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Design and Promotion of a Full-Process Medical Waste Safe Tracking System

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Abstract

This study focuses on the design and promotion of a full-process medical waste safe tracking system. It outlines the design concept, advantage analysis, and promotion strategies, offering insights for industrialization and marketization of the product.

Subject Areas

Electronic Information

Keywords

Medical Waste, Safe Tracking, Design and Promotion

1. Introduction

Medical waste [1] is a special category of waste with unique hazardous properties. Strict management protocols are required during loading and transportation, with stringent supervision throughout the transfer process. However, during collection, storage, and internal transfer within hospitals, real-time tracking is often weak. Given that hospitals are densely populated spaces, improper management, unexpected movement, or accumulation of medical waste can lead to severe consequences. Real-time tracking and management of medical waste are therefore essential and of significant importance.

The standard positioning accuracy of Beidou Navigation Satellite System [2] (BDS) is approximately 10 meters, which is insufficient for the high-precision real-time positioning required. To address this, the project adopts ultra-wideband (UWB) technology to achieve centimeter-level accuracy while keeping costs low.

The project aims to promptly alert and track when medical waste bags are moved accidentally or improperly, preventing pollution incidents. By integrating

Beidou's wide-area positioning capabilities, the system ensures stricter real-time supervision and a more standardized full-process management of medical waste.

UWB [3], a wireless carrier communication technology, is a recently militarized-to-civilian technology. It boasts low system complexity, low signal power spectral density, resistance to channel fading, difficulty in interception, high positioning accuracy, simplicity in engineering, and affordability. Compared to traditional positioning systems, UWB is well-suited for high-speed wireless access in dense multipath environments such as indoor spaces.

Our team attaches UWB tags to medical waste bags to enable detection and related operations. For example, when medical waste needs to be transported, the system uses stored hospital maps to plan optimal routes, avoiding crowded areas. If medical waste accidentally drops and goes unnoticed, the system detects the distance between the bag and the transporter and triggers an alarm if it exceeds a predefined threshold.

The remainder of this paper is organized as follows: Section 2 provides an overview of the design plan, detailing the integration of Ultra-Wideband (UWB) technology and Beidou Navigation Satellite System (BDS) to achieve precise real-time tracking and management of medical waste. Section 3 discusses the key advantages of the proposed system, highlighting technological, innovation, safety, and market benefits that differentiate it from existing solutions. Section 4 elaborates on the product features, including the prevention of improper disposal, the implementation of electronic fencing to avoid accidental loss of medical waste, and the planning of optimized transport routes to ensure safety and efficiency. Section 5 focuses on the hardware and software design of the system, outlining the collaboration between UWB tags, anchor nodes, and base stations, as well as the integration of Beidou navigation for external transport tracking. Sections 6 and 7 provide comprehensive market research and environmental analysis, examining the growing demand for medical waste management solutions, the regulatory landscape, and the potential for widespread adoption of the system. Finally, Section 8 presents the promotion strategy, detailing how the system will be marketed through differentiated approaches tailored to specific market segments, aiming to enhance adoption and long-term sustainability in the medical waste management industry.

2. Overview of the Design Plan

Key Research Areas: Develop custom algorithms tailored to the system and specific hospital needs, optimizing routes through iterative improvements. Establish an overarching system design plan: deploy multiple base stations within hospitals to maximize cost-effectiveness. Use two-way ranging techniques to improve positioning accuracy. Implement UWB for internal hospital tracking and complement it with Beidou navigation for external transport to enhance efficiency.

2.1. Internal Hospital Positioning

When medical waste is stored within the hospital, UWB technology is used. UWB

tag nodes (positioning tags) are attached to concentrated medical waste bags, while anchor nodes (positioning base stations) are placed in storage rooms, corridors, and other key areas.

The tag sends positioning commands to various base stations, which respond. After receiving responses, the tag sends a final command. Base stations calculate flight times based on time differences, and these times are transmitted to the main station. The main station relays the data via Bluetooth to an upper-level control system, which calculates location information in real time. If the position exceeds the predefined range, an alarm is triggered automatically.

2.2. External Transport Route Positioning

During the transfer of medical waste to designated disposal sites, vehicles are tracked using Beidou navigation. Beidou satellites are distributed across six orbital planes, enabling simultaneous observation of at least four satellites from any angle or location on Earth. This setup ensures effective reception of ground parameter data and precise calculation of ground coordinates, laying a solid foundation for real-time navigation and tracking.

