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Research on Intelligent Agricultural Machinery Control Systems

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Abstract. With the development of precise farming and the arrival of industry 4.0 era, agricultural robot is moving towards more intelligent and automated directions. As the core component of agricultural robots, control systems greatly affect the operation accuracy and efficiency. This paper summarizes current status of relevant research and important technologies about control systems for agricultural robots. Its presents crop protection unmanned aerial vehicle (UAV), smart sprayers and combined fertilizer irrigation system. Discussing their operation features and control problems. Also, this paper studies three control techniques: programmable logic controller (PLC) control, microprocessors / microcontrollers for control applications, proportional-integral-derivative (PID) controllers and higher order control techniques. The features and applicable cases for every technologies have been discussed. At last, this paper summarized the technical limitations like a high cost, constraints of environment, difficulties for implementing algorithms, and directions for the further development (e.g., multisource information integration), edge computing-enabled intelligent processing, and cloud based collaborative control.

Keywords: control system, programmable controller, proportional-integral-derivative, embedded system

1. Introduction

As world populations grow while farmland shrinks, many of these large-scale farming techniques have proven to be severely lacking, including high costs, low yields, and severe pollution. In response, utilizing modern information technology for precise management throughout the agricultural production process and advancing smart agriculture has become a focal point in global agricultural competition. Agricultural machines are an important link of production and determine the degree of agrarianizing. Nowadays, conventional agricultural machinery control systems rely on mechanical regulation or open-loop electronic control, lacking real-time monitoring capabilities and dynamic adaptation capabilities. This limitation leads to low fertilizer and pesticide utilization rates and suboptimal operational quality. Therefore, the development of smart farm machine controls that are capable of perceiving their environment, autonomous decision making capability, precision of operation etc., have become the areas of concern for agricultural engineers.

The research of smart agricultural machinery control at home and abroad are gradually shifting from one factor control to multifactorial control, with intelligent analysis. Unmanned crop

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protection helicopter is extensively utilized in the field of aerial agriculture application to combat pests and diseases. However, changes of the pesticides concentrations in operation bring about great variation in flying attitude which deteriorates the operation quality. To overcome all those difficulties, Amertet et.al. have introduced the concept of a hybrid proportional-integral-derivative (PID) controller which is given as, substantially enhancing the attitude control accuracy in the presence of random winds [1]. Likewise, Shen et al. developed an onboard STM32 avionics system which implements a coupled flight-spray cascade PID control law. Ground equipment: Overcome current nozzle constraints regarding their ability to control application rates according to crop canopy characteristics [2]. Jeon, et.al. used stereovision for achieving adaptive variable rate based upon the plants spatial information. In combined fertigation systems, where the presence of system delay as well as time varying nature is predominant, dedicated programmable logic controller (PLC) are used for accurate control [3]. Tang et al. gave an idea of the use of a fuzzy PID controller in water-fertilizer integrated irrigation [4]. Serea et al. presented a modular irrigation-adding fertilizer unit based on PLC for network irrigation and fertilization management, as a practical means to achieve high-precision, large scale irrigation [5].

Even with the development of hardware-software co-design and control algorithm, some problems still exist such as low multi-source information fusion level and difficulty in applying high-level control algorithm to limited resources embedded platform. It is difficult to achieve a balance between these factors: system cost effectiveness, reliability, and real time are still important problems to be solved for intelligent agricultural machine researches. Hence, in order to provide a guide for further study, the types of intelligent agricultural machinery are classified and reviewed according to their control technologies in this article.

2. Classification of intelligent agricultural machinery

Agricultural machinery covers a wide range of types and stages in agricultural production—from land preparation and planting to field management and harvesting. Aerial applications are prominently represented by crop protection unmanned aerial vehicles (UAVs), while ground-based systems feature intelligent sprayers and integrated fertigation systems. These represent the most typical applications across the ground-and-aerial domains and are the fastest-growing and most widely used control technologies in agriculture.

2.1. Crop protection unmanned aerial vehicle systems

Due to their high operational efficiency, minimal terrain constraints, and ability to avoid human exposure to pesticides, plant protection UAVs are widely used in agricultural pest control. However, agricultural UAVs differ from general-purpose aircraft. During pesticide spraying, they are affected by factors such as center-of-gravity shifts induced by pesticide depletion and fluid slosh, ground effect, and spray recoil forces. This places high demands on the robustness of the flight control system.

