Functionalization of Wireless Control and Fuzzy Systems to Hybrid Mini-Loaders

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ABSTRACT In this work, a wireless remote-control function and fuzzy control function were added to the mini-loader of a hybrid gas-electricity powertrain. The loader uses a long-range (LoRa) protocol for communication, which is capable of long-distance signal transmissions and has a high level of sensitivity. A frequency-hopping mechanism based on received signal strength, center frequency, and sensitivity information was constructed for the LoRa system, which aids the transmission of information over long distances in a stable manner. This allows the loader to be utilized in remote regions or topographically complex areas. A fuzzy controller was incorporated to alleviate the fuel consumption problems of the hybrid powertrain and provided efficient and stable hybrid power by tuning the torque and rotation speed of the motor. The functionalized mini-loader has achieved data transfer success rates greater than 90% in wireless transmissions within a range of 100 m. The energy consumption of the functionalized powertrain was lowered by 8%.

INDEX TERMS Wireless remote-control, fuzzy control, mini-loader, long range (LoRa).

I. INTRODUCTION
The increasing severity of extreme weather events in recent years has greatly increased the frequency and strength of natural disasters around the globe. At present, miniature search-and-rescue (SAR) equipment is mainly used to search for signs of life in disaster zones or to gauge the damage caused by a disaster. Excavations in SAR operations are mainly performed using large excavators. However, large machinery cannot operate in small spaces or transport supplies. Consequently, many disaster cleanup operations must be performed by human SAR teams, who are either armed only with shovels or are working in conjunction with large machinery, at risk to their lives. Therefore, the development of a remote-controlled, hybrid-powered multifunctional mini-loader that could extend robot operating times and allow robots to be used in harsh and dangerous environments is imperative. Mini-loader vehicles used in agricultural operations have the potential to be refitted as multi-purpose disaster relief machines [1]. At present, products that satisfy the above requirements have already been developed and commercialized. For example, the company Remoquip (USA) [2] has developed remote-controlled excavators. These excavators use heavy-duty hydraulic equipment and remote-control systems, which enable these machines to operate safely in harsh environments. The Remoquip remote-control modules operate in the 902–928 MHz band, in compliance with the Federal Communication Commission 15.247 standard, and they have an operating range of 20 m. The LP401 developed by Hard-Line (USA) [3] is a remote-controlled mini-loader with an operating range of 50 m, and it can be used to perform operations such as tunnel excavation and conveyor cleaning in areas that cannot be accessed by human workers. However, both these products are simple remote-controlled systems that do not possess any Internet of Things (IoT) capabilities, and they cannot be used for disaster relief communications.

Low-power wide area networks (LPWANs) are popular among communication system providers owing to their long operating range and low cost. At present, the Sigfox, long range (LoRa), and narrowband-IoT (NB-IoT) communication protocols have the greatest market shares in the LPWAN market [4]. The Sigfox protocol developed by Sigfox (France) has the lowest data transfer rate amongst the dominant...
LPWAN protocols, with each message having a width of 100 Hz. The Sigfox protocol is well-suited to applications that require the communication of simple messages over long distances with low levels of power consumption, such as in water meters, electricity meters, and low-rate networks [5]. However, as more sensors are added to the Sigfox network, the latter becomes unresponsive. The NB-IoT protocol is noted for its deep coverage, low cost, low power consumption, and strong security features. This protocol was designed for carrier-grade networks created for IoT applications, and it has excellent capabilities in terms of network security and communication quality [6]. The NB-IoT protocol has a data transfer rate of 21.25 kbps, and it can be supported by current 4G Long Term Evolution networks with minor adjustments by telecommunication service providers. However, this technology can only be used by telecommunication operators. These issues effectively increase the overall cost of NB-IoT solutions [7]. LoRa is an LPWAN protocol proposed by Semtech (USA) [8]. In the past, low power consumption and long range were mutually exclusive traits in wireless communication. However, the advent of LoRa has made it possible to achieve long-range transmission, low power consumption, and low cost in a single package [9]. The LoRa protocol uses the frequency band of 915 MHz, which does not interfere with the various protocols that operate around 2.4 GHz (e.g., Bluetooth, Wi-Fi, Zigbee, and RC modules). LoRa is usually used for applications that involve low-bit-rate inter-device communications over long distances.

