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OPTIMIZATION OF STEPPER MOTOR CONTROL IN VARIOUS OPERATING MODES

ОПТИМІЗАЦІЯ КЕРУВАННЯ КРОКОВИМ ДВИГУНОМ У РІЗНИХ РЕЖИМАХ РОБОТИ

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Abstract. *The article investigates the topical issue of increasing the efficiency of stepper motor control, which are key elements in positioning systems within robotic platforms. The possibilities of using three popular controllers are considered and compared: Jetson Nano, ESP32 (as affordable solutions for basic control), and Raspberry Pi 5 (for more complex scenarios due to higher computing power and expanded interfaces).*

Within the scope of the research, dynamic mathematical models were developed to simulate the loss of control signal at frequencies of 433 MHz, 915 MHz, 2.4 GHz, and 5.8 GHz, taking into account the influence of distance (up to 5000 m) and terrain relief (from -10 to 15 m). The experimental setup included a Nema 17 stepper motor with a TB6600 driver, powered by a 36V battery via a DC/DC converter, with remote control implemented using the CRSF protocol.

A separate model was developed to analyze the influence of torque, heat dissipation, and positioning accuracy of the Nema 17 stepper motor at a voltage of 12V and a current of 1.1A. The simulation results demonstrated the dependence of signal loss on distance and terrain relief, as well as the impact of altitude (as a representative of external conditions) on motor temperature and the dependence of positioning accuracy and torque on terrain relief.

A comparative analysis of the control platforms was conducted based on the criteria of ease of setup, programming, and debugging, revealing their advantages and limitations for various stepper motor control tasks in robotics.

Particular attention was paid to the application of additive technologies (3D printing using a P1P printer and PETg LBL plastic) for rapid prototyping and the fabrication of housing and mounting elements, which significantly optimized the development process.

The obtained results contribute to a deeper understanding of the capabilities of various hardware and software tools for the effective control of stepper motors in robotic platforms, considering the influence of external factors and the specifics of remote control. This lays the groundwork for further research in the development of adaptive control systems, energy consumption optimization, and the expansion of the functional capabilities of robotic complexes.

Анотація. *У статті досліджено актуальну проблему підвищення ефективності керування кроковими електродвигунами, що є ключовими елементами систем позиціонування в робототехнічних платформах. Розглянуто та порівняно можливості використання трьох популярних контролерів: Jetson Nano, ESP32 (як доступних рішень для базового керування) та Raspberry Pi 5 (для складніших сценаріїв завдяки вищій обчислювальній потужності та розширеним інтерфейсам).*

В рамках дослідження розроблено динамічні математичні моделі для імітації втрати сигналу керування на частотах 433 МГц, 915 МГц, 2.4 ГГц та 5.8 ГГц з урахуванням впливу відстані (до 5000 м) та рельєфу місцевості (від -10 до 15 м). Експериментальна установка включала кроковий двигун Nema 17 з драйвером TB6600, що живився від акумуляторної батареї 36В через DC/DC перетворювач, а дистанційне керування здійснювалося за протоколом CRSF.

Для аналізу впливу крутного моменту, тепловиділення та точності позиціонування крокового двигуна Nema 17 при напрузі 12В та струмі 1.1А було розроблено окрему модель. Результати моделювання продемонстрували залежність втрати сигналу від відстані та рельєфу, а також вплив висоти (як представника зовнішніх умов) на температуру двигуна та залежність точності позиціонування і крутного моменту від рельєфу.

Проведено порівняльний аналіз платформ керування за критеріями простоти налаштування, програмування та відлагодження, виявлено їхні переваги та обмеження для різних завдань керування кроковими двигунами в робототехніці.

Окрему увагу приділено застосуванню адитивних технологій (3D-друку з використанням принтера P1P та пластику PETg LBL) для швидкого прототипування та виготовлення корпусних і кріпильних елементів, що суттєво оптимізувало процес розробки.

