Design and Development of Multi-Terminal USV Remote Control System Based on LoRa WAN

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***Abstract*—This paper presents a novel multi-terminal remote control system for Unmanned Surface Vehicles (USVs) utilizing LoRa technology. The proposed system includes a remote controller, mobile APP, Data Transfer Unit (DTU) for ground-side and USV-side. The system realizes bidirectional data transmission from the USVs to the ground station, and the communication distance is greatly improved compared with the traditional 2.4GHz remote control, which overcomes the defect of insufficient communication distance of traditional remote control for USVs caused by the interference of water reflection. In addition, our system also supports smart devices such as mobile phones and computers to participate in the cooperative remote control of USVs, making the control of USVs more convenient and flexible. Experimental results show that when the data transmission frequency of the DTU for gorund-side and USV-side is 0.1s and 2s respectively, the packet loss rate is about 3.28%, and the system has low communication delay and high flexibility, which meets our requirements.**

***Index Terms*—LoRa, multi-terminal control, IoT, unmanned surface vehicles, embedded system**

I. Introduction

Unmanned Surface Vehicles (USVs) based on telemetry, autonomous navigation, visual obstacle avoidance, and other emerging technologies have a wide range of applications in logistics transportation, environmental monitoring, geographic mapping, agricultural irrigation, etc. [1]. However, traditional remote controllers for these USVs using frequencies of $2.4GHz$ or $5GHz$ have a limited communication distance when transmitted over the water surface due to absorption and scattering [2], [3]. This is caused by multipath interference due to water reflection, which increases with higher radio frequencies [4], [5]. Therefore, selecting the appropriate communication frequency is crucial for effective operation of USVs.

Furthermore, certain application scenarios necessitate bidirectional data transmission capabilities within the USV control system to relay crucial real-time information. Concurrently, the evolution of intelligent terminal equipment has diversified USV remote control technology. While traditional remote controls align with user habits, emerging methods, such as mobile phone applications, offer advantages in data visualization. Consequently, our system must integrate various control devices while preventing conflicting control information.

Optional communication protocols include LoRa, 4G/5G networks, Wi-Fi, Bluetooth, or ZigBee [6]. However, extant $2.4GHz$ RF technologies have limited communication range and are prone to interference, making them unsuitable for remote USV control. 4G/5G communication requires base station equipment to cover the application range. For USVs, lake/ocean areas usually do not have the corresponding communication stations.

LoRa is a kind of Low-Power Wide-Area Networking (LPWAN) protocol designed for long-range communications with low bandwidth requirements [7]. This protocol uses Chirp Spread Spectrum (CSS) modulation and sub-GHz frequency bands such as $868MHz$, $915MHz$, and $433MHz$ to achieve communication over tens of kilometers distance in open areas [7]. The LoRa protocol has been widely adopted in various applications, including smart cities, industrial automation, agriculture, and healthcare, due to its cost-effectiveness, scalability, and reliability. Therefore, we use the LoRa communication protocol to develop a new USV remote control system, in order to increase the effective communication distance between USVs and operators as much as possible by using a remote controller and mobile APP simultaneously.

Section II focuses on some related research progress in this field. Section III proposes the system architecture of the multi-terminal USV remote control system. Section IV and V details the design scheme of the hardware and software of our system, respectively. Section VI shows the test results of the system, including functional verification and communication packet loss rate test.

II. Related Work

The communication between USVs and ground stations has been explored through various methodologies. Some studies have employed ZigBee [8] or 4G modules [9] as communication means with the USV. Additionally, in a prior research conducted by our team [10], 4G technology was also utilized for USV control. However, practical application has revealed certain limitations in these approaches, notably the suboptimal transmission range associated with $2.4GHz$-based communication protocols, and the inherent constraints of the

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4G protocol limit communication to the base station specified by the carrier, thus limiting the communication distance and incurring additional communication costs.