In addition, the key design of the hybrid-power system is that each power source can operate in its best efficiency range, thus reducing fuel consumption. The working environment of mini-loader is mostly uneven terrain, such as rough and muddy, which results in unstable speed; therefore, a more efficient power allocation is required. Advanced technologies could be applied to an electrified mini-loader like fuzzy control [10], [11] and sliding-mode control [12], [13]. We adopted fuzzy control in this study to improve the performance of the system. The speed modes of hybrid-power vehicles can be divided into fast, common, and slow orders. These orders could be based on the rule of thumb to make judgments and achieve better work efficiency. Once fuzzy control is used to output the torque and speed command of the motor, the control can adjust the logic according to the designer's control experience to achieve better efficiency.

Our group previously developed a multifunctional mini-loader of a hybrid gas-electricity powertrain [14]. Hybrid vehicles can reduce greenhouse gas emissions and improve energy efficiency [15], [16]. Furthermore, the electrification would allow the mini-loader to be further functionalized with remote control and fuzzy systems. The functionalized loader will not require people to manually operate in a harmful manner. Thus, we have constructed a stable, long-range wireless communication system to avoid risk to the operator's life. Wireless communication with the loader was performed using the LoRa protocol to enable the construction of a long-distance, low-power, and low-cost remote-controlled system and to enhance the stability of its wireless connection. In addition, a fuzzy control system was used to assist the operation of the powertrain of the loader and improve its energy efficiency. For example, the loader can be switched to electric motor operation when operating in small spaces to minimize air pollution. If the engine does not have sufficient torque, the torque and rotation speed of the motor can be increased by the control system to increase the output of the engine. The hydraulic system was switched from a manually controlled system to a battery-powered, remote-controlled, electronically assisted system. A current sensing and feedback mechanism was built into the system to prevent the hydraulic pump from "dry running," which could increase its temperature and cause heat damage [17]–[21].

In this study, the operability and energy efficiency of the hybrid mini-loader were increased by functionalizing the wireless remote-control function and control system. In the wireless remote-control function, full testing of a 2.4 GHz module, a fixed frequency LoRa module, and a LoRa frequency-hopping module were compared in the long-distance transmission rate. In the control system, the microcontroller and fuzzy controller are used to improve the operation abnormality, safety, and energy consumption of the hydraulic system.

II. METHODS
A. REMOTE COMMUNICATIONS SYSTEM
Long-range wide area network (LoRaWAN) is a communication protocol and system architecture specifically developed for long-distance LoRa communication networks. In this architecture, the end nodes and gateways are distributed on different channels with different data transfer rates and spreading factors; the selected data rate and spreading factor determine the data transfer volume and power consumption of the LoRa system. LoRa communications do not necessarily require LoRaWAN servers, as a simple LoRa application may only need two nodes passing messages to each other. However, the LoRa chip must be used with a microcontroller in this instance. The microcontroller handles the information passed by the LoRa wireless radio by writing a setting to the scratchpad of the LoRa chip. The microcontroller communicates with the LoRa chip through a hardware serial peripheral interface, and the parameters are read and written to the scratchpad. When SX127X-series LoRa chips are connected to a non-LoRaWAN gateway, a wired connection is not required for information transfers between two end nodes. Information can be passed between these end nodes simply by setting them to the same channel, as long as the distance between these nodes is within the data transmission range of the LoRa chip.

In this work, the Dragino LoRa Shield, which provides spread spectrum communication and high interference immunity [22], was used as the LoRa firmware. The LG01-N single-channel LoRa IoT gateway was used as the LoRa IoT gateway [23], which allows wireless LoRa sensor networks to
TABLE 1. Frequency-hopping table of the gateway.

| Num. | Value  | Num. | Value  | Num. | Value  |
|------|--------|------|--------|------|--------|
| 1    | 916.5 MHz | 11   | 925.5 MHz | 21   | 910 MHz |
| 2    | 923.5 MHz | 12   | 905.5 MHz | 22   | 920 MHz |
| 3    | 909 MHz   | 13   | 903 MHz   | 23   | 911.5 MHz |
| 4    | 912.5 MHz | 14   | 913 MHz   | 24   | 926.5 MHz |
| 5    | 902 MHz   | 15   | 909 MHz   | 25   | 902 MHz |
| 6    | 920.5 MHz | 16   | 911 MHz   | 26   | 921 MHz |
| 7    | 913.5 MHz | 17   | 902.5 MHz | 27   | 917.5 MHz |
| 8    | 909 MHz   | 18   | 916 MHz   | 28   | 918 MHz |
| 9    | 926 MHz   | 19   | 925.5 MHz | 29   | 903 MHz |
| 10   | 910.5 MHz | 20   | 918.5 MHz | 30   | 924 MHz |

