DESIGN OF AN INTELLIGENT MONITORING SYSTEM FOR A PESTICIDE SPRAYING MACHINE BASED ON ZIGBEE TECHNOLOGY
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基于 ZIGBEE 技术的农药喷施机智能监控系统设计

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Abstract: *Implementing intelligent control in pesticide spraying machines is a key technology in improving spray efficiency, decreasing pesticide pollution, and lowering production cost. This paper presents an intelligent monitoring system for pesticide spraying machines. This system focuses on the ZigBee technology and integrates sensors, motors, a Wi-Fi camera, and a 32-bit embedded controller. This intelligent monitoring system consists of a monitoring node of a rotary pesticide selection unit, monitoring node of a real-time preparation unit, monitoring node of a nozzle unit, monitoring node of an intelligent mobile platform, a Wi-Fi camera image collecting module, and a PDA remote controller. Test results show that the average packet drop ratio of the ZigBee network is 0.21%, and the success ratio of sending 10,000 commands through the responder communication strategy of the ZigBee network is 100%. This intelligent monitoring system can be remotely controlled from a distance of up to 110 m.* The spraying efficiency is 2–3 times greater than of manual spraying. *The wireless remote operation is also convenient for pesticide preparation and operator safety.*

Keywords: *Pesticide Spraying Machine; ZigBee; PDA; Embedded Controller; Sensor*

INTRODUCTION

Given the excessive use of pesticides, the additive effect of toxicity residues in the environment and food is an increasingly serious problem that has exceeded the natural degrading capacity of the environment. Thus, it has caused underground water and surface water pollution, as well as toxin accumulation in foods [11]. Therefore, intelligent pesticide application technology developed on the basis of agricultural mechanical equipment is an efficient way to promote the health and sustainable development of agriculture, as well as lower the harmful effects of pesticides on the environment and human body [8].

Researchers have proposed many methods in terms of pesticide spraying technologies in recent years [1], [2], [5]. Spraying technologies presented in literature [3], [6], [7], [9] mainly realize variable application control. Spraying machines are usually costly, whereas some application technologies are in high demand in the landform. This paper presents a pesticide application technology based on ZigBee technology to realize its operation in a diversified environment, decrease waste and excessive use of pesticides, prevent operators from directly contacting with pesticides, and improve the spraying efficiency of pesticides. ZigBee technology is a short-distance wireless network communication technology with low energy consumption, cost, and complexity [10]. It is applicable to multipoint control

摘要: *对农药喷施机实施智能控制是提高喷施效率、减少农药污染、降低生产成本的关键技术。该文以 ZigBee 技术为核心，结合传感器、电机、Wi-Fi 摄像头、32 位嵌入式控制器等对农药喷施机设计了智能监控系统。该监控系统由旋转式选药装置监控节点、实时配药装置监控节点、喷头装置监控节点、智能移动平台监控节点、Wi-Fi 摄像头图像采集模块和 PDA 遥控器组成。试验测试结果表明，ZigBee 网络平均丢包率为 0.21%，通过应答式通信策略 ZigBee 网络发送 1 万个指令的成功率达 100%。该智能监控系统的遥控距离可达 110m，*喷施效率是人工的 2～3 陪，*无线遥控操作保障了配药作业的便捷和作业人员的安全。*

关键词: *农药喷施机; ZigBee; PDA; 嵌入式控制器; 传感器*

引言

农药的过量使用，在环境和食物中残留毒性的积累效应已日益成为严重问题，超过了环境对农药的自然消解能力，造成了地下水以及地表水污染，形成了食物中有害毒素的积累[11]。因此，为促进农业的健康和可持续发展，减少农药对环境和人体的危害，发展基于农业机械装备的智能施药技术是一种有效途径[8]。

近年来，针对农药喷施技术研究人员提出了很多方法[1]、[2]、[5]，文献[3]、[6]、[7]、[9]提出的喷施技术主要实现变量施药控制，其中，有些喷施设备成本高，有些喷施技术对地形要求较高。为了实现多种环境作业、减少农药的浪费和过量使用，避免作业人员与农药直接接触，提高农药喷施效率本文提出一种以 ZigBee 技术为核心的施药技术。ZigBee 技术是一种低能耗、低成本、低复杂度的短距离无线网络通信技术[10]，适合多点控制应用系统，农药喷施机通常是由多个装置组成，因此，采用 ZigBee

application systems. A pesticide spraying machine consists of multiple units. Therefore, an intelligent monitoring system for such a machine is developed by employing ZigBee technology combined with a personal digital assistant (PDA) to realize intelligent control of pesticide selection, pesticide preparation, multi-mode spraying, and nozzle.

MATERIAL AND METHOD

The Structure and Principle of the Pesticide Spraying Machine

This pesticide spraying machine consists of a rotary pesticide selection unit, real-time preparation unit, nozzle unit, and intelligent mobile platform. Figure 1 shows pesticide spraying machine [4].

The rotary pesticide selection unit mainly consists of a solution tank, laser photoelectric sensor, solenoid valve, and stepper motor. The operator selects the exact type of pesticide according to the images sent to the PDA remote controller. It then controls the rotation of the solution tank and makes it rise to a corresponding height to draw the pesticide. The solution tank is divided into eight sections with the same volume for holding eight types of pesticides. The corresponding solenoid valve hole is mounted at the bottom of each section for the operator to select appropriate pesticides according to the state of crop disease.

