Intelligent Bicycle Tail Light: Design and Implementation

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Abstract: With economic development, emission issues have intensified, making environmental protection and green travel subjects of great concern. Cycling has become the preferred choice for the public when going out. However, the low visibility at night poses significant safety hazards for cyclists. This paper has designed and implemented an intelligent bicycle tail light system based on STM32 microcontroller and 3D printing technology, aiming to enhance the road safety of cyclists in nighttime and low-light environments. The system utilizes an MPU6050 six-axis motion sensor to collect the bicycle's motion status in real time. By combining the Kalman filter algorithm to fuse and process the data from the gyroscope and accelerometer, it significantly improves the accuracy and stability of attitude recognition, enabling effective identification of turning and braking intentions.

Keywords: smart tail light; 3D printing; Kalman filter; stm32

1. INTRODUCTION

With the global popularity of the concept of green travel and the promotion of healthy lifestyles, bicycles, as an environmentally friendly and healthy means of transportation, have regained widespread favor. Especially in China, as the world's largest producer and consumer of bicycles, bicycles and shared bikes have become the preferred tools for addressing the "last-mile" travel demand, and the size of the cycling population continues to expand.[1]

However, bicycles are relatively slow in speed and small in size compared to other vehicles. Under low-light conditions such as dawn, dusk, or nighttime, they are easily overlooked by other road users, leading to frequent traffic safety accidents.[2]

Statistical data shows that a significant proportion of nighttime bicycle accidents can be attributed to the insufficient visibility of cyclists.[3] In real-world road environments, the complex road conditions of non-motorized lanes, mixed traffic environments with both pedestrians and vehicles, as well as limitations in road quality and space, further increase the risks associated with bicycle riding.[4] Besides road environmental factors, the inadequacy of bicycle safety design, particularly the limitations of traditional tail lights in terms of visibility and intelligent alert functions, is also a crucial contributor to accidents. Therefore, the development of high-performance intelligent bicycle tail light systems is of great significance for enhancing cycling safety.

To enhance bicycle safety, some cycling enthusiasts install simple tail lights at the rear of their bicycles. These tail lights are connected to a push-button switch via wires, with the switch mounted at the front of the bike. Generally, this type of tail light requires manual control by the rider. When braking, the rider operates the push-button switch to turn on the tail light as a braking signal, alerting nearby pedestrians or vehicles. Meanwhile, this simple tail light lacks turn signal indications and has a single function, making it inconvenient to operate.[5]

This paper proposes an intelligent bicycle tail light system based on an STM32 microcontroller and 3D printing technology. By integrating a multi-axis motion sensor, the system can detect real-time motion states of the bicycle, such as steering and braking, and automatically switch to the corresponding warning modes. Utilizing 3D printing technology, personalized enclosures are fabricated, and combined with a mobile app interface, it achieves a high degree of customization and user experience optimization. Meanwhile, the system employs an efficient energy management module, significantly extending usage time and providing urban cyclists with a safe, intelligent, and personalized solution.

2. Design and construction

2.1 3D printed enclosure

The design of instrument enclosures often leads to structural complexity when pursuing lightweight construction and compact size. Manufacturing such precision parts through traditional mechanical machining methods not only presents significant technical challenges but also incurs high costs for low-volume production. **Error! Reference source not found.**In contrast, utilizing 3D printing technology to produce these components can significantly reduce costs and enable rapid production, making it particularly well-suited for low-volume tasks without incurring substantial additional expenses. This approach greatly enhances production flexibility and cost-effectiveness.[7]

As shown in Figure 1, this component is a 3D model created using SolidWorks software. The model mainly consists of two parts: On the left side, there is a sliding channel structure that is fixed beneath a bicycle saddle using screws, while on the right side, there is a housing designed to accommodate a PCB (Printed Circuit Board) and a battery. To minimize the overall weight, the housing is designed with relatively compact dimensions, specifically measuring $57 \times 37 \times 26$ mm.
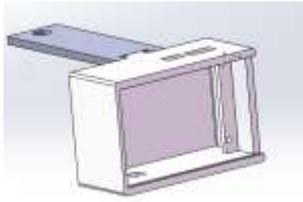
Figure 1 3D model

After completing the structural modeling, we generated a high-precision STL file and utilized a Bambu Lab P1S 3D printer for physical prototyping. The printing material chosen was white PETG, an environmentally friendly copolyester material that combines excellent impact resistance with good processing adaptability. Its impact strength is claimed to be 15 to 20 times that of ordinary acrylic materials. As can be seen from Figure 2, the printed instrument housing accurately reproduced the designed form, providing a reliable foundation for subsequent assembly and testing work.