In a hospital setting, the movement of medical waste requires careful planning to avoid congestion and ensure timely transport. The proposed system uses a dynamic route optimization algorithm designed to adapt to real-time hospital conditions for efficient waste management. The process begins with an initial route calculation using a greedy approach, selecting the most direct path based on the hospital's floor plan and real-time data from an ultra-wideband (UWB) system. This initial route takes into account factors such as distance, corridor accessibility, and the avoidance of obstacles like restricted rooms or ongoing procedures. To enhance the route, the algorithm enters an iterative refinement phase. During this phase, it evaluates factors like crowd density (using real-time sensor data), time-of-day traffic variations, and hazardous zones (e.g., operating rooms, infectious disease areas), adjusting the route accordingly. As the waste is transported, the system continuously re-evaluates the path based on real-time location feedback from UWB tags, adjusting for any unexpected events or obstructions, such as blocked corridors or elevator malfunctions. The algorithm employs multi-objective optimization, balancing several priorities: minimizing transport time, optimizing energy efficiency, and minimizing risks by avoiding high-traffic or high-risk areas. Additionally, a feedback loop powered by machine learning analyzes historical data to identify recurring bottlenecks and improve future routing decisions. This adaptive, real-time approach ensures that medical waste is moved safely and efficiently, minimizing disruption to hospital operations and ensuring compliance with safety protocols.

3. Product Advantages

3.1. Technological Advantages

UWB Technology: High Precision: UWB offers centimeter-level positioning,

making it highly effective for indoor use. Strong Coexistence: With low power spectral density, UWB minimizes interference with existing wireless technologies. High Interference Resistance: Short pulse signals at the 2ns level reduce signal collision probabilities. Even in collisions, UWB signals can be easily identified, offering high signal-to-noise ratio. Low Power Consumption: UWB uses periodic pulses, significantly reducing energy consumption.

Cost-Effectiveness: While UWB systems incur some initial hardware costs, they require fewer devices due to wide coverage (50 - 150 meters radius). Once deployed, the system operates with minimal adjustments for over a decade, lowering operational costs.

Strong Security: UWB's wide bandwidth and low power spectral density make data interception and interference improbable.

Beidou Technology: Mature technology, widely available, and cost-effective with global continuous coverage.

3.2. Innovation Advantages

UWB technology's low power consumption reduces maintenance and operational costs while aligning with sustainability goals.

The project addresses critical post-pandemic issues in medical waste management, aligning with contemporary needs and trends.

3.3. Safety Advantages

Combining UWB for precise indoor tracking with Beidou for outdoor navigation ensures effective prevention of improper reuse or disposal of medical waste.

3.4. Market Advantages

The market demands effective pandemic prevention strategies. A comprehensive tracking system for medical waste offers robust regulatory solutions, particularly for highly infectious waste. With limited competition and a growing focus on environmental awareness and supportive policies, this field presents significant market potential.

4. Product Features

4.1. Prevention of Improper Disposal

The cost of handling medical waste is high, with low returns. Therefore, some hospitals in China have inadequate supervision of medical waste transportation and disposal. To prevent pollution caused by improper disposal of medical waste, the UWB system can enable real-time monitoring, reduce regulatory costs, and improve efficiency.

4.2. Electronic Fencing [4]

Considering the potential for medical waste packaging to accidentally fall off during transportation, the system can set up an electronic fence around the transportation

personnel. If the staff does not notice the packaging falling and is too far from it, the system will automatically trigger an alarm to remind the personnel of the packaging loss, thus preventing pollution or other consequences caused by the loss.

4.3. Planning of Reasonable Transport Routes

During the transportation from the hospital to the medical waste storage area, routes may involve densely populated areas. When medical waste packaging is damaged or lost, it could pose a threat to the safety of patients and doctors. The system can automatically plan the route to avoid crowded areas, improving safety.

5. Product Design

5.1. Hardware Design

The UWB monitoring part of the system consists of two components: anchor nodes and tag nodes. Both the anchor node and tag node are designed with the same hardware, using the STM32F103C8T6 microcontroller as the main chip. The peripheral circuits include the DW1000 chip, power management module, LED indicator module, reset module, etc. The role of each node is switched via USB commands. The system uses the STM32F103C8T6 microcontroller, which has a high clock speed of 72 MHz, and includes 20KB SRAM, 64KB FLASH, three 16-bit general-purpose timers, one 16-bit advanced timer, one DMA controller (with seven channels), two SPI, two IIC, three UART, one USB, one CAN, two 12-bit ADCs, one RTC, two watchdog timers, and 36 general-purpose I/O ports. The timers support PWM output, input capture, and output comparison.

The radio frequency transceiver module used for the nodes is the DW1000 wireless transceiver chip from DecaWave, which adheres to the IEEE802.15.4-2011 UWB protocol standard. It supports four RF frequency bands ranging from 3.5 GHz to 6.5 GHz and integrates MAC support for bidirectional ranging and TDOA. GPIO5 and GPIO6 of the DW1000 chip are used to configure SPI communication between the main controller and the DWM1000 module.