Recent research endeavors have showcased the efficacy of LoRa technology in the domain of low-power, long-distance wireless transmission. For instance, LoRa has been employed to extend the range of Wi-Fi for enhanced data transmission distance [11], to facilitate data transmission for remote positioning systems [12], and to offer gateway services for sensors collecting radioactivity data from stone materials [13], among others. The literature has consistently demonstrated that LoRa confers distinct advantages in the realm of low-power and long-distance data transmission [14]. Notably, Chen W et al. have investigated the application of LoRa for USV control [15]; however, their study did not address the issue of multi-terminal cooperation.

III. System Architecture

The multi-terminal remote control system of USVs is composed of remote controller, mobile APP, Data Transmission Unit (DTU) for ground-side and USV-side, which is shown in Figure 1.

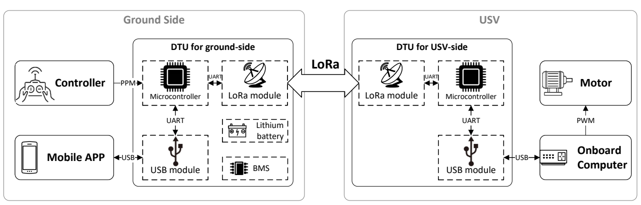


Fig. 1: System Architecture

We design a coordination mechanism for the system to ensure that only one device controls the USV at any given time, to prevent conflicts between the remote controller and mobile app. Specifically, when either the remote controller or mobile app is connected to the DTU for ground-side, it will control the USV exclusively. If both devices are connected simultaneously, the remote controller will be assigned default control. The user can then switch to mobile APP control using the toggle switch on the remote controller.

When the ground-side DTU receives the control information from the remote controller or mobile APP, it is responsible for relaying the data to the USV-side DTU via LoRa. The latter then sends this data to the onboard computer for further processing and control. The USV status information transmitted by the onboard computer is received by the USV-side DTU, which is then relayed to the ground-side DTU and subsequently sent to the mobile APP.

IV. Hardware Design

The ground-side DTU requires two data interfaces to connect with both the remote controller and the mobile device. Specifically, a USB interface is mandatory for linking with the mobile device, while an interface capable of reading PPM electrical signals is necessary for connecting with the remote controller. The LoRa technology we use operates at $868MHz$ and enables remote control of the USVs within the required communication range. However, the maximum instantaneous power of the LoRa module exceeds $650mA$, which may exceed the maximum power supply capacity of some mobile devices. For ease of use, lithium batteries need to be designed for this module to meet the power demand. Therefore, a Battery Management System (BMS) for the device needs to be designed.

The USV-side DTU receives control instructions from the ground-side DTU, parses them, and forwards them to the onboard computer via the USB interface. Since the USV can provide a $5V$ power supply with sufficient power to the device, there is no need to design a battery power supply for the device.

A. *Design of DTU for Ground-side*

According to the above requirements, this module uses STM32-F103C8T6 as the Microcontroller Unit (MCU), which is a more general model. It has three UART interfaces, two I^2C interfaces, and the highest clock frequency can reach $72MHz$, which can realize low hardware delay data processing [16], and meet the requirements of this device.

Figure 2 is the peripheral circuit designed for STM32 MCU. In order to achieve high-speed communication, we designed an $8MHz$ external crystal oscillator for the MCU. UART port 1 of MCU is used to communicate with USB interface, and UART port 2 is used to communicate with LoRa module. In addition, its PB-11 GPIO is used to read the PPM signal of the remote controller, and the PB-14 GPIO is used to control an LED to show the device working status.

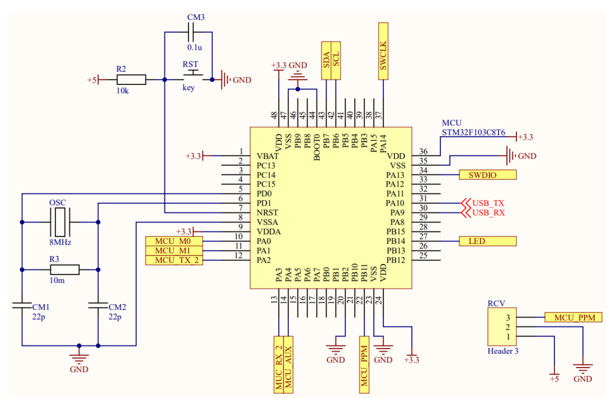
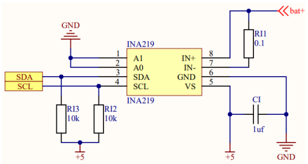


