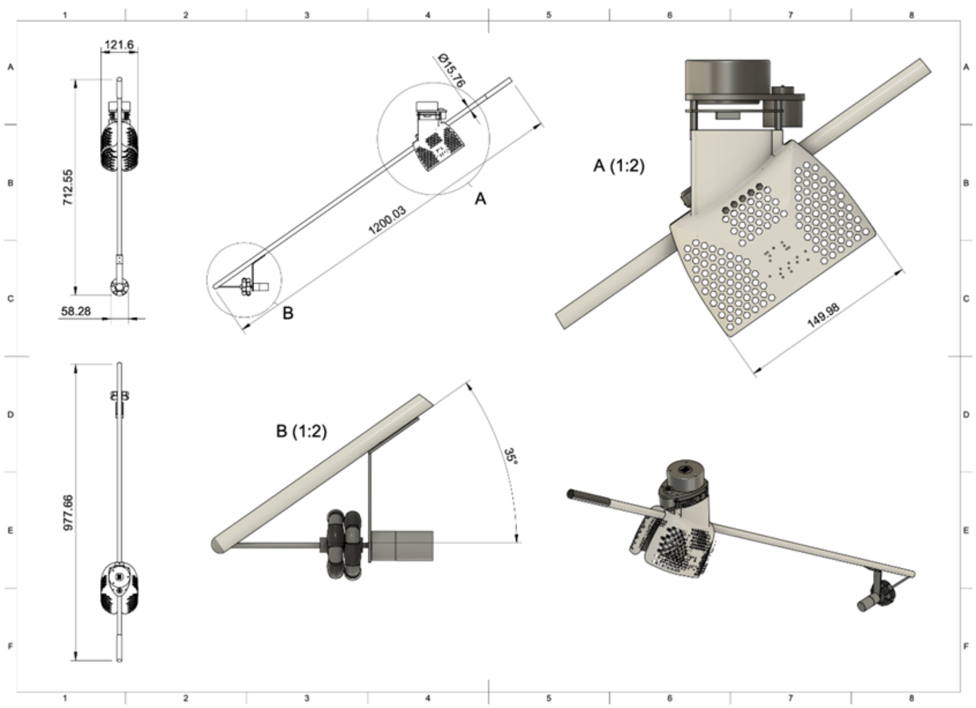

Figure 1: Physical Design Diagrams

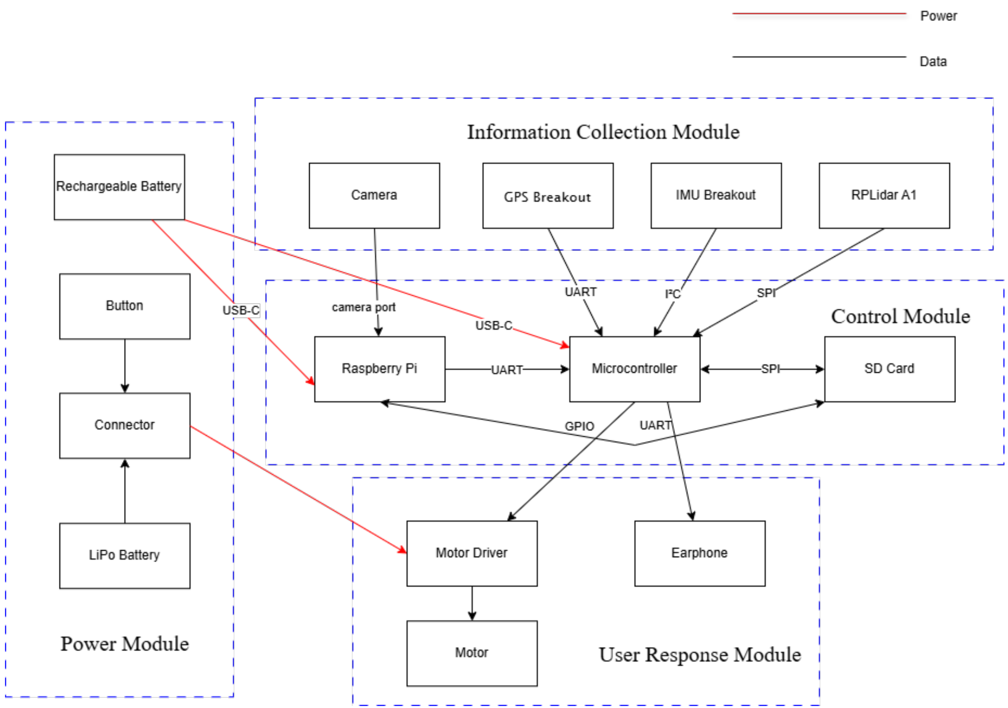

Figure 2: Block Diagrams

2.2 Block Descriptions

2.2.1 Control Module:

The control module gets in and handles the environment information from laser radar, camera, IMU, and GPS through SPI and UART communication, it will control the motor to avoid obstacles and follow the planned routes. Also, the information will be informed to the users through Bluetooth earphones. The microcontroller will handle the data from laser radar, IMU, and GPS directly, and the image captured by the camera will be first processed by Raspberry Pi and then used in the microcontroller.