Beidou Monitoring Section: The system is divided into three parts: the monitoring center, the communication system, and the vehicle terminal.

1) The monitoring center hardware can be optionally equipped with a computer, server, large screen, projector, etc.

2) The communication system connects the monitoring center and the vehicle terminal. Communication modules are installed in the monitoring center and receiver, and a SIM card is placed in the vehicle device to obtain the vehicle's location by querying the corresponding number.

3) The Beidou vehicle terminal is mainly responsible for positioning, listening, manual alarm, fuel/electricity cut-off functions, and terminal power-off alarms (anti-tampering). The terminal receives Beidou satellite signals and sends vehicle position and speed information to the system at regular intervals. The monitoring center can issue commands to modify terminal parameters for

control. The STM32F103C8T6 microcontroller is used for processing, and the serial port receives Beidou signals, which are displayed on the LCD screen after processing.

5.2. Software Design

UWB Part:

The system first initializes the MCU and DW1000, begins distance measurement, and determines whether it is a measurement target. If it is not, it returns to the MCU peripheral and reconfigures. The system checks whether the target is a measurement object again, and if it is, the tag sends a request for location information to the base station. The base station receives the information and sends a report, after which the tag receives the response and sends a final message, thus obtaining three timestamps. Multiple tags and base stations communicate in a polling manner, and data is ultimately collected by the main base station. The left half of the flowchart represents the tag, and the right half represents the base station, illustrating the data transmission and reception process, with the final position calculation.

Beidou Part:

The monitoring center consists of monitoring software and related hardware. The software is composed of GIS platform, electronic map database, communication module, real-time tracking module, cargo management module, alarm handling module, and relational database, which receives and analyzes vehicle location and status information sent by the vehicle terminal.

The modules mainly include real-time tracking and waste unloading management. Based on GIS (Geographic Information System), these are integrated into the hospital client interface. When a hospital performs an operation, the system points to the corresponding data location and command, and retrieves the vehicle's position, status, and specific task, thus enabling the scheduling and control of moving targets.

The core of the Beidou navigation design is the communication between the Beidou receiving module and the STM32 microcontroller. The STM32 processes the received information and sends the location data, including time, module antenna, address, longitude, and latitude, to be displayed on the LCD screen. The software module design is divided into three parts: LCD module, Beidou receiving module, and STM32 module. When the module receives data, it displays the information on the LCD screen.

6. Market Research

6.1. Market Research Statistics

Since the 1950s, medical waste disposal [5] has attracted widespread attention worldwide. In the mid-1990s, environmental sanitation departments began to manage and dispose of medical waste, establishing special agencies and assigning dedicated personnel to collect and dispose of medical waste from healthcare

institutions regularly. This gradually improved the management system for controlling medical waste pollution. On June 4, 2003, the "Medical Waste Management Regulations" were approved at the 10th State Council executive meeting. It stipulates that medical waste must be handled by licensed medical waste disposal companies, as medical waste contains a large number of infectious pathogens, which are more hazardous than ordinary domestic waste. If not properly managed or disposed of, it can easily cause pollution to water, soil, and air, and serve as a source for virus transmission.

With the outbreak of the COVID-19 pandemic, the need for medical waste disposal became urgent. Major medical waste generated by COVID-19 includes masks, gloves, protective clothing, goggles, as well as wipes contaminated with respiratory fluids and blood. The World Health Organization estimated that during the pandemic, frontline healthcare workers consumed approximately 89 million masks, 76 million gloves, 30 million protective suits, 1.6 million goggles, and 2.9 million bottles of hand sanitizer per month, all of which eventually became medical waste.

Medical waste has the characteristics of spatial pollution, acute infectious risk, and latent pollution. The microbial hazards it carries are dozens, hundreds, or even thousands of times greater than ordinary domestic waste. If not handled properly, it can become a source of hospital infections and environmental pollution, even leading to disease outbreaks. Surprisingly, many healthcare institutions do not pay enough attention to the dangers of medical waste and continue to discharge it improperly, seriously harming human health. Therefore, tracking medical waste has become crucial.

6.2. Market Research Analysis

To prevent medical waste loss and the resulting pollution, tracking devices are necessary. Currently, China uses UWB positioning systems and Beidou positioning systems for this purpose. UWB modules, which offer centimeter-level positioning accuracy, are widely used due to their strong penetration, low power consumption, resistance to multipath interference, high security, low system complexity, and precise positioning. These are employed in applications such as nursing homes, hazardous work environments (e.g., coal mines), and factory warehouse management. Meanwhile, the Beidou module, which has matured over time, provides meter-level positioning accuracy and is widely used in fields like transportation, security, and agriculture. However, no country in the world has yet applied both technologies to track medical waste. The main reasons are that UWB has a small coverage range and high cost, while Beidou has a wide coverage but lacks precision.