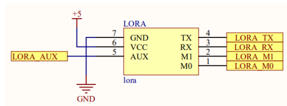
Fig. 2: Schematic diagram of the MCU peripheral circuit

To monitor the lithium battery level, a digital power meter is designed using the I^2C port 1 of the MCU for communication. The INA219 is selected as the digital power meter, which monitors the battery's voltage and load current in real-time and calculates the power of the device using the chip's built-in multiplier [17]. For LoRa communication, an SX1268 chip-based module is chosen that directly enables LoRa to UART communication and connects with the MCU [18]. To enable

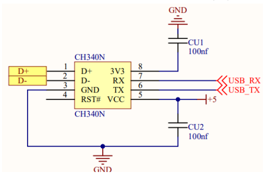
UART port 1 to communicate with the mobile device, the CH340N chip is used to convert UART communication to USB. The corresponding circuit is shown in Figure 3.



(a) Battery galvanometer



(b) LoRa module



(c) USB to TTL module

Fig. 3: Schematic diagrams of several components

In addition, this equipment uses the TP-5400 as the charge and discharge management chip, which can also increase the battery voltage to $5V$ for use by the LoRa module and step down to $3.3V$ by the AMS-1117 chip for use by the MCU. Its peripheral circuit is shown in Figure 4.

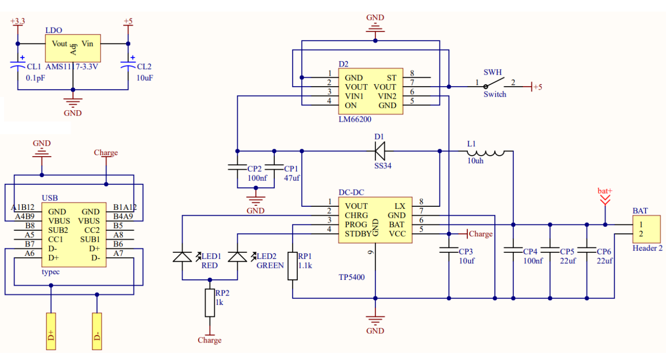


Fig. 4: Schematic diagram of the power supply and lithium battery management module

B. Design of DTU for USV-side

Since the function of USV-side and ground-side DTU is similar, the hardware design of DTU for USV-side is simplified based on it. For the MCU peripheral circuit part, we remove the INA219 digital power meter and cancel the connection between it and the I^2C interface of MCU, and the rest of the parts are the same as Figure 2. For the LoRa communication parts, the circuit adopted by this module is completely consistent with the DTU for ground-side, which is shown in Figure 3. For the power supply and USB to UART communication parts, we simplify the design of the battery charge and discharge module, as shown in Figure 5.

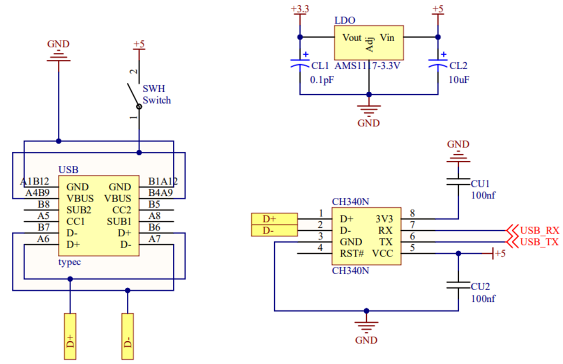


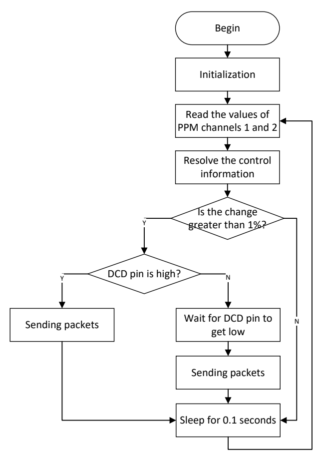
Fig. 5: Schematic diagram of the MCU peripheral circuit