The real-time preparation unit mainly consists of a solution preparation tank, solution temporary storage tank, water storage tank, and level switch. When the level switch in the solution temporary storage tank detects that the level of the solution is lower than the set value, it immediately starts to prepare the solution for the next round of spraying. The real-time preparation unit can realize real-time rapid preparation.

The nozzle unit mainly consists of a lifting rod, stepper motor, water pump, and nozzle, which adjust the nozzle height by driving the lifting rod with the stepper motor.

The intelligent mobile platform employs Beijing Borch Company's Traveler No. 4 whole landform mobile platform, which is applicable for traveling on sand, soil, and grass. It can also run in diversified environments such as fruit gardens, vegetable bases, and greenhouses.

技术为核心结合 PDA（Personal Digital Assistant）等技术开发出农药喷施机智能监控系统，旨在实现选药智能控制、实时配药智能控制、多模式喷施智能控制和喷头智能控制。

材料与方法

农药喷施机的结构与原理

该农药喷施机由旋转式选药装置、实时配药装置、喷头装置、智能移动平台等组成，农药喷施机如图 1 所示[4]。

旋转式选药装置主要由溶液箱、激光光电传感器、电磁阀、步进电机构成，作业人员依据传至 PDA 遥控器的图像选择出正确的农药类型，继而控制溶液箱旋转并上升至相应的高度，以便进行农药的抽取。其中，溶液箱被分割成 8 个相同容积的区域，用于盛放 8 种类型的农药， 8 个区域的低部均安装有对应的电磁阀孔，以便工作人员依据农作物病况选择合适的农药类型。

实时配药装置主要由喷施液配制箱、喷施液暂存箱、蓄水箱和液位开关等组成。当喷施液暂存箱内的液位开关检测到喷施液的液位低于设定值时，随即启动下一轮喷施液的配制，实时配药装置可达到实时快速配制目的。

喷头装置主要由升降杆、步进电机、水泵、喷头组成，通过步进电机驱动升降杆实现喷头高度调节。

智能移动平台，选用北京博创公司旅行家 4 号全地形移动平台，能适应沙石、泥土、草地行走，可在果园、蔬菜基地、农作物、大棚等多种环境中作业。

Fig. 1 - The pesticide spraying machine

Design of an Intelligent Monitoring System

By monitoring the working state of a pesticide spraying machine with sensors and cameras, this monitoring system coordinates the rotary pesticide selection unit, real-time preparation unit, and nozzle unit to enable the pesticide spraying machine to spray in three modes: automatic fixed spot spraying mode, automatic travel spraying mode, and manual mode. The design project of the intelligent monitoring system is shown in Figure 2. This plan consists of two major parts of the spraying machine monitor and PDA remote controller. The spraying machine monitor is designed on the basis of ZigBee and consists of a monitoring node of the rotary pesticide selection unit, monitoring node of real-time preparation unit, monitoring node of nozzle unit, monitoring node of intelligent mobile platform, and a Wi-Fi camera image collecting module. The PDA controller communicates with the Wi-Fi camera image collecting module through Wi-Fi and communicates with the ZigBee monitoring node through the ZigBee network. The Wi-Fi camera collects images with the CS-R5110 module, whose main performance parameters are as follows: 1280 × 760 pixels; 8-direction pan/tilt/zoom (PTZ) that can rotate in 335° horizontally and 120° vertically; built-in Wi-Fi communication chips; wireless communication distance of up to 120 m; and fully meets the spraying machine's demands of image collection. The 4 monitoring nodes and PDA remote controller are powered by 12 V, 5 AH storage batteries. A 5 V and 3.3 V DC is provided after the power is regulated by LM2596-5 and LM1117-3.3 regulating chips. The intelligent mobile platform is powered by 48 V, 20 AH storage batteries.

智能监控系统设计

通过传感器、摄像头监测农药喷施机的工作状态，该智能监控系统控制旋转式选药装置、实时配药装置和喷头装置协调工作，使得农药喷施机可以实现三种喷施作业模式，即定点喷施自动模式、边走边喷自动模式和手动模式。智能监控系统设计方案如图 2 所示，此方案由农药喷施机监控器和 PDA 遥控器两大部分组成。农药喷施机监控器以 ZigBee 技术为核心进行设计，由选药装置监控节点、实时配药装置监控节点、喷头装置监控节点、移动平台监控节点和 Wi-Fi 摄像头图像采集模块共同构成。PDA 遥控器与 Wi-Fi 摄像头图像采集模块通过 Wi-Fi 实现相互通信，与 ZigBee 监控节点通过 ZigBee 网络实现相互通信。Wi-Fi 摄像头图像采集模块采用 CS-R5110 模块，其主要性能参数是，支持 1280*760 像素，自带 8 方位云台支持水平 335°，上下 120°范围转动，内置 Wi-Fi 通信芯片且无线通信距离达 120m，完全满足农药喷施机作业图像采集需求。4 个监控节点和 PAD 遥控器都采用 12V5AH 蓄电池提供电能，经 LM2596-5、LM1117-3.3 调压芯片调整提供 5V 和 3.3V 直流供电电压。智能移动平台采用 48V20AH 蓄电池提供电能。