In China, medical waste recycling still relies on two main parts: collection and storage in hospitals, and centralized disposal afterward. Thus, we can leverage the strengths of both positioning systems—UWB for indoor hospital tracking and Beidou for outdoor transport monitoring—offering complementary advantages.

7. Market Environment Analysis

7.1. Macroeconomic Environment Analysis

With the approval of the State Council, the National Development and Reform Commission and the former State Environmental Protection Administration jointly released the "National Hazardous Waste and Medical Waste Disposal Facility Construction Plan" (hereinafter referred to as "the Plan"). Local authorities have begun tendering projects for the construction of medical waste disposal facilities and require that medical waste transport vehicles comply with the GB 19217-2003 regulations. The "Plan" points out that China plans to build 300 centralized medical waste disposal facilities and increase the daily disposal capacity by 2080 tons.

In 2003, China faced the SARS outbreak, which spread rapidly across the country, making medical institutions the first line of defense. The virus spread easily through droplets, and infection rates were high. At the same time, large amounts of medical waste were generated. The transportation and disposal of this waste required strict protective measures to prevent the spread of pathogens. At that time, the management of medical waste disposal was inadequate, and the need to regulate medical waste transport vehicles became evident. The construction of centralized disposal facilities lagged, and a significant amount of medical waste was mixed with domestic waste. Medical waste collection, transportation, and storage were unregulated, and dedicated packaging, containers, and vehicles were absent. Pollution during transportation could not be fully prevented, and during the SARS period, the situation was even more critical. Ensuring environmental safety and public health was a pressing issue.

The COVID-19 pandemic has prompted a new phase of reform in medical waste disposal systems. Various regions have increased investment in disposal facilities and are improving their medical waste disposal systems. The entire medical waste disposal industry is entering a new period of growth opportunities. The pandemic has further pushed the development of the medical waste disposal industry chain. It is expected that by 2023, the market size for medical waste disposal will exceed 10 billion yuan, and the total medical waste generated will reach approximately 2.5 million tons. Sales of mobile medical vehicles and medical waste transport vehicles are on the rise. The sales ratio for mobile medical vehicles is 8.4%, while the ratio for medical waste transport vehicles is 5.5%.

7.2. Microeconomic Environment Analysis

With the increase in medical waste, many hospitals with poor management have experienced incidents of medical waste being discarded improperly, which poses a threat to public health, especially in the ongoing pandemic. Hospitals are currently unable to implement AI-powered monitoring of medical waste, and they are unaware of the waste's whereabouts. The lack of medical waste monitoring has become a major challenge for hospitals.

Competitor Analysis: We are a follower in this industry. Given that current medical waste transport vehicles cannot supervise the location of medical waste during transportation, leading to potential waste leakage, we have incorporated UWB positioning technology. By tagging medical waste, it is monitored in real-time within the coverage area of the hospital and waste processing areas, and Beidou technology is used for real-time tracking of medical waste during transport, preventing potential loss and improper disposal.

7.3. Consumer Market Segmentation

Practicality: The current problem in many hospitals is that monitoring medical waste during transportation is difficult. The UWB and Beidou full tracking system meets the need for monitoring and management, ensuring the safety of the medical waste handling process and preventing potential harm to human health caused by improper handling of medical waste.

Targeting: Our product tracks medical waste throughout the entire process, aiming to solve the issue of insufficient supervision in hospitals, which can lead to pollution and health hazards. The product is specifically developed to address the immediate needs of hospitals, so its market focus is more concentrated, and sales are mainly targeted to hospitals and medical waste disposal facilities.

8. Promotion Strategy

The system primarily incorporates UWB and Beidou positioning modules. For instance, the SWM1000 UWB module supports high-precision positioning and multi-base-station/multi-tag operations, costing around 100 RMB.

The research goal is to enhance production efficiency and stability while reducing costs. The plan includes building industrial and research bases, extending into related tracking system components, and establishing a complete production chain. Continuous investment in R&D will foster innovation and enable the development of advanced tracking systems.

Currently, UWB's application in medical waste management is in its infancy, and Beidou-based enterprises are also limited. However, as environmental consciousness grows, the expansion of application scenarios and policy support are likely to drive the industry forward.

A differentiated marketing strategy is proposed, targeting specific market segments with tailored strategies. Customers can customize system features based on their needs, enhancing competitiveness by addressing diverse customer demands effectively.

Conflicts of Interest

The author declares no conflicts of interest.

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