V. Embedded Software Design

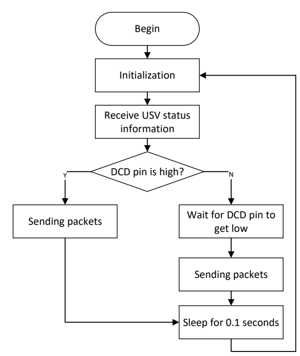
For effective control operations, the USV control system must exhibit reliable and high real-time performance. However, due to the half-duplex nature of the LoRa protocol, extended-range communication may result in packet loss or transmission error. Therefore, a communication mechanism that ensures the dependable delivery of control information while minimizing uplink and downlink data interference is crucial.

A. Communication Process

We designed separate communication process for the DTUs for ground-side and the USV-side, as shown in Figure 6.



(a) DTU for ground-side



(b) DTU for USV-side

Fig. 6: Communication process of two DTUs

When each PPM signal is received, the ground-side DTU checks whether there has been a change in the received USV control information. If the change is less than 1%, it does not send it to the USV to reduce LoRa communication usage. Additionally, both the ground-side and USV-side DTUs will check the LoRa Data Carrier Detection (DCD) pin before data transmission. If the DCD pin is high, the data will be stored in a buffer and transmitted only after the DCD pin becomes low, preventing communication blocking or loss due to LoRa half-duplex.

This communication process ensures that the control information is transmitted reliably and accurately between the DTU for ground-side and USV-side, enabling smooth and efficient control of the USV.

B. Message Packet Design

Effective communication is crucial for controlling USV, and the design of message formats plays a critical role in ensuring reliable data transmission. Feasible schemes include adding specially formatted characters to mark packet information such as its beginning, end, length, or correctness, etc. The message format we designed consists of the following parts:

1) Start byte: A 1-byte field, represented by the hexadecimal constant 0xFF at the packet's start.
2) Device type: A 1-byte field, used to identify the device's role on the system, with the DTU for ground-side represented by the hexadecimal constant 0x00, and the DTU for USV-side represented by the hexadecimal constant 0x01.
3) Message type: A 1-byte field, used to identify the message type. The hexadecimal constant 0x00 represents the unmanned vessel velocity information and 0x01 represents the direction information. Other types of messages can also be customized to support system extensions.
4) Index: A 1-byte field, serves to detect packet loss during transmission by incrementing automatically with each sent packet. If the receiver detects that the index of a received packet is not contiguous with that of its predecessor, it indicates lost packets during transmission.
5) Body: 1-256 bytes field, responsible for transmitting the message's main content, depending on requirements.
6) Check byte: A 1-byte field, uses the CRC-8 check algorithm to ensure the packet content's correctness.

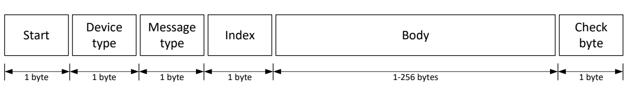


Fig. 7: Message packet structure

C. Design of DTU for Ground-side

The embedded software of the DTU for ground-side contains three tasks, which are USB receiving task, PPM reading task and battery voltage detection task. Therefore, we apply FreeRTOS for multitask management. FreeRTOS is a kind of Real-Time Operating System (RTOS) for MCU or small microprocessors, which can run multiple parallel tasks in a single-core MCU as efficiently as possible [19].

For the PPM reading task, the program reads the PPM signal of the remote controller every $100ms$ interval and parses it into the velocity and direction values of the USV. The velocity ranges from 0 to 1, and the direction ranges from -180 to 180. The PPM value of the remote controller output contains eight channels, each of which has a value range between $1000ms$ and $2000ms$. We adopt channel 1 and channel 2 for control. Among them, channel 1 represents the vertical stroke of the remote controller left joystick, and channel 2 represents its horizontal stroke. Therefore, the formula for converting the PPM signal to the velocity of the USV is as follows:

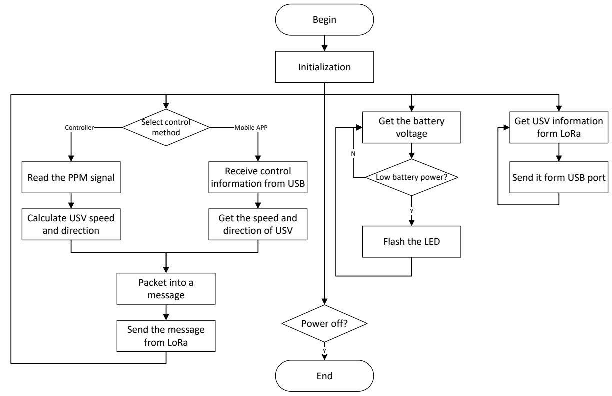


Fig. 8: DTU for ground-side software flow chart

$$S = \left| \frac{I_1 - 1500}{500} \right| \tag{1}$$

Accordingly, the direction of the USV is calculated as follows:

$$D = \begin{cases} \left(\frac{I_2-1500}{500}\right) \times 90, & I_1 \geq 1500 \\ 180 - \left(\frac{I_2-1500}{500}\right) \times 90, & I_1 < 1500 \text{ and } I_2 \geq 1500 \\ -180 + \left(\frac{I_2-1500}{500}\right) \times 90, & I_1 < 1500 \text{ and } I_2 < 1500 \end{cases} \tag{2}$$

where S represents the velocity, D represents the USV direction, and I_1 and I_2 represent the channels 1 and 2 of PPM signal, respectively.

Since the hardware has established USB to TTL communication, the USB receiving task can be accomplished by implementing UART sending and receiving in the program. To improve communication efficiency and minimize hardware delay, the UART transceiver is managed using Direct Memory Access (DMA) of STM32 [20]. This involves a DMA receive buffer size of 128 bytes. When incoming data exceeds this limit, the MCU generates an interrupt to transfer the data from the DMA buffer to a linked list. Upon receiving data, the MCU generates a UART idle interrupt which triggers the program to concatenate the data from the linked list into a string and transmit it to LoRa through UART port 2.

For the voltage monitoring task, we read the data from the INA219 sensor from the I^2C port every 60 seconds. If the voltage value of the battery is less than $3.7V$, it is considered to be undercharged. At this point, MCU will control an LED to flash to remind the user that the device is low power; Otherwise, the LED will light constantly to remind the user that the device is working properly.

D. Design of DTU for USV-side

The embedded software of the DTU for USV-side contains two parts, which are LoRa reception and USV information return. For the LoRa reception task, the program reads the control information from the DTU for ground-side from UART port 1 and converts it into a JavaScript Object Notation (JSON) format that can be parsed by the onboard computer and sends it to the USB interface through UART port 2; For the USV information return task, the program parses the information received from UART port 2 into the current state of the USV, such as velocity and position, and sends it to the ground side through UART port 1.

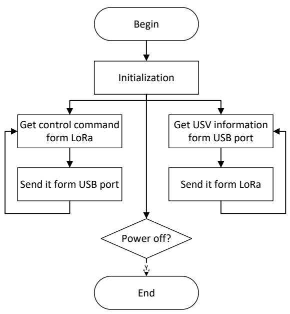
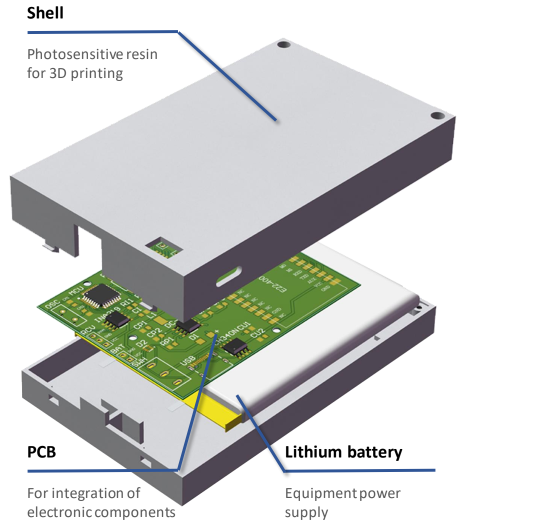
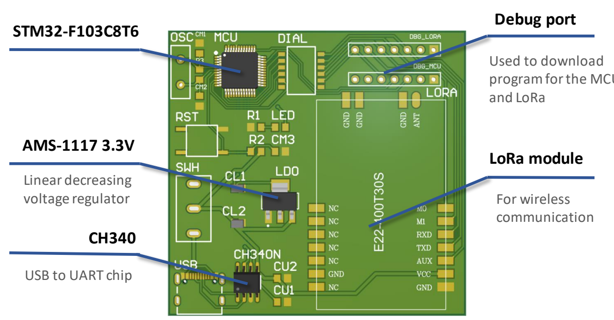