be connected to IP networks via Wi-Fi, ethernet, and 3G/4G. The software architecture can be divided into gateways and end nodes. In the gateway, the frequency range is from 902 to 927 MHz, which is divided into 30 sets as shown in Table 1. This frequency-hopping design table is consistent with the end node frequency-hopping table in order to avoid receiving no messages. During the initialization of a LoRa chip, information can be transmitted immediately after the initialized LoRa chip has sent a synchronization message to the gateway. The gateway will then wait for messages on the first channel (F1). If a message arrives, the gateway will then continue to receive messages via the frequencies on the frequency-hopping table; if a message does not arrive, the gateway will continue to wait. Even if a message does not receive a reply, the message counter will continue to count the messages. If the data transfer success rate is lower than 90%, the gateway will transmit frequency-hopping information to resynchronize the end node to prevent the accumulation of errors in the hop timings of the end node.

B. CONTROL SYSTEM

For the previous mini-loader driven by an internal combustion engine, it was not possible to actively vary the control strategy of the powertrain according to its operating conditions. This resulted in unnecessary energy consumption during the operation of the loader. Our group had previously developed a gas-electricity hybrid powertrain that uses the belt-driven starter generator architecture [14]. Furthermore, in this study, the manually operated clutch would then be replaced by a remote-controlled clutch if the mini-loader were to be operated via a wireless remote-control system. A controller area network (CANBus) motor/generator controller, fuzzy controller, electronic clutch, and electronic hydraulic system were added to the upgraded mini-loader. The architecture of the functionalized mini-loader is shown in Fig. 1.

C. CANBus MOTOR/GENERATOR CONTROLLER

The CANBus protocol, which is widely used as a vehicle communications standard, was used as the communications protocol of the motor controller. The controller was designed to override the master–slave relationship typically used in CANBus communications. Hence, each chip is allowed to exchange information with all other devices in the vehicle via a CANBus. The SEVCON Gen4 48/96 was used as the motor controller, which can be configured to provide the power necessary for achieving the torque and rotation speed required by the loader. The CANBus of the controller was configured with a receive process data object setup with a communication baud rate of 1 MHz and time interval of 10 ms, and ID 0 × 101, ID 0 × 105, and ID 0 × 111 were used to configure the basic settings of the controller based on a demand-driven design. Table 2 lists the 0 × 101 commands corresponding to the rotation speed and torque of the motor and Table 3 lists the 0 × 105 settings for the charge and discharge current requirements of the motor. Table 4 lists the 0 × 111 settings for the basic requirements of the loader.

In Table 2, the 7th and 6th bytes are the throttle setting of the controller; the 5th and 4th bytes are the target torque of the controller; the 3rd, 2nd, 1st, and 0th bytes are the target speeds of the controller, which are the key control points of the hybrid mini-loader. In Table 3, the 7th and 6th bytes are used for charging the battery, and the 5th and 4th for stopping battery charging. In Table 4, the 7th, 6th, and 5th bytes are the controller switch and drive mode; the 4th and 3rd bytes are the manual braking and motor reversing functions, respectively.
TABLE 4. Settings for the basic requirements of the loader.

| CAN-ID | Item            | Byte | Controller Index |
|--------|-----------------|------|-----------------|
| 0x111  | Forward Switch  | 7 6 5| 0x2121          |
|        | Driver select 1 | 4 3 2| 0x2125          |
|        | Driver select 2 |      | 0x2127          |
|        | Handbrake Switch| 1 0  | 0x2122          |

D. FUZZY CONTROLLER

To allow the powertrain of the loader to maintain a high level of efficiency in all operating conditions and reduce fuel consumption, we used digital controllers to control the operations of the internal combustion engine, motor, and generator. The control strategies of the hybrid powertrain are managed by a microcontroller (MCU) unit (MCU F28027, Texas Instruments, TX, USA), which uses the Simulink block library embedded coder support package [25] to generate and compile machine codes automatically, thus enabling modular software development. In the Simulink fuzzy controller, all input data must be normalized to 0–1, converted into membership functions, and then sent to the fuzzy logic controller. The value ranges of the input and output variables are as follows:

1. Target rotation speed (input): The range of motor rotation speeds is \([0, 1500]\) rpm (normalized to 0–1, with 0 being “stop”). “Slow,” “fast,” and “very fast” correspond to the low-speed, high-speed, and very-high-speed settings, respectively. In particular, a normalized value of 0.35 corresponds to 525 rpm, which is the most efficient rotation speed of the loader.