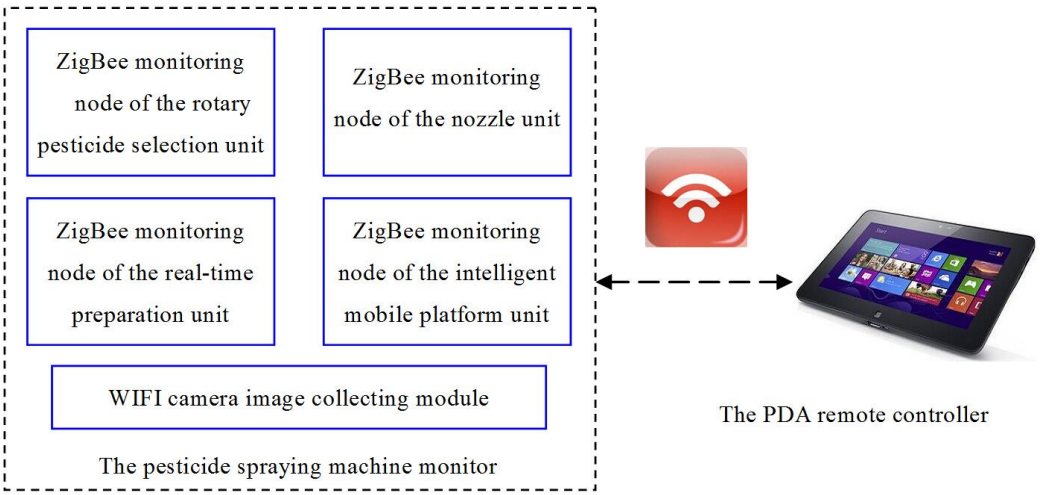

Fig. 2 - Design project of the intelligent monitoring system

Design of the pesticide spraying machine monitor

All the monitoring nodes of the rotary pesticide selection unit, real-time preparation unit, nozzle unit, and mobile platform are designed with the CC2530 wireless single chip microcomputer (SCM) as the core. The CC2530 wireless SCM is a type of system-on-chip developed by TI, a US company. By integrating the RF transceiver with leading performance and industrial standard enhanced 8051 CPU, this chip has excellent sensitivity, anti-interference capacity and strong GPIO

农药喷施机监控器设计

选药装置监控节点、实时配药装置监控节点、喷头装置监控节点和移动平台监控节点都以CC2530无线单片机为核心进行设计。CC2530无线单片机是由美国TI 公司研制出的一种片上系统，它结合了性能领先的RF收发器和业界标准的增强型8051 CPU，具有出色的灵敏度和抗干扰

interface, and it follows ZigBee protocol. The three monitoring nodes are designed by employing the minimum applied system circuit proposed by TI and integrating the GPIO interface circuit. The secondary application development is performed for monitoring the node program on the basis of TI's Z-Stack-CC2530 protocol stack.

Monitoring node of the rotary pesticide selection unit

The stepper motor drives the solution tank of the rotary pesticide selection unit to rotate and select the pesticide type to be sprayed. The stepper motor then uses the 57BYGH module. The P1.0 to P1.2 ports of the CC2530 wireless SCM are connected to the pulse port CLK, direction port DIR, and enabling port EN of the 57BYGH module, respectively. The CC2530 wireless SCM control rotation of the solution tank is in accordance with the commands sent by the PDA controller. The emission heads of 8 laser photoelectric sensors are installed at the bottom of the solution tank, and each head corresponds to a section of the tank. The P0.0 to P0.7 ports of the CC2530 wireless SCM drive the eight relay switches, and their output ports control the corresponding emission head to emit laser. The laser photoelectric sensor uses M12NPN geminate transistors such that the laser beam is concentrated and has intensive energy that largely decreases the false ratio. The external interrupt input port INT1 of the CC2530 wireless SCM connects the output port NO of the receiver of the laser photoelectric sensor. When the receiver receives laser signals, the output low level of the NO port triggers external interruption of the CC2530 wireless SCM, so that pesticide selection control is realized. The steps of the pesticide selection control are as follows:

(1) The CC2530 wireless SCM drives the corresponding emitter to emit laser on the basis of the commands of the PDA remote controller. The solution tank stops rotating when the receiver receives laser signals. At this point, the solenoid valve installed at the bottom of the areas that correspond to the solution tank is aligned with the pesticide drawing tube of the real-time preparation unit to realize positioning for pesticide selection.

(2) With the stepper motor, the CC2530 wireless SCM drives the solution tank to move up or down to an appropriate height. The pesticide drawing tube of the preparation unit is then inserted into the solution of the corresponding section of the solution tank through a solenoid valve hole to draw the pesticide for preparation.