Flight stability control is a critical component of agricultural plant protection UAVs. Shen et al. designed a flight controller centered on the STM32F428IGT6 chip, integrating an MPU6000 module and MS5611 pressure sensor to obtain real-time spatial attitude data of the aircraft [2]. The controller implements a cascaded PID control strategy. The inner loop operates as a velocity channel for angular rate control, while the outer loop functions as a position channel for angular control. This configuration resolves lag issues inherent in traditional single-loop PID control, enabling smooth flight performance. However, during pesticide spraying, the UAV's mass and moment of inertia

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undergo dynamic changes, making it a time-varying control system. Consequently, Li et al. established dynamic equations for a hexacopter UAV and designed a self-tuning fuzzy PID control algorithm. Simulation results demonstrated its ability to automatically adjust PID parameters based on load variations, reducing overshoot (from 1.20% to 0.86%) and enhancing flight quality during the mission cycle [6].

For precise, fixed-point spraying, conventional UAV face inconsistencies in spray rates when flight speeds vary, as nozzle flow rates remain constant. Recently, Amertet et al. expanded their focus beyond controlling aircraft attitude, incorporating pesticide flow rate into their analysis, and developing a hybrid fuzzy PID controller. Simulation tests using Simulink demonstrated that this approach achieves excellent and uniform pesticide distribution under gusty conditions, effectively addressing the challenge of coupled control over UAV speed and spray volume [1]. For complex spraying environments such as between trees, Yu et al. proposed a radial basis function (RBF) neural network hybrid controller, enhancing the UAV's obstacle avoidance and tracking capabilities in irregular areas, enabling intelligent operations [7].

2.2. Intelligent sprayers and robotic systems

The ground based intelligent sprayer is mainly used for plant protection work on the large-scale field or orchard. Although it has higher performance than the UAV of payload carrying weight, endurance, etc. They have problems like varying forward velocities, poor target detection rate, etc. Precision spray-on-demand research seeks to adjust the amount of pesticides sprayed in real time according to plant population, growth stages, and machine speed to achieve less chemical use with better results and protect the environment.

The problem that speed-pressure is coupled together always exists in agricultural machine automation. During the operation process, due to irregular terrain surface, tractor's operating speed will change dynamically. If not considering the dynamic pressure adjustment, pesticide waste happens, and local under-application. For that reason, Meng et al. designed and implemented an intelligent spraying control system based on fuzzy PID. The control law computes the error in volume of spray, difference between the real and theoretical one, to regulate the pulse width modulation (PWM) duty cycle driving the solenoid valves on the injectors: simulations show how it is possible to quickly follow speed variations reducing lag time, have achieved stable use-rates [8]. On the other hand, Wang et al. adopted a single neuron PID control algorithm and used the self-learning ability of the neural network for optimizing the control parameters, which makes it possible for the system to run at different working speed [9].

As computer vision technology develops further, "precision targeted spraying" also makes great progress. Jeon et al. presented an intelligent variable rate spraying system based on stereovision. Taking the advantage of two cameras to capture three-dimensional image of fruit tree, the system evaluates the canopy volume to compute and adaptively control the PWM duty cycle of the spray nozzles. The field tests showed a reduction of more than 30 % of pesticides with respect to traditional continuous application while maintaining effectiveness [3].

2.3. Integrated fertigation systems

Integrated fertigation can be described as an irrigation system in which the water used for irrigation is blended with fertilizer prior to its application. Integrated fertigation applies both water and nutrient directly at the roots of crops via piping systems, is one of the most important methods to conserve water and fertilizer efficiently. The biggest problem is how to control the electrical

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conductivity (EC) value and pH of the irrigation water. The system is a multi-variable coupling system with large delay time characteristics and strong non-linear dynamics that is not easy to control.