2. Present rotation speed (input): The range of motor rotation speeds is \([0, 1500]\) rpm (normalized to 0–1). “Stop,” “slow,” “fast,” and “very fast” correspond to the motor being stopped, rotating at low speeds, rotating at high speeds, and rotating at very high speeds, respectively.

3. Output rotation speed (output): The range of motor rotation speeds is \([0, 1500]\) rpm (normalized to 0–1). “Stop,” “slow,” “fast,” and “very fast” correspond to the motor being stopped, rotating at low speeds, rotating at high speeds, and rotating at very high speeds, respectively.

4. Output torque (output): The range of torque that can be outputted by the motor is \([0, 5]\) Nm (normalized to 0–1). “L,” “M,” and “start” are defined as the low-torque, medium-torque, and engine starting states, respectively. The “starting state” refers to the large amount of torque that must be applied to overcome the stall current when the engine is started. The torque state of the motor (low or medium) will be adjusted according to the rotation speed of the motor (high or low).

After the value ranges of each variable have been defined, the corresponding membership function is then substituted into the conditional statement. The fuzzy controller mainly uses the AND logical operator, and the conditional statement is set according to the desired result, as shown in Fig. 2.

E. ELECTRONIC CLUTCH

As the previous loader used a belt-driven pulley as its transmission system, the operator had to manually engage the clutch to start the engine. This was incompatible with the remote-control functionality of the upgraded loader. To overcome this issue, we designed an electronic clutch and integrated a stepper motor, motor driver, and clutch reel. In this design, we used a 57 stepper motor that produces a 2.5 N-m torque with a current of 3 A. A DM542 stepper driver with a peak motor driving current of 4.2 A and a maximum step number of 25600 steps/rev was used as the motor driver.

F. HYDRAULICS CONTROLLER

The monoblock directional control valve (MB-3, Youlid Hydraulic Industrial Co., Ltd., Taichung, Taiwan) was used in the mini-loader. The controllability of the hydraulic system was improved in the upgraded loader, as we added an MCU, driver circuit, and a galvanometer-based feedback mechanism for the P-to-A and P-to-B modes of operation. Each control point consisted of an N-type metal-oxide-semiconductor (NMOS), a 1 K\(\Omega\) resistor, and a 10 K\(\Omega\) resistor. As the NMOS is highly efficient and sensitive, the gate-to-source voltage in the NMOS can exceed the threshold voltage owing to noise alone, thus causing the gate to open abnormally. The role of the 10 K\(\Omega\) resistor is to connect the NMOS to ground (GND) before a control command arrives.

Although electronic controls have been installed in the hydraulic valves and hydraulic pumps of the previous loader, the hydraulic circuit will lock up when the hydraulic cylinder is fully extended. A locked hydraulic circuit will cause the
hydraulic pump to “dry run,” which will increase the temperature of the pump and possibly lead to heat damage. To resolve this problem, the upgraded loader has been equipped with an automated detection and control system comprising current sensors, a hydraulic drive circuit, hydraulic pumps, and hydraulic valves. Based on the specifications of the hydraulic pump (Smith’s Hydraulics Inc., GA, US) system used in the upgraded loader, the motor of the hydraulic pump will be damaged if it operates at > 40 A for more than 10 min. A Winson’s current sensor (WCS1600) was used to acquire current signals; if the current of the pump exceeded its safe operating limit (40 A), the hydraulic pump was automatically stopped.

### III. RESULT AND DISCUSSION

The hybrid power of the mini-loader is the same in the upgraded and previous system, that is, it can climb slopes of up to 30% when the loader is fully loaded with a load, i.e., 720 kg. The transmission efficiency of the track when climbing is 0.89, the track-to-ground resistance coefficient is 0.15, and the maximum speed at full load is 2.5 km/h. At this time, the maximum power required is 3.47 kW, so whether the motor (4.0 kW) or the internal combustion engine (4.6 kW) is used, or even the hybrid power, it can meet the power supply demand [14]. To ensure that the performance of the upgraded mini-loader is superior, field tests were performed, and the communication capabilities, powertrain controllability, and hydraulics performance of the new loader were tested and validated. The specifications of the upgraded mini-loader are listed in Table 5. The following subsections describe the results of the remote-controlled tests performed on the remote communication system, control system, and remote operation of the loader.