Отримані результати сприяють глибшому розумінню можливостей різних апаратних та програмних засобів для ефективного керування кроковими двигунами в робототехнічних платформах, враховуючи вплив зовнішніх факторів та особливості дистанційного керування. Це створює основу для подальших досліджень у напрямку розробки адаптивних систем керування, оптимізації енергоспоживання та розширення функціональних можливостей робототехнічних комплексів.

Keywords: *stepper motor, Raspberry Pi, ESP32, Jetson Nano, remote control, signal loss modeling, thermal analysis, positioning accuracy, additive manufacturing, robotic platform.*

Ключові слова: *кроковий двигун, Raspberry Pi, ESP32, Jetson Nano, дистанційне керування, моделювання втрати сигналу, тепловий аналіз, точність позиціонування, адитивне виробництво, робототехнічна платформа.*

Introduction.

The development of unmanned technologies in Ukraine demonstrates significant dynamics, requiring continuous improvement of both software and hardware. In the context of rapid technological progress, particular attention is drawn to the issues of efficient control of actuators [1], especially stepper motors, which are key elements of positioning and motion systems in robotic platforms.

The relevance of the research is driven by the increasing need for reliable and precise control systems for the moving elements of robotic platforms, especially in the context of remote control and operation in complex conditions [2]. Existing control approaches often do not account for dynamic changes in the quality of the control signal and the influence of external factors on the operational characteristics of motors, which can lead to a decrease in the efficiency and reliability of system operation [3].

In this context, the study of various hardware platforms for stepper motor control, such as Raspberry Pi 5, ESP32, and Jetson Nano, is important in terms of their functionality, remote control capabilities, and integration into robotic complexes. Particular attention is paid to the analysis of the impact of control signal loss on motor operation [4], which is critical for ensuring the stable functioning of remotely controlled systems. Understanding the influence of operational parameters such as torque, heating, and positioning accuracy on the efficiency of stepper motor operation under various conditions is also significant.

To enhance the efficiency of development and adaptation of robotic systems, the study also considers the application of additive technologies for rapid prototyping and the fabrication of housing elements and auxiliary equipment.

Given the above, the aim of the research is to increase the efficiency of stepper motor control under dynamically changing operating modes by developing and analyzing appropriate mathematical models, assessing the influence of external factors, and conducting a comparative analysis of different hardware control platforms.

Thus, this research is aimed at optimizing the process of stepper motor control in robotic systems by modeling various aspects of their operation and comparatively analyzing hardware solutions, which is an important step in the development of reliable and efficient unmanned technologies.

Literature review and problem statement. The efficient and precise control of stepper motors is paramount in the realm of robotics, enabling accurate positioning and controlled motion. The reviewed literature highlights different approaches to achieve this, focusing on control methodologies and interface design.

The paper [5] presents a stepper motor drive utilizing a hybrid two-phase model. The core functionality of a stepper motor, converting pulse signals into discrete angular displacements, is emphasized. To manage speed and torque variables within a defined design range, the study employs a closed-loop control technique incorporating Park transformation. The findings are supported by both simulation and hardware implementation, with results concerning motor voltage, current, speed, and torque being discussed. The hardware implementation specifically utilizes an Arduino microcontroller for speed regulation, indicating the feasibility of using low-cost microcontrollers for basic yet effective stepper motor control in robotic applications. This work suggests that for applications where precise speed control within a moderate range is crucial, an Arduino-based closed-loop system can offer a viable solution.

Expanding on the control interface, the article [6] focuses on the realization of a real-time controllable interface for stepper motors, acknowledging their widespread use in industrial settings. The key innovation lies in substituting expensive industrial control panels with interface screens on embedded system cards. The developed interface, running on a 7" display connected to a Raspberry Pi, allows for the manipulation of crucial stepper motor parameters such as cycle, number of steps, direction, and speed. The control commands generated through the touch screen interface are transmitted to the stepper motor drivers via the Raspberry Pi's general-purpose input/output (GPIO) pins. This study exemplifies the development of more innovative and cost-effective control solutions by leveraging embedded system cards and touch screen technology. The provision of remote access further enhances the flexibility and usability of the control system. This approach is particularly relevant for robotic applications requiring a user-friendly interface for real-time parameter adjustments and remote operation.