1) Microcontroller:

   We chose the ESP32 as the microcontroller for our smart assistive guide stick, mainly because of its high performance, low power consumption, and rich peripheral interface. With a 240MHz dual-core processor and 520KB SRAM, the ESP32 can efficiently process data from the RPLIDAR A1 LiDAR while managing the Adafruit 746 Ultimate GPS for accurate positioning. The ESP32 has built-in Wi-Fi and Bluetooth 4.2/BLE for wireless communication with the Raspberry PI 4 generation and supports UART, I2C, and SPI to ensure a stable connection to the sensor. In addition, its deep sleep mode power consumption is as low as 10μA, significantly extending battery life, and making the guide stick more reliable for long periods of use. Taking into account computing power, interface support, and power consumption management, the ESP32 is the ideal choice for this project.

2) Raspberry PI 4:

The Raspberry PI 4 is used as a computer vision processing unit to capture real-time images captured by Raspberry PI cameras and perform traffic light recognition, traffic sign detection, and road condition analysis. The Raspberry PI 4 is powered by a quad-core Cortex-A72 64-bit processor at 1.5GHz and supports 4GB of RAM to efficiently run OpenCV, YOLOv4-Tiny, or TensorFlow Lite for real-time target detection. Its USB 3.0 interface provides data transfer rates of up to 5Gbps, greatly improving the processing speed of camera data, while dual-band Wi-Fi and Gigabit Ethernet ensure stable communication capabilities in high-data applications. The results of the computer vision processing, such as traffic light status, recognized road signs and traffic flow information, are transmitted via the UART to the ESP32 microcontroller for further control of the motor, voice feedback or other auxiliary functions.

Req 1: The ESP32 microcontroller must be able to communicate over UART and SPI with external sensors, including the RPLIDAR A1, Adafruit 746 Ultimate GPS, and IMU, ensuring stable data exchange with an update rate of at least 10Hz. It must handle motor control commands and Bluetooth transmission with a latency of no more than 100ms to provide real-time feedback to the user. Additionally, the ESP32 must support low-power deep sleep mode with a power consumption below 10μA.

Req 2: The Raspberry Pi 4 must capture images at 3280 × 2464 resolution and process them using CV algorithm for traffic light recognition, traffic sign detection, and road condition analysis with high accuracy. The entire processing pipeline, from image capture to sending results to the ESP32 via UART at a speed of no less than 115200 bps, must be completed within 1.5 seconds to ensure timely navigation assistance. The system must maintain stable data transmission via dual-band Wi-Fi or Gigabit Ethernet, ensuring uninterrupted operation in real-world environments.

2.2.2 Information Collection Module:

The Information Collection Module utilizes the devices including RPi Camera, GPS breakout, IMU, lidar and so on to collect the information from the outer environment of the cane and send the information back to the control unit through SPI, URAT communication and the ports on Raspberry Pi for an optimal nest step decision. And then we will introduce the functionality of the information collection devices one by one.

1) RPi Camera:

The RPi Camera Module we used in our design is the Raspberry Pi Camera Module v2, which can capture high-resolution images and videos. It interfaces with the Raspberry Pi via the MIPI CSI-2, which allows for high-speed data transmission. The camera supports resolutions up to 8 megapixels. The Raspberry Pi camera interface consumes low power, making it suitable for embedded and battery-powered projects.

2) IMU Breakout:

We used the Adafruit LSM6DSOX + LIS3MDL IMU as the inertial measurement unit of the smart guide stick to monitor the attitude, direction and motion state of the guide stick in real-time. The module integrates the LSM6DSOX 6-axis inertial sensor and LIS3MDL 3-axis magnetometer to provide 9-DOF motion tracking. The LSM6DSOX has an acceleration measurement range of ±2g to ±16g and an angular velocity detection capability of ±125 to ±2000 dps (degrees per second), ensuring that the guide stick can accurately detect tilt Angle, vibration and rotation direction as it travels. The LIS3MDL magnetometer supports a magnetic field measurement range of ±4 to ±16 gauss and can be used in an electronic compass function to provide an absolute directional reference to help blind people stay oriented in complex environments.