#### A. REMOTE COMMUNICATION FUNCTIONS

The performance of LoRa communication was tested with different bandwidths, as shown in Table 6. The system should have received 5000 4-byte messages in total. 77 packets were lost when the bandwidth decreased from 500000 to 62500, and the lost signal increased by a factor of 3. The signal strength also decreased when the bandwidth was reduced to 31200. The bandwidths of 20800 and lower were incapable of supporting the transmission/reception of 4-byte messages.

In the subsequent test, the data transfer lost signal, success rate, and received signal strength indication (RSSI) values were measured for a 2.4 GHz module, a LoRa fixed frequency communication module, and a LoRa frequency-hopping communication module at different distances (10, 20, 30, 40, 50, 100, 200, and 300 m). The results of this test are summarized in Table 7. At 10–30 m, few signals were lost, the success rates of all the modes were generally greater than 0.99, and the RSSI values of the various modes of communication were similar. At 40 m, the success rates decreased significantly; at 50 m, the 2.4 GHz module lost more than 500 of the 5000 messages. At 100 m, LoRa fixed frequency and LoRa frequency-hopping were the only modes that could receive any signals at all, and their RSSI values fell below −80 at this point. At 300 m, LoRa frequency-hopping was the only mode of communication that could maintain a data transfer success rate greater than 0.9. Moreover, LoRa frequency-hopping significantly improved the success rate of data transmissions compared to a LoRa fixed frequency module over distances greater than 100 m. This includes the 100 m transmission completion rate, which increased from 0.926 to 0.959; the 200 m transmission completion rate, which increased from 0.914 to 0.952; and the 300 m transmission completion rate, which increased from 0.894 to 0.924. It improved the success rate by 3% compared with fixed-frequency LoRa.

#### B. CONTROL SYSTEM FUNCTIONS - THE CANBus CONTROLLER AND FUZZY CONTROLLER FOR THE MOTOR/GENERATOR

The hybrid powertrain was combined with an electronic clutch, fuzzy controller, and CANBus motor controller,
TABLE 7. Lost signal, success rate and RSSI of the transmission in three different modules.

| Transmission distance (m) | Lost signals (1) | Transmission success rate (2) | RSSI (3) |
|--------------------------|------------------|------------------------------|---------|
|                          | (1)  | (2)  | (3)  | (1)  | (2)  | (3)  | (1)  | (2)  | (3)  |
| 10                       | 1    | 2    | 1    | 0.9996 | 0.9996 | 0.9998 | -56  | -41  | -41  |
| 20                       | 15   | 4    | 3    | 0.9916 | 0.9992 | 0.9999 | -61  | -46  | -47  |
| 30                       | 42   | 20   | 12   | 0.9516 | 0.9516 | 0.9576 | -64  | -48  | -48  |
| 40                       | 100  | 105  | 73   | 0.9868 | 0.9794 | 0.9834 | -70  | -72  | -72  |
| 50                       | 576  | 178  | 101  | 0.8868 | 0.9644 | 0.9758 | -77  | -60  | -60  |
| 100                      | N/A  | 367  | 262  | N/A   | 0.9266 | 0.9996 | N/A  | -49  | -87  |
| 200                      | N/A  | 450  | 257  | N/A   | 0.814  | 0.9526 | N/A  | -40  | -95  |
| 300                      | N/A  | 527  | 379  | N/A   | 0.8546 | 0.9342 | N/A  | -115 | -101 |

Note: (1) 2.4 GHz module; (2) LoRa (fixed frequency) module; (3) LoRa frequency-hopping module.

FIGURE 3. Current consumption between previous and upgraded mini-loader.

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which were linked to each other via the I^2C protocol. This allowed the system to be remotely controlled, and it also improved its energy efficiency. A fuzzy controller was incorporated into the remote-controlled system, and a set of control rules for rotation speed and torque was established for the fuzzy controller. Based on the experimental results shown in Fig. 3, the average motor current (i.e., power consumption) decreased from 10.2 A to 9.4 A. The upgraded loader had a power consumption which was approximately 8% lower than the previous loader. The controller can also make adjustments based on other input parameters to save energy.

C. CONTROL SYSTEM FUNCTIONS – ELECTRONIC CLUTCH AND HYDRAULIC SYSTEM

The main purpose of the electronic clutch was to replace the manually operated clutch. In the previous loader, the clutch had to be manually engaged to start the motor. In the optimized control process, the addition of a clutch controller to the fuzzy-functionalized loader saves a significant amount of time as it eliminates time wastage owing to being unable to start the engine. In the electronic clutch, a reel will roll up the clutch line by rotating in the counterclockwise direction. During our tests, it was observed that the electronic clutch was capable of engaging the clutch within 3 s.