Another relevant study [7] proposes an Arduino Uno-based speed control for stepper motors implemented wirelessly via Bluetooth technology (HC-05 module and an Android application). Beyond speed regulation, a key focus of this work is mitigating the jerking issue inherent in stepper motor operation during step transitions. The article [8] proposes a low-cost, mobile device-based learning system for stepper motors, featuring a web-based remote laboratory. This system aims to facilitate learning about rotational principles, control methods, and programming in stepper motors for young engineers. The authors highlight the importance of hands-on laboratories in electrical machinery education but acknowledge the constraints of time, space, and the cost of equipment. Their proposed system allows students to remotely conduct experiments on a real stepper motor using devices like smartphones. The combination of a remote and virtual laboratory is intended to be user-friendly. The system's design utilizes low-cost microcomputers like Raspberry Pi and Arduino, avoiding expensive software like LabVIEW and MATLAB, ensuring both affordability and compatibility with mobile devices.

The article [9] details the development of a smart control device for a Universal Arc Plasma Sintering (U-APS) system, specifically designed for material synthesis and treatment of high-temperature materials. The control unit is based on a Raspberry Pi 3B+ microcomputer programmed in Python, chosen for its prevalence in academic and research settings. The Raspberry Pi coordinates key U-APS components through a straightforward algorithm, ensuring precise synchronization. This includes controlling a bipolar stepper motor (via a TB6600 driver) responsible for the sample stage movement with a resolution of at least 0.1 mm per step and adhering to a strict lower limit using a limit switch. All commands are input through a graphical user interface displayed on a monitor connected to the Raspberry Pi. The authors conclude that a Raspberry Pi 3B+-based control system offers a cost-effective and reliable solution for automating process for advanced research, demonstrating successful control of motor movement and sintering duration.

The existing body of literature highlights significant advancements in stepper motor control methodologies, ranging from closed-loop speed regulation using microcontrollers like Arduino to the development of user-friendly and remotely accessible control interfaces based on platforms like Raspberry Pi. Furthermore, research addresses specific challenges such as reducing jerking for smoother operation and creating remote laboratory systems for educational purposes using cost-effective hardware. These studies collectively underscore the importance of precise, reliable, and accessible stepper motor control in various applications, including robotics and automated systems.

However, a gap remains in the specific optimization of these advancements for the unique demands of ground unmanned systems (UGS), particularly concerning the control of articulated modules like video surveillance systems. While the reviewed literature provides valuable insights into control algorithms, interface design, and addressing mechanical limitations, it does not fully address the integrated challenges of UGS, which include power efficiency, robustness in dynamic environments, seamless integration with other UGS subsystems, and the need for control solutions tailored to specific operational requirements. Therefore, the existing problem lies in the lack of focused research on optimizing stepper motor control strategies and interfaces specifically for the enhancement of UGS functionalities, particularly for articulated payloads like high-precision, low-power video surveillance systems operating in complex field conditions.

Aim and objectives of the research. The aim of the research is to increase the efficiency of stepper motor control under dynamically changing operating modes by developing and analyzing appropriate mathematical models and assessing the influence of external factors.

The main objectives of the research include:

1. To conduct a systematic review of existing hardware and software tools for stepper motor control, identifying their advantages, disadvantages, and limitations.

2. To develop dynamic mathematical models that simulate the process of control signal loss at selected frequencies (433 MHz, 915 MHz, 2.4 GHz, 5.8 GHz), taking into account the influence of distance and terrain relief.

3. To develop a comprehensive model that simulates the key operational characteristics of the Nema 17 stepper motor with a TB6600 driver, including torque, heat dissipation, and positioning accuracy, depending on power