Figure 2 Translated Printed Model

2.2 Circuit Design

A common issue with regular bicycles or shared bicycles is their inability to inform vehicles behind about their intended maneuvers through the rear bicycle light. As a result, vehicles trailing behind cannot accurately anticipate the bicycle's actions and thus fail to make timely deceleration or pre-braking maneuvers, increasing the likelihood of traffic accidents. Therefore, the following design has been developed to address these issues.
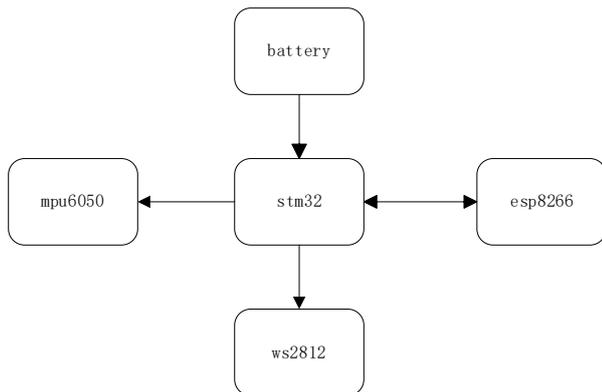

Figure 3 Hardware Design Structure

As shown in Figure 3, this is the power module structure of the system. The system uses a 3.7V, 450mAh lithium battery as its core power source. The battery is equipped with built-in charge and discharge protection circuits, ensuring safe power supply for the entire system. When fully charged, the system can operate for approximately 24 hours in flashing mode and about 12 hours in continuous mode. Charge and discharge management is handled by the IP5306 chip, a highly integrated power management SOC that supports synchronous

switch charging and discharging, providing up to 2.4A output current and 2.1A charging current, and features power path management functionality. Structurally, a USB charging port is reserved at the top of the model, and a full charge typically takes about one hour. During charging, four LED indicators provide an intuitive display of the current battery status.[9]

This design selects the STM32F103C8T6 as the main control chip. [8]This chip has sufficient pins and abundant peripheral resources, fully meeting the system control requirements. The STM32 communicates with the ESP8266 WiFi module via a serial port. The ESP8266 is responsible for establishing a WiFi connection with the mobile phone and transmitting data based on the TCP protocol: when the mobile app sends steering or color-changing commands, the signals are transmitted to the STM32 via the ESP8266. The lighting module uses WS2812 RGB LEDs, arranged symmetrically on both sides. Multiple color changes can be achieved through series control, and the brightness is sufficient in dark environments to ensure clear identification by vehicles behind.

The MPU6050 is a six-axis motion tracking sensor that integrates a three-axis MEMS (Micro-Electro-Mechanical Systems) gyroscope and a three-axis MEMS accelerometer. By measuring acceleration and angular velocity along three axes, it provides a data foundation for dynamic pose perception. In a bicycle intelligent turn indication system, it is responsible for collecting the motion data of the bicycle body. Its measured data is transmitted to the STM32 microcontroller (main control chip) via the I²C protocol for analysis, thereby enabling the judgment of motion states and the execution of control strategies.
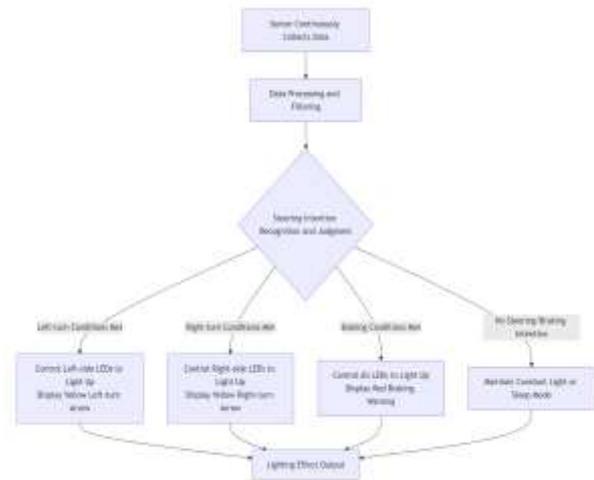
2.3 Software Design