3) RPLIDAR A1 Lidar:

RPLIDAR A1 Lidar is used as the core perception module of the guide stick, which is responsible for measuring the distance of obstacles and transmitting the data to the ESP32 microcontroller for real-time processing. It can work excellently in all kinds of indoor environment and outdoor environments without sunlight. The RPLIDAR A1 has 360° environmental scanning capability and can complete up to 8,000 distance measurements per second, ensuring safe navigation for blind people in complex environments. It has a maximum detection range of 12 meters, allowing the wand to sense obstacles in advance and make travel decisions. Lidar uses an adjustable scan frequency of 2-10Hz, allowing it to optimize data acquisition at different walking speeds, while its low-power design (about 5W) is suitable for portable battery-powered devices. The ranging data is transmitted through the SPI interface to the ESP32, which is parsed by the microcontroller and used to control the motor to help the blind sense the obstacles ahead and plan a safe path.

4) GPS:

The Adafruit Ultimate GPS Breakout is used as a navigation module for the smart guide cane, providing highly accurate geolocation information. The GPS module supports 66-channel MTK3339 chip and has a 10Hz update rate to ensure real-time navigation data. Its positioning accuracy and velocity accuracy can reach 1.8 meters and 0.1meter/s separately, and it has an ultra-high sensitivity of -165 dBm in open environments, even in urban tall buildings or under the shade of trees, and can receive satellite signals stably. The Adafruit Ultimate GPS has a built-in antenna and an external antenna interface to optimize signal reception and provide more stable navigation in different environments. Power usage is incredibly low, only 20 mA during navigation.

Req 1: The RPi Camera Module v2 must capture images at a resolution of 3280 × 2464 pixels and record 1080p video at 30fps while ensuring low power consumption (¡250mW) for battery efficiency.

Req 2: The IMU module must measure acceleration in the range of ±2g to ±16g and angular velocity between ±125 dps to ±2000 dps, with an update frequency of no less than 100Hz to ensure accurate motion tracking.

Req 3: The RPLIDAR A1 must perform at least 8,000 distance measurements per second, covering a 360° scanning range with a minimum detection distance of 12 meters. It must maintain stable communication with the ESP32 microcontroller via SPI.

Req 4: The GPS module must support a minimum update rate of 10Hz, provide positioning accuracy within 1.8 meters, and function in urban environments with a sensitivity of -165 dBm. It must operate at a power consumption of $\leq$ 20mA for extended battery life.

2.2.3 User Response module:

The User Response Module primarily consists of a motor, motor driver, and earphone, serving as the key components for delivering the microcontroller's processed decision outputs to the user. It connects to the microcontroller via GPIO and UART, ensuring efficient communication. By utilizing the motor for haptic feedback and the earphone for auditory feedback, the system delivers information to the user quickly and accurately, enhancing responsiveness and interaction.

1) Motor:

   We use motors to provide stable, precise motion control for the cane. We chose a 12V DC brush motor combined with a 4.4:1 metal gear reduction box, which can reach 1800 RPM under no load, ensuring smooth running of the guide stick in different ground environments. In addition, the motor provides 0.71 kg·cm (10 oz·in) of torque at maximum load and has a 1.8A lock-in current, which is suitable for the efficient power output of the smart guide stick.

2) Motor Driver:

   We use the Adafruit DRV8871 DC Motor Driver Breakout Board as the motor drive module of the smart guide stick, which is responsible for controlling the motor. The DRV8871 driver supports 6.5V-45V input voltage, is fully compatible with 12V DC motors, and provides up to 3.6A peak current output, ensuring stable operation of the guide stick under different terrain and load changes. The driver is controlled by PWM and enables precise speed adjustment and direction control via ESP32 to optimize the dynamic response of the guide stick at different travel speeds and obstacle avoidance strategies.

3) Earphone:

   The earphones used in our design provide wireless audio transmission and hand-free communication. They connect to devices via Bluetooth, sending audio information to users with low latency, low power consumption and high accuracy, making them a good choice for conveying the decision make by the smart cane.

Req 1: The motor must be capable of operating at 12V DC, achieving at least 1800 RPM under no load and delivering a torque of 0.71 kg·cm (10 oz·in) at maximum load. It must maintain a power efficiency of at least 85% and support precise motion control via PWM signals.

Req 2: The motor driver must support an input voltage range of 6.5V–45V and provide a peak current output of 3.6A to ensure stable operation. It must feature built-in thermal protection, current limiting, and under-voltage protection to enhance safety.

Req 3: The earphones must support Bluetooth 4.2/BLE with an audio transmission latency of no more than 100ms to provide real-time feedback. They must operate at a power consumption of less than 50mW, ensuring prolonged usage without frequent recharging.