Fig. 9: DTU for ground-side software flow chart



(a) DTU for ground-side



(b) DTU for USV-side

Fig. 10: Equipment prototype

VI. System Test and Result Analysis

A. Functional Verification

Figure 10 presents a equipment prototype described in this paper. The ground-side DTU shell was designed and fabricated using 3D printing technology. A gain antenna is connected to the SubMiniature Version-A (SMA) interface on the far right of the device, while the remote controller is connected via the XH-2.54 terminal on the left. A USB port is available at the bottom of the device for mobile app connectivity. For the USV-side DTU, a USB interface was reserved for device communication with the USV.

We tested the response speed of this system. Experiments show that when the distance between the USV and the ground station is about $500m$, its manipulation response through the remote controller or mobile APP is good, and the delay is below $0.5s$. The result shows that the system achieves the expected design goal.

B. Communication Packet Loss

Experiments were conducted to evaluate the packet loss rate of the system. Preliminary investigations revealed that the half-duplex communication mode of LoRa was the primary cause of packet loss, as the DTU for USV-side occupies the channel while transmitting USV state information back, thereby blocking transmission from the DTU for ground-side. To address this issue, we performed simulations of various ground side and USV side communication frequencies in order to determine an optimal combination scheme.

To ensure prompt response of the USV, the remote controller requires frequent updates of control information. A low transmission frequency would result in slow response. Therefore, the transmitting frequency of the ground-side DTU is fixed at $0.1s$ with a packet size of 7 bytes. The return frequency of USV state information can be adjusted dynamically. To minimize data loss, we implemented the packet and communication design discussed in section V during the experiment. We tested packet loss rates at intervals of $0.5s$, $1s$, $2s$, and $3s$, with a packet size of 200 bytes. Results of the experiment are presented in Table I.

TABLE I: Experimental Data for Packet Loss Rate

Receiving Interval ($second$)	**Number of Sent**	**Number of Received**	**Packet Loss Rate**
0.5	6221	5710	8.12%
1.0	6410	6122	4.49%
2.0	6313	6106	3.28%
3.0	6291	6166	1.99%

As a comparison, when the DTU for USV-side did not send back any data, the packet loss rate was 0%, indicates that the transmission link itself is stable.

After comprehensive comparison, we decided to set the return frequency of the receiver to $2s$, in order to increase the update speed of USV state information as much as possible under the condition of acceptable packet loss rate. Moreover, in real applications, the actual packet loss rate may be lower than the experimental value because the DTU for ground-side does not continuously send control information when the control information is unchanged.

VII. Conclusion

This paper presents a multi-terminal remote control system for USVs that utilizes a remote controller, mobile APP, DTU for ground-side and USV-side to provide long-distance, low-latency, and reliable communication. Our system addresses the issue of short communication distance caused by water interference encountered by traditional $2.4GHz$ remote-controlled USV. Furthermore, we developed a coordination mechanism that allows the remote controller and mobile APP to control the USV collaboratively, resulting in more diverse operation modes. This system provides a more diversified and visualized approach to controlling USV and holds great potential for practical applications.

In the future, our primary focus for optimization lies in expanding the system's capabilities to accommodate more kinds of USVs and remote controllers. Moreover, to further enhance the system's performance and minimize packet loss, a well-structured flow control mechanism tailored specifically for LoRa technology can be designed, thereby maximizing the efficiency and reliability of data transmission. These prospective improvements will undoubtedly bolster the system's capabilities, fostering wider deployment and bolstering its potential for diverse real-world applications.

Acknowledgment

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