To solve the above problems, scholars have done a lot of engineering researches. Tang et al. designed an S7-200 PLC water-fertilizer integration control system. In order to solve the problem that there is lag in the change of soil moisture content and fertilizer solution concentration, they designed a fuzzy PID control table with 49 rules, and after implementation it was verified that the error of water-fertilizer ratio stays in [−0.1, 0.1] mS/cm, achieved 30% water saving and 26.5% fertilizer reduction [4]. Jin et al. worked with the sensing and control of nutrients uptake. They measured nutrient flow accumulation through counting pulses in a cycle of PWM, overcoming the problem of flow meters not measuring pulsating flows properly and at the same time, by means of PID parameter tuning, they controlled the EC values at their steady state within 3% [10].

In the greenhouse environment, it is important to obtain environmental information in time. Sun et al. proposed a kind of internet of things (IoT)-based intelligent water fertilizer integrated management method for greenhouse by installing soil thermometers, moisture sensors, and light intensity meters inside the greenhouse to adjust the water and fertilizer feed according to the environmental condition of the crops [11]. As for the control approach, Yan, et al. suggested that the PID control does not adequately address system nonlinearity. They set up a back propagation (BP) feed forward compensation model of water fertilizer blending to reduce the influence of time delay effect, improve control quality [12].

3. Classification of intelligent control systems for agricultural machinery

Intelligent control system analysis on the modern agriculture machinery can be divided to two parts, namely hardware part and software part. The hardware includes two kinds, one is industry-level PLC control system, the other is consumer-level embedded microcontroller system; while software mainly include PID and its improved algorithm.

3.1. Programmable logic controller systems

As a matured PLC technology comes from the field of industry automation and provides high degree of reliability, robustness in terms of electromagnetic immunity capability, and high modularity. It can meet requirements imposed by difficult and demanding working conditions in agriculture, especially in the case of medium-to-large scale integrated fertigation systems as well as greenhouses.

The main benefit that a PLC offer is its industry level hardware platform. Farm settings can have extreme levels of moisture, high temperature, and electromagnetic interference generated by big electric devices, which may lead to common microprocessors crashing system failures or resetting. Both Tang et al. and Chunqiu et al. used the Siemens S7-200 series programmable controller as the kernel part of the controller. This system uses standard analog input modules for taking in signal from the industry control instruments (e.g. PH meter, (pressure transmitters). The relays are directly driving big motors (water pump), which gives a straightforward and reliable control loop [4,10].

The graphical nature of PLC programming languages like ladder diagrams makes it easy to visualize programs which can be helpful when designing them and for routine debugging/maintenance by an agricultural machinery engineer. Sun et al. used the built-in PID wizard feature of the PLC while developing a control system for greenhouses to quickly implement a closed loop control scheme. They have also used the technology of RS485 bus communication to

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communicate with human machine interface touch panel for transmitting the information, which greatly simplifies system debug and maintenance [11].

3.2. Embedded control systems

In contrast with the PLCs, the embedded-control implementations based on microcontroller units (MCUs), e.g., STM32 and ESP32 provide several benefits including small footprint, low power consumption, low price (usually only 1/10 the cost of PLCs) and powerful processing functions. It is very suitable for use in small agricultural machinery, e.g., agricultural UAV (crop protection) or a small field robot) [6].

Nowadays, ARM Cortex-M series chips like STM32 have been widely adopted for the embedded system design of agricultural machinery. Shen et al. developed an UAV flight controller using the powerful STM32F428 chip. The clock speed is up to 180MHz with hardware floating point unit (FPU) support.it can realize the rapid calculation for high frequency attitude information provided by MPU6000 sensor, complete complicated flight attitude calculation. This microsecond level of response time is hard for PLC to implement [2]. Yan et al. also use the STM32F407 chip, which takes advantage of the powerful hardware resources on it to realize accurate milliseconds level timing control for multiple water and fertilizer solenoid valve [12].

In addition to conventional MCUs, single-board computers (SBCs) which can run complete operating systems such as Raspberry Pi are also being deployed for automated farming applications. Ting et al. proposed a smart drip irrigation system design based on Raspberry Pi 4B, implementing fuzzy controllers and web based remote monitoring with the use of python programming language and its inbuilt library [13]. Jeon et al. used high-performance embedded personal computers (PCs) to implement complicated image processing algorithm when developing a vision assisted variable application mechanism [3]. Open-source ecosystem on embedded system provides more space to study agriculture machineries' controlling algorithm.