2.2.4 Power Module:

Our power supply unit utilizes high-performance lithium batteries, equipped with premium lithium-ion cells. Despite its lightweight of only 40 grams, it delivers a rated energy of up to 4.995Wh, providing long-lasting and stable power support for devices. It also boasts robust power output capabilities, with a continuous discharge current of up to 33.75A, easily meeting the power demands of high-power devices such as motor drives, ensuring stable operation and preventing performance degradation due to insufficient power supply. Additionally, it features a wide voltage range, with a rated output voltage of 11.1V and a full charge voltage of 12.6V, making it compatible with a variety of devices and providing stable voltage output to effectively protect device circuits. For interface connectivity, it uses a standard XT30 plug for a convenient connection.

Req 1: The power module must provide a minimum rated energy of 4.995Wh and support a continuous discharge current of at least 33.75A, ensuring stable power delivery for motor drives and other high-power components.

Req 2: The battery must operate within a voltage range of 11.1V to 12.6V and include a standard XT30 plug for secure connectivity, ensuring consistent power output while protecting device circuits from voltage fluctuations.

2.3 Tolerance Analysis

In our project, the most critical part is the accuracy and latency of computer vision processing, which directly affects the user's perception of traffic lights, road signs and obstacles, as well as the final walking decision. If the computer vision recognition accuracy is too low or the processing delay is too high, blind people may not be able to access critical information in a timely manner, leading to potential security risks.

Design challenges include how to improve recognition accuracy and reduce processing latency. Computer vision needs to be at least 85% accurate to provide reliable information to the user, and is subject to changes in lighting conditions, occlusion, and weather. The Raspberry PI 4 takes less than 1.5 seconds to complete the process from camera capture to analysis and transmission to the ESP32. The computer vision processing time is determined by the computational power of the Raspberry PI and the computational complexity of the model. High-resolution images (3280 × 2464) may result in increased processing time, so it may be necessary to adjust the frame rate or reduce the image resolution to ensure real-time performance.

Mathematic Analysis:

- Let N_{total} be the total number of targets and $N_{correct}$ be the number of correctly identified targets. The recognition accuracy is given by:

$$Accuracy = \frac{N_{correct}}{N_{total}} \times 100\%$$

- The goal is to maintain recognition accuracy $\geq 85\%$. If the accuracy decreases in low-light or occluded environments, algorithm adjustments are required, such as Data Augmentation or using a more robust model.

Processing Delay Calculation:

- The total image processing time $T_{\text{processing}}$ is mainly composed of:

$$T_{\text{processing}} = T_{\text{capture}} + T_{\text{preprocess}} + T_{\text{inference}} + T_{\text{communication}}$$

  where:

  - T_{capture}: Image acquisition time (approximately **30ms**)
  - $T_{\text{preprocess}}$: Image resizing and normalization (approximately **100ms**)
  - $T_{\text{inference}}$: Model inference time (approximately **1.2s**, YOLOv4-Tiny on Raspberry Pi 4)
  - $T_{\text{communication}}$: Transmission via UART to ESP32 (approximately **50ms**)

- **Total processing time target:** $\leq 1.5s$

Solution: Use YOLOv4-Tiny or quantized TensorFlow Lite for faster reasoning.Appropriately reduce the camera resolution, reduce the amount of data, and improve the frame rate. Optimize data transmission, using UART or Wi-Fi to ensure stable data transmission and avoid additional latency. If the processing time is longer than 1.5s, the computational complexity can be reduced, for example, by using region cropping to analyze only a specific region, such as the location of a traffic light.

3 Ethics and safety

For ethical concerns, safety and versatility issues remain most difficult. Our product aims to help disabled people in their daily lives, thus if safety bugs weren't found during the product testing stage or the versatility is not satisfactory, it may not fulfill the purpose of helping disabled people. For instance, poor lighting, weather conditions, or obstructed views could degrade detection accuracy. This must be clearly communicated so users know when to exercise extra caution. Also, it is important to be open about known limitations. For example, if the system might fail in certain conditions or if some user actions lead to malfunctions, we must explain that clearly. The sensor might inaccurately track speed or direction, so routine checks are essential to maintain safe feedback. Disclosing these potential inaccuracies aligns with honesty about system limitations. Our device mainly helps with physical tasks, but it can still collect some data. Any data we collect must be stored or sent safely, and privacy must be respected.[10]

For safety concerns, if the camera or algorithm does not detect traffic lights or signs well, the user might unknowingly move into dangerous traffic. A sudden power loss, caused by poor battery monitoring or not enough runtime, can disable important features and put the user at risk. Ensuring the battery and power regulation systems do not overheat or short-circuit is vital for user safety. Following established lab rules and ensuring proper component design mitigates these dangers. We must also maintain strong electrical and mechanical safety measures, follow lab rules, and ensure designs have no hazards. In the lab, careful testing, use of protective equipment, and following standard procedures help reduce risks.[11]

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