We then tested the hydraulics controller. The control rule set of the hydraulics system pertains to two sets of hydraulic valves (A and B), which may operate in the P direction, T direction, or C (closed) state. The feedback mechanism of the hydraulics system consists of a current sensor, which can automatically stop the hydraulic pumps. The working currents of the functionalized and previous hydraulic systems are compared in Fig. 4. The differences between the current distributions are minimal when the hydraulics system first begins to operate. However, when the hydraulic cylinder is fully extended (approximately 3.6 s), the hydraulic pumping causes a “dry run,” which significantly increases the current to 90 A. After the current sensor is introduced, detection starts when the hydraulic cylinder has completed its operation. When the current exceeds 40 A, the current sensor activates the feedback mechanism to generate a signal, so the pump will not increase to 90 A, and the entire process can save 60 A. During the test where the A1B0, A2B0, A0B1, and A0B2 commands were being transmitted continuously, the system automatically stopped whenever the current exceeded 40 A, and the hydraulic mechanism could operate smoothly.

D. REMOTE OPERATING TEST OF THE MINI-LOADER

To ensure that the loader, electronic clutch, LoRa communications module, and hybrid powertrain can be operated remotely in real time, a dynamic remote-controlled test was performed with the loader carrying a load of 500 kg. The signals measured during this process included “LoRa remote controller,” “LoRa receiver,” “I^2C,” “CANBus,” and “Motor and Track.” In this test, a “move” command
was remotely issued to the hybrid powertrain. The response of each component to this signal were as follows and shown in Fig. 5. First, the user used the remote to issue the “move” command. After a remote delay, the “move” message was passed from the LoRa receiver to the F28027 MCU via the I²C communications protocol; the signal was then simultaneously sent out to each MCU. The CANBus controller then issued the appropriate CAN signal to the motor driver based on the rotation speed and torque information computed by the fuzzy controller. Finally, the motor provided the driving force to move the loader.

IV. CONCLUSION

In this study, we improved a gas-electricity hybrid mini-loader by functionalizing wireless remote-controlled capabilities and fuzzy control systems, which improved the operability and energy efficiency of the loader. The conclusions obtained during the development of this new system (which includes the hardware design process, software engineering process, physical machining, system assembly, and field testing) are summarized below:

1. A LoRa communication terminal, vehicle-mounted LoRa end-device, LoRa router, hybrid powertrain controller, electronic clutch, hydraulic mechanism, and hydraulic valve circuit were constructed for the upgraded mini-loader. The bandwidth is recommended to be set between 31,200 and 500,000 in order to have a success rate of more than 95%.

2. The overall data transfer success rate of the LoRa frequency-hopping communication system was greater than 90% throughout all the stability tests. Furthermore, it was demonstrated that its success rate did not decrease with an increase in the transmission distance, as long as all the end nodes were over 100 m from the gateway. Packet loss generally increased with transmission distance for all other communication technologies.

LoRa frequency-hopping significantly improved the success rate of data transmissions compared to that of a LoRa fixed frequency module over distances greater than 100 m. The 100 m transmission completion rate increased from 0.926 to 0.959; the 200 m increased from 0.914 to 0.952; and the 300 m increased from 0.894 to 0.924. It improved the success rate by 3% compared with fixed-frequency LoRa.

3. A CANBus controller and electronic clutch were constructed for the hybrid powertrain of the loader to replace the manually controlled motor and clutch. These improvements allowed the upgraded loader to operate more quickly, with a greater degree of freedom.

4. Field tests were performed on the control system, which demonstrated that the fuzzy controller could effectively control the torque and rotation speed of the motor, and also reduce energy wastage. It was observed that the power consumption of the functionalized loader was 8% lower than that of the previous loader, on average.

5. MCUs were added to the hydraulic system of the upgraded loader, which provided auxiliary control via the current feedback mechanism when the hydraulic system encountered an operational abnormality. The entire process can save 60 A. Energy wastage due to “dry running” was greatly reduced. This also reduced the risk of heat damage in the hydraulic pump owing to excessively high temperatures, thus improving the safety of the hydraulic system.

6. The upgraded mini-loader can be remotely operated with a load of 500 kg, which means that the LoRa remote controller, LoRa receiver, I²C, CANBus, and Motor and Track units can be smoothly connected and run. In particular, the CANBus controller can obtain the speed and torque information provided by the fuzzy control function and then sends a signal to the driver, which is driven by the motor to drive the loader.

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