Monitoring node of a real-time pesticide preparation unit

The OKD-HZ21WA Hall flow meter sensor module is used and installed in the water drawing tube. The preparation unit consists of a preparation tank and temporary storage tank. A mixer, temperature sensor, and heater are installed in the preparation tank. The preparation unit works as follows:

(1) The amounts of water and pesticide are controlled. The water in the water storage tank and the pesticide in the solution tank are drawn through the mini pump, flow meter sensor module, and under the control of the solenoid valve as per the required amount into the

能力，同时还具有强大的GPIO接口，遵循ZigBee协议。3个监控节点采用TI公司推荐的最小应用系统电路，并结合GPIO接口电路设计而成，监控节点程序在TI公司Z-Stack-CC2530协议栈的基础上进行二次应用开发。

旋转式选药装置监控节点

旋转式选药装置的溶液箱由步进电机驱动其旋转，用于选择待喷施的农药类型。其中，步进电机选用57BYGH模块。CC2530无线单片机的P1.0-P1.2端口分别接57BYGH模块的脉冲端口CLK、方向端口DIR和使能端口EN。CC2530无线单片机根据PDA遥控器发送的指令，用于控制溶液箱的转动。8个激光光电传感器的发射头安装在溶液箱的底部，每个发射头对应溶液箱的一个分割区域。CC2530无线单片机的P0.0-P0.7端口驱动8个继电器开关，8个继电器开关的输出端口控制相应发射头发出激光。激光光电传感器选用M12NPN对管，激光发射光束集中且能量强，可以极大地降低误报率。CC2530无线单片机的外部中断输入端口INT1连接激光光电传感器的接收头的输出端口NO，当接收头接收到激光信号时，NO端口输出的低电平触发CC2530无线单片机的外部中断，从而实现了选药控制。选药控制的步骤为：

（1）根据PDA遥控器的指令，CC2530无线单片机驱动相应的发射头发出激光，接收头接收到激光信号时，溶液箱停止转动，此时，安装在溶液箱对应区域低部的电磁阀对准了实时配药装置的取药管，实现选药定位；

（2）CC2530无线单片机通过步进电机驱动溶液箱升降至合适的高度，配药装置的取药管通过电磁阀孔插入溶液箱相应区域的药液里，进行农药的抽取以便配药所用。

实时配药装置监控节点

流量计传感器模块选用OKD-HZ21WA霍尔流量计传感器模块，安装在抽水管中。配药装置由配制箱和暂存箱组成，配制箱内安装有搅拌器、温度传感器和加热器。配药装置的监控步骤为：

（1）水量和农药量的控制。通过微型水泵、流量计传感器模块和电磁阀控制，将蓄水箱的水和溶液箱内的药液按所需量抽入喷施液配制箱内。CC2530无线单片机的

solution preparation tank. The P1.2 port of the CC2530 SCM drives the relay switch to the output power to control the mini pump. The external interruption counter port is connected to the pulse signal output port of the OKD-HZ21WA module, so the metered water is drawn by indirectly measuring the water drawing amount through pulse counting. The P1.0 port of the CC2530 wireless SCM controls the pesticide drawing solenoid valve and realizes quantitative pesticide drawing each time together with eight solenoid valve holes at the bottom of the solution tank.

(2) Pesticide preparation and temperature in the preparation tank are controlled. When the required amounts of water and pesticide are drawn into the preparation tank of the pesticide preparation unit, the CC2530 wireless SCM controls the actions of the mixer through the P1.3 port. The CC2530 wireless SCM also monitors the temperature of the mixture in the preparation tank to thoroughly blend the pesticide solution. The DS18B20 digital temperature sensor is used for the temperature sensor. The CC2530 wireless SCM is also connected with the DQ port of DS18B20 through its P1.4 port to directly read the temperature data measured by DS18B20. The CC2530 SCM also controls the heater mounted at the bottom of the preparation tank through the P1.5 port to heat up the mixture in the preparation tank to the required temperature.

(3) The spraying of the temporary storage tank is controlled. Two level switches are installed in the temporary storage tank to detect the solution height in the tank. The MJ-0825PX mini switches are used for level switches. P2.0 and P2.1 ports of the CC2530 wireless SCM are connected to the two level switches to detect the solution level in the temporary storage tank. When the upper limit level switch in the temporary storage tank detects that the solution level exceeds the upper limit, the CC2530 wireless SCM closes it by controlling the solenoid valve between the preparation tank and the temporary storage tank through the P2.2 port. When the lower limit level switch in the temporary storage tank detects that the solution level is below the lower limit, the CC2530 wireless SCM opens it by controlling the solenoid valve to place the mixed solution into the temporary storage tank. Thus, the nozzle unit can spray in real time and start to prepare the solution for the next round.

Monitoring node of the nozzle unit

The nozzle unit of the pesticide spraying machine can spray in all directions. The nozzle height can be adjusted in real time according to the height of the crops to be sprayed. The CC2530 SCM drives the lifting rod through the stepper motor to adjust the nozzle on such rod to an appropriate height according to the wireless control command sent by the PDA remote controller. The P1.0 to P1.2 and P2.0 to P2.5 ports of the CC2530 wireless SCM are then connected to the stepper motor driver. The spraying angle of the nozzle is controlled by four telescopic rods connected to the nozzle. The four rods are divided into two groups that are time-sharing controlled by two motors. The CC2530 wireless SCM controls the four telescopic rods through the driving motor to realize clockwise and counterclockwise flexible spraying.