Figure 4 Software Design Structure

The Figure 3 clearly illustrates the complete workflow of an intelligent lighting control system. The process begins with the continuous acquisition of data by sensors, followed by data processing and filtering to enhance signal quality. The preprocessed data then enters the core module for "steering intention recognition and judgment." At this stage, the system performs conditional branching: if left-turn conditions are met, the left-side LEDs are activated to display a yellow left-turn arrow; if right-turn conditions are satisfied, the right-side LEDs light up with a yellow right-turn arrow; upon detection of braking conditions, all LEDs are illuminated to show a red braking warning; and in the absence of any steering or braking intention, the system either maintains a constant light or enters

sleep mode. Ultimately, all branches converge at the "lighting effect output" unit, completing the closed-loop control process from data collection to light respons

3. SYSTEM Design

3.1 Kalman Filter

The Kalman filter is a mathematical method used for estimating system states. [10]It is based on the linear relationship between observed data and the system dynamics model, and provides an optimal estimate of the system state by continuously updating the state estimate. The core idea of the Kalman filter is to fuse the observed data with the predictions from the system model to obtain a more accurate state estimate. [11]

When applied to the MPU6050, the core of Kalman filtering lies in establishing a dynamic trade-off mechanism that skillfully combines the long-term stability of the accelerometer with the short-term precision of the gyroscope. For the bicycle intelligent turn indication system, the stabilized attitude angles obtained after filtering can significantly enhance the accuracy of turn intention recognition, reduce false triggers, and thereby make the signals of the rear warning lights more reliable, ultimately improving cycling safety.

Figure 5 The signal passes through Kalman filtering

As shown in Figure 5, the red and blue curves exhibit changing trends in the time series. The red curve, with significant fluctuations, represents the raw data, while the blue curve, which is relatively smooth and shows an upward trend, represents the data processed by Kalman filtering or other filtering algorithms. This comparison visually demonstrates the optimization effect of filtering technology on raw data: it effectively suppresses noise while preserving the overall trend, thereby enhancing the stability and reliability of the data.

3.2 App Design

Qt offers significant advantages in Android development and serves as an efficient cross-platform solution. [12]With its "write once, deploy everywhere" feature, it can easily adapt to various Android devices such as smartphones and tablets, substantially reducing development complexity and costs.[13]

As shown in Figure 6, the smart bicycle taillight App typically connects to the hardware via Wi-Fi, offering users centralized control and personalized settings for various functions of the taillight. Its main features include lighting mode adjustment (such as switching between constant illumination, flashing modes, and adjusting brightness levels), intelligent safety alerts, and vehicle location assistance.

Figure 6 Android cycling app developed based on Qt

4. CONCLUSION

This design presents an intelligent bicycle taillight control system based on wireless communication, with its core components comprising a mobile application control interface and hardware-based taillights. The control interface is simple and intuitive, featuring functional buttons for "Connect," "Disconnect," and "Exit" to facilitate pairing and link management of the taillight. Users can trigger real-time display of corresponding turn signal indications on the taillight by selecting options for "Left Turn," "Right Turn," or "None" in combination with the "Send" button, effectively enhancing the accuracy of intention communication and rear-end safety during cycling. The "Constant Illumination" switch allows users to toggle the basic lighting mode of the taillight, meeting visibility requirements in various environments. Overall, the design adopts a user-centric approach, emphasizing clear functionality and convenient operation while balancing practicality and interactive experience, making it suitable for safety alert scenarios in modern urban cycling.

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