3.3. PID algorithms

The PID control algorithm is at the heart of any strategy in a whole control system regardless it being built over PLCs or microprocessors, but due to the complex and random characteristics of the operation process on the agricultural fields, it is difficult for traditional PID control algorithm to achieve accurate control results. Therefore, different optimal PID control strategies are proposed.

The traditional PID control algorithm is simple and reliable, but it has the problem of being unable to adjust the parameters in time when faced with a nonlinear system or a large delay system. Such as: a spray control scheme with fuzzy control theory as basis, design a fuzzy PID controller [3]. The controller uses fuzzy logic to online-tune related parameter according to error and rate of change of error. The experimental results showed that the fuzzy PID could reduce the system overshoot of traditional PID by about 40%, and shorten the response time by about 30%. The fuzzy PID was successfully used in the UAV tracking control under the change of load and the precision drip irrigation control of intelligent sprinkler [5, 8], which makes it a very popular optimization method.

Neural network based PID control approaches are developed with the development of artificial intelligence technology. A adaptive neuro-fuzzy inference system (ANFIS) controller is proposed [14]. Based on the adaptability of ANFIS and fuzzy logic inference, which can approximate any nonlinear function and performs well for the uncertain dynamical model of spray robot.

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4. Conclusion

This paper investigates the development of three categories of intelligent agricultural machinery: crop protection UAVs, intelligent sprayers, and integrated fertigation integrated systems. It compares the characteristics of PLCs, embedded control methods, and improved PID algorithms. This paper reveals that control methods for various intelligent agricultural machinery are shifting from traditional single-loop PID feedback control to data-driven control based on multi-sensor information.

4.1. Current technical challenges

Despite the success of such smart-control methods on a testbed scale, there are some challenges to deploying these systems into real-world environments and scaling up for mass production:

The first one is that of accuracy versus price. At present there are a lot of precise control systems which employ industrial level sensors, which contain costly elements like fiber optic gyroscopes and optical lenses. For example, the sensors and controllers of industrial grade in use are costly, limiting the use of these on small scale farming [4,5]. The use of inexpensive embedded systems such as the STM32 lowers costs but its robustness against challenging environmental circumstances and durability need more practical testing.

Second, insufficient robustness and interference resistance. Field environments introduce many uncertainties—such as temperature and humidity fluctuations, equipment vibration, and electromagnetic signals—that can introduce errors into collected data. Although fuzzy PID control and other methods compensate for nonlinear effects, when the system faces sudden external perturbations or rapid drops in light intensity, recognition accuracy still requires improvement.

4.2. Real-time performance and complexity

The widespread application of the control algorithm such as an artificial intelligence algorithm (radial basis function neural network, (adaptive neural fuzzy inference systems), which leads to an increase in the number of control system algorithms, which makes it difficult to implement the control algorithm on small processors (MCUs and edge computers), but also requires maintaining a certain level of real-time operation and guarantees for processing and executing control commands quickly.

4.3. Future development directions

To solve the above technical challenges and problems, smart farm equipment management system will have some new development trends:

The first is the multi-sensor cooperative intelligent identification technology. The future control system develops from a passive controller to a proactive control system with "eyesight". Image processing and artificial intelligence algorithm can be integrated in agricultural machine to real-time monitoring and detection of crop status to achieve adaptive control in a "detect and act" manner. The works of Jeon et al. can be concluded that stereo vision helps in depth calculation which plays a vital role in the manipulation of precise variables [3].

Second, a unified "edge-cloud" computing paradigm: In order to boost the computation capability, the unified "edge cloud" computing paradigm shall be extensively utilized. The online task such as attitude control and obstacle avoidance may be tackled by on-board edge computer

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(e.g., NVIDIA Jetson) but also offline big data analysis (e.g., plant growth prediction and agriculture path planning) could be conducted on cloud for full use of computation resources.

Third, integrated navigation, communication, and remote sensing with clustering: Supported by 5G communication technology and Beidou satellite navigation positioning, future agricultural machinery will evolve from individual operations to coordinated multi-unit collaboration. Designing communication protocols and rules will enable integrated air-ground-space autonomous operations, achieving all-weather, round-the-clock precision agricultural production.

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