P1.2端口驱动继电器开关，继电器开关输出端口控制微型水泵的电源，CC2530无线单片机的外部中断计数端口接OKD-HZ21WA模块的脉冲信号输出端口，通过脉冲计数间接测得抽水的流量实现按量抽水的功能。CC2530无线单片机的P1.0端口控制取药电磁阀，并结合溶液箱低部的8个电磁阀孔控制，实现每次定量取用农药。

（2）配制箱内的配药和温度控制。当所需的水量和农药量抽入配药装置的配制箱内后，CC2530无线单片机通过其P1.3端口控制搅拌器的动作。为了喷施药液的充分混合，CC2530无线单片机还进行了配制箱内混合液的温度监控。温度传感器选用DS18B20数字温度传感器。CC2530无线单片机通过其P1.4端口与DS18B20的DQ端口相连接，从而直接读取DS18B20测量的温度数据。CC2530无线单片机通过其P1.5端口控制安装在配制箱底部的加热器工作，使得配制箱内的混合液温度达到所需温度。

（3）暂存箱的喷施控制。暂存箱内安装有2个液位开关用于检测箱内的喷施液高度。液位开关选用MJ-0825PX微型开关，CC2530无线单片机的P2.0、P2.1端口与2个液位开关相连接，用于采集暂存箱内喷施液的液位高度。当暂存箱内的上限液位开关检测到喷施液的液位高于上限值时，CC2530无线单片机通过其P2.2端口控制配制箱和暂存箱之间的电磁阀，使之关闭；当暂存箱内的下限液位开关检测到喷施液的液位小于下限值时，CC2530无线单片机控制配制箱和暂存箱之间的电磁阀，使之开启，从而将配制好的喷施液从配制箱放入暂存箱内，以供喷头装置实时喷施，并同时启动下一轮喷施液的配制。

喷头装置监控节点

农药喷施机的喷头装置可以实现全方向的喷施动作，喷头的高度可以依据所需喷施农作物的高度实时调节。根据PDA遥控器发送的无线控制指令，CC2530无线单片机通过步进电机驱动升降杆动作，使得安装在升降杆上的喷头调整至合适的高度。其中，CC2530无线单片机的P1.0-P1.2、P2.0-P2.5端口与步进电机的驱动器相连接。喷头的喷施角度由4个连接在喷头上的伸缩杆进行控制，伸缩杆分成2组由2个电机进行分时控制。CC2530无线单片机通过驱动电机控制4个伸缩杆从而实现顺时针和逆时针灵活喷施。

Monitoring node of the intelligent mobile platform

The Traveler No. 4 whole landform mobile platform of Borch Company is employed. It is a powerful whole landform mobile platform with an open system, flexible expansion, excellent cross-country capacity, and all-weather operation capacity. It can travel on sand, soil, and grass, and it has a loading capacity of up to 60 kg. This mobile platform reserves the RS232 communication interface. The RXD and TXD ports of the CC2530 wireless SCM are connected to the RS232 communication port of the Traveler No. 4 whole landform mobile platform and control the proceedings of such platform by writing commands.

Design of the PDA remote controller

The PDA controller uses ARM11 core architecture 32-bit S3C6410 embedded controller and is designed with an LCD touch screen. This controller has strong data processing capacity, low energy consumption, a user-friendly interface, and simple operation.

Design of the PDA remote controller circuit

The PDA remote controller adopts the design concept of the core board with the base board added to improve the electromagnetic compatibility of the circuit design and maintenance convenience. Its structure is shown in Figure 3. The core board consists of a S3C6410 embedded controller, a 256 MB SDRAM with two pieces of K4X1G163PC-FGC6 memory, and a 4 GB NAND Flash with two pieces of K9GAG08U0E-S memory. The base board mainly consists of a power supply module, USB interface, JTAG interface, LCD interface, and URAT interface. The UART interface of the S3C6410 embedded controller is linked to the serial port of the ZigBee coordinator node to achieve communication between the ZigBee control nodes. The IIC interface of the S3C6410 embedded controller is linked to the Wi-Fi communication module to realize communication with the image collecting module of the Wi-Fi camera. The PDA remote controller employs an AT070TN83V 7” LCD touch screen for visual display to facilitate manipulation by touch.

Design of the PDA controller program

The PDA remote controller uses Microsoft Platform Builder and is customized by the WinCE6.0 graphical embedded operation system. The SQLite embedded database is transplanted in WinCE6.0 to store prompt data of the expert system. SQLite is small, open source, simple to operate, and requires only a small memory. The SQLite database is realized by adding two database files, namely, sqlite.lib and sqlite.dll, to the application project and calling its API function to read and write in the database. An application program for the monitoring system of the pesticide spraying machine is developed on the WinCE6.0 embedded operation system. Its program flow is shown in Figure 4.

Figure 5 shows the monitoring interface of the application program of the monitoring system for a pesticide spraying machine. This interface consists of pesticide selection control, mode selection, travel route control, camera control, nozzle unit control, and residual amount and temperature display modules.

智能移动平台监控节点

选用博创公司旅行家 4 号全地形移动平台，它是一款功能强大、系统开放、扩展灵活、具有出众越野能力和全天候工作能力的全地形移动平台，能适应沙石、泥土、草地行走，具有 60kg 负载工作能力。该移动平台预留 RS232 通信接口，CC2530 无线单片机的 RXD、TXD 端口与旅行家 4 号全地形移动平台的 RS232 通信接口相连，通过写入指令控制旅行家 4 号全地形移动平台行进。

PDA 遥控器设计

PDA 遥控器采用 ARM11 内核架构的 32 位 S3C6410 嵌入式控制器，并结合液晶触摸屏进行设计，具有数据处理能力强、功耗低、界面友好和操控简单的优点。

PDA 遥控器的电路设计

通为提高电路设计的电磁兼容性和维护的方便性，PDA 遥控器采用核心板加底板的设计思路，其结构如图 3 所示。核心板由 S3C6410 嵌入式控制器、两片 K4X1G163PC-FGC6 存储器接成 256MB 容量的 SDRAM、两片 K9GAG08U0E-S 存储器接成 4GB 容量的 NAND Flash 共同组成；底板主要由电源模块、USB 接口、JTAG 接口、LCD 接口、URAT 接口组成。S3C6410 嵌入式控制器的 UART 接口与 ZigBee 协调器节点的串口相连，实现与 ZigBee 控制节点之间的相互通信。S3C6410 嵌入式控制器的 IIC 接口与 Wi-Fi 通信模块相连，实现与 Wi-Fi 摄像头图像采集模块相互通信。为了直观显示和方便操控，PDA 遥控器选用 AT070TN83V 七寸液晶触摸屏，以便实现实时显示和触摸操控。

PDA 遥控器的程序设计

PDA 遥控器采用微软在 WinCE6.0 上移植 SQlite 嵌入式数据库存储专家系统提示数据。Platform Builder 软件，自行定制出 WinCE6.0 图形化的嵌入式操作系统，SQlite 具有体积小、开源、运行内存所需存储量小、操作方便等优点，SQlite 数据库的实现方式是将 sqlite.lib 和 sqlite.dll 两个库文件加入应用程序工程，调用其 API 函数即可读写数据库。在 WinCE6.0 嵌入式操作系统上开发出农药喷施机监控系统应用程序，其程序流程如图 4 所示。

农药喷施机监控系统应用程序的监控界面如图 5 所示，由选药控制模块、模式选择模块、行走路线控制模块、摄像头控制模块、喷头装置控制模块和剩余量及温度显示模

Figure 5 shows that this monitoring system provides all-around monitoring functions by determining the human–machine monitoring interface. The functions of each monitoring module are described as follows:

(1) The pesticide selection control module consists of a crop variety selection button, expert system prompt box, drop-down pesticide, or nutrient solution selection list, preparation proportion setting box, and pesticide or nutrient selection indicator light. Before the pesticide spraying machine works, operators determine the variety of pesticide or nutrient solutions and proportion them on the basis of the spraying object, expert system prompt box, and their own experiences.

(2) The mode selection module consists of six buttons for fixed distance automatic mode, travel spraying automatic mode, manual mode, cleaning, reset, and stop preparing. The real-time preparation unit is cleaned automatically by clicking the washing button. All units of the pesticide spraying machine are reset by clicking the reset button. The pesticide spraying machine performs spraying in accordance with the pre-set program by clicking the fixed distance automatic mode button or travel spraying automatic mode. The operator controls the pesticide spraying machine by itself by clicking the manual mode button. The pesticide solution preparation tank stops preparing the pesticide by clicking the stop preparing button. The solution temporary storage tank then sprays all the solution inside.

(3) The travel route control module consists of five buttons, namely, forward, backward, turn left, turn right, and stop. The operator can control the travel route of the intelligent mobile platform according to the monitoring video transmitted by the image collecting module of the Wi-Fi camera under the manual mode.

(4) The nozzle unit control module consists of four buttons, namely, ascending, descending, clockwise, and counterclockwise. The operator can adjust the nozzle height using the ascending and descending buttons under the manual mode.

(5) The camera control module adjusts the camera angle using four buttons, namely, upward, downward, leftward, and rightward. The camera shooting and video monitoring are controlled by the shooting and video buttons.

(6) The residual amount and temperature display module displays the residual amount of the solution, residual water amount, and temperature in the preparation tank.

块组成。

由图 5 所提供的人机监控界面可知，该监控系统提供了全面的监控功能。各个监控模块的功能分别描述如下：

（1）选药控制模块由作物种类选择按钮，专家系统提示框，农药或营养液选择下拉菜单，配制比设置框和农药或营养液选择指示灯共同组成。农药喷施机作业前，作业人员根据喷施对象、专家系统提示框的帮助信息和自身经验，确定农药或营养液种类以及配比。

（2）模式选择模块由定点距离自动模式、边走边喷自动模式、手动模式、清洗、复位和停止配药 6 个按钮组成。点击清洗按钮，自动完成实时配药装置的清洗。点击复位按钮则农药喷施机所有装置全部复位。点击定点距离自动模式按钮或边走边喷自动模式，农药喷施机按照事先设置好的程序执行喷施工作。点击手动模式按钮，作业人员自行控制农药喷施机作业。点击停止配药按钮，则农药喷施液配制箱停止配药，喷施液暂存箱将其内部的喷施液全部喷施完毕。

（3）行走路线控制模块由前进、后退、左转、右转和停止 5 个按钮组成，在手动模式下作业人员可根据 Wi-Fi 摄像头图像采集模块传输回来的监控视频，对智能移动平台的行进路线进行控制。

（4）喷头装置控制模块由上升、下降、顺时针、逆时针 4 个按钮组成。在手动模式下作业人员通过上升、下降按钮调节喷头装置的高度。

（5）摄像头控制模块由上调、下调、左调、右调 4 个按钮调节摄像头角度，拍照按钮和视频按钮控制摄像头拍照和视频监视。

（6）剩余量及温度显示模块显示溶液的剩余量、水量剩余量和配制箱内的温度。

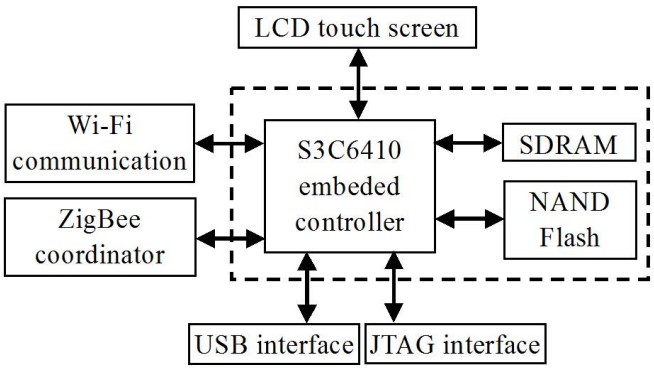

Fig. 3 - Hardware structure of the PDA remote controller

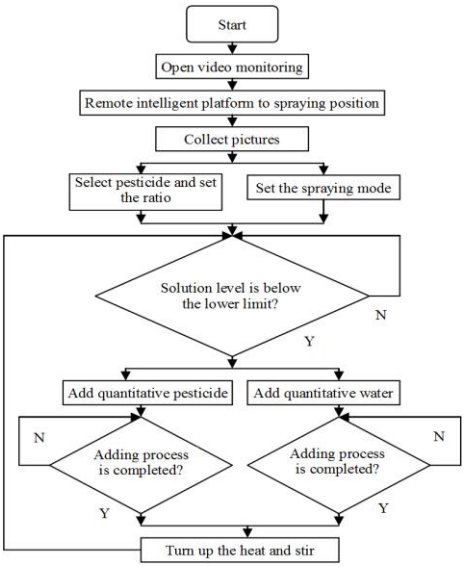

Fig. 4 - Program flowchart of the intelligent monitoring system

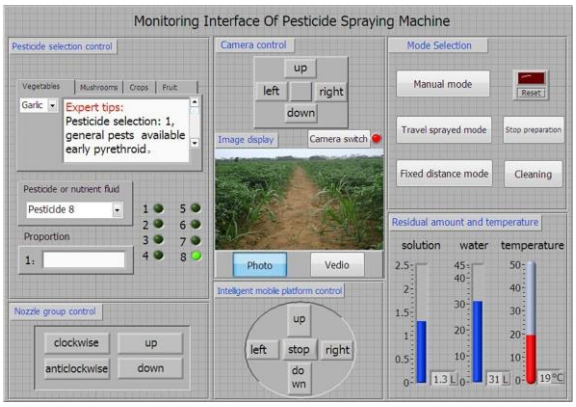

Fig. 5- Monitoring interface

RESULTS

The test was performed in June when weeds were flourishing. The test site was the test park of a farm. An intelligent monitoring system was set up based on the structure shown in Figure 2. This system comprises four ZigBee monitoring nodes, a PDA remote controller, and a Wi-Fi camera module. The test mainly includes a packet drop ratio of the ZigBee network and performance test of a PDA controller.

Test of the packet drop ratio of the ZigBee network

Given the test of the packet drop ratio of ZigBee network, command data packets are sent through the PDA remote controller. The data packets received by the ZigBee monitoring node are then counted to determine the data transfer stability of ZigBee network. The test results are shown in Table 1.

The data in Table 1 show that the maximum packet drop ratio of a single node is 0.24%, whereas the average packet drop ratio of the entire ZigBee network is 0.21%. These results show that the wireless transfer of data is highly stable. Each control command is responsively sent to further improve the reliability of data wireless transfer. The ZigBee monitoring node sent responsive signals upon receiving the control command from the PDA remote controller. If the PDA remote controller does not receive the responsive signals, it resends the control command. Through tests of 10,000 wireless control commands sent by the PDA remote controller with this method, the success rate of command sending is determined to be up to 100%.

Performance test of the PDA remote controller

The response time and remote control distance of the monitoring nodes of the pesticide selection unit, real-time preparation unit, nozzle unit, and intelligent mobile platform are measured by sending control commands through the PDA remote controller in the performance test of the PDA remote controller. The test results are shown in Table 2. The data show that the response time of each monitoring node is fast, the PDA remote control can completely control each monitoring node in real time, and the effective control distance is up to 110 m.

结果

试验时间选在杂草生长茂盛的6月份，试验地点选在农场试验园区。按照前述的图2所示结构构建起智能监控系统。该系统包括4个ZigBee监控节点、1个PDA遥控器、1个Wi-Fi摄像头模块，测试试验主要包括ZigBee网络的丢包率和PDA遥控器的性能测试。

ZigBee网络丢包率测试

ZigBee 网络传输丢包率测试，通过 PDA 遥控器发送控制指令数据包，对 ZigBee 监控节点接收的数据包进行统计，得出 ZigBee 网络数据传输稳定性的结论。测试结果如表 1 所示。

从表 1 数据可知，单个节点最大丢包率为 0.24%，整个 ZigBee 网络的平均丢包率为 0.21%，这表明数据的无线传输稳定性高。为进一步提高数据无线传输的可靠性，每条控制指令采用应答式发送。ZigBee 监控节点收到来自 PDA 遥控器的控制指令后发出应答信号，若 PDA 遥控器未收到应答信号，将重新发送控制指令。采用此种方式对 1 万个 PDA 遥控器发送的无线控制指令进行测试，指令发送成功率达 100%。

PDA 遥控器的性能测试

PDA 遥控器的性能测试，就是通过 PDA 遥控器发送控制指令，测试选药装置监控节点、实时配药装置监控节点、喷头装置监控节点、智能移动平台监控节点的响应时间和遥控距离，测试结果如表 2 所示。从表 2 中数据可知，各个监控节点的响应时间快，PDA 遥控器完全可以实时控制各个监控节点，其有效遥控距离可达 110m。

Spraying efficiencies test

Sichuan Province of China belongs to the basin and hilly area. For the pesticide spraying operation, there is no intelligent mechanical equipment suitable for the ground walking, using artificial piggyback operation completed. Spraying efficiencies of the machine, obtained through calculating practical spraying area within a unit of time, are shown in Table 3. According to the data, the spraying efficiency of the spraying machine in time unit is 2–3 times bigger than that in artificial spraying.

喷施效率测试

中国四川省属于盆地、丘陵地区，当前农药喷施作业无适合地面行走的智能机械设备，采用人工背负式操作完成。喷施机的喷施效率见表 3。其中，喷施效率通过对喷施机单位时间内实际喷施面积的测量得出。从表 3 的数据可知，该喷施机单位小时的喷施效率是人工喷施效率的 2～3 倍。

Table 1

Packet drop ratio of the ZigBee network

ZigBee monitoring node	Sent data packets	Received data packets	Packet drop ratio / %
Pesticide selection unit	2880	2874	0.21
Real-time preparation unit	2880	2875	0.17
Nozzle unit	2880	2873	0.24
Average	2880	2874	0.21

Table 2

Performance test of the PDA remote controller

Remote control distance / m	Pesticide selection response time / ms	Real-time preparation response time / ms	Nozzle response time / ms	Spraying response time / ms	Intelligent mobile platform response time / ms
1	15	18	16	15	23
20	18	20	17	17	25
50	22	22	21	23	28
80	24	25	23	25	31
100	27	29	28	26	36
110	29	32	30	30	45
120	380	No response	860	710	No response

Table 3

Spraying efficiencies

Working environment	Lawn	Greenhouses	Orchard
Artificial piggyback operation / $m^2.h^{-1}$	1917	1203	1003
Machine operation / $m^2.h^{-1}$	6018	3527	3012

CONCLUSIONS

An intelligent monitoring system is developed to improve the safety and intelligence of pesticide spraying machines. Focusing on the mechanical structure of the pesticide spraying machine, the ZigBee technology-based design project is proposed. The monitoring node of the rotary pesticide selection unit, monitoring node of the real-time preparation unit, monitoring node of the nozzle unit, Wi-Fi camera image collecting module, monitoring node of the intelligent mobile platform, and PDA controller are also designed.

The graphics-embedded operating system of WinCE6.0 is designed on the PDA remote controller and transplanted with the embedded SQLite database to achieve strong data processing and management capacity. This system employs an LCD touch screen with a friendly human–machine interface that is easy to use and publicize. A dialogue box-based monitoring system program is developed to increase pesticide spraying

结论

为提高农药喷施机作业的安全性及智能化水平开发出智能监控系统，针对农药喷施机的机械结构，提出基于 ZigBee 技术为核心的设计方案，设计出旋转式选药装置监控节点、实时配药装置监控节点、喷头装置监控节点、智能移动平台监控节点、Wi-Fi 摄像头图像采集模块和 PDA 遥控器。

在 PDA 遥控器上设计出 WinCE6.0 图形化的嵌入式操作系统并移植了嵌入式 SQlite 数据库，实现强大的数据处理与管理能力。系统采用液晶触摸屏操控，人机界面友好，使用简单，易于推广。为提高农药喷施效率，开发出基于

efficiency. This program has three spraying modes, namely, fixed spot spraying automatic mode, travel spraying automatic mode, and manual mode. The spraying efficiency is 2–3 times bigger than of manual spraying.

The system wiring is decreased and the machine can be flexibly used with ZigBee technology. The ZigBee network transfers data stably. The average packet drop ratio of the entire ZigBee network is 0.21%, and the effective remote-controlled distance is up to 110 m.

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对话框的监控系统程序，可实现三种喷施作业模式即定点喷施自动模式、边走边喷自动模式、手动模式，喷施效率是人工的 2～3 陪。

采用 ZigBee 技术减少了系统布线，使用灵活。ZigBee 网络数据传输稳定，平均丢包率为 0.21%，有效遥控距离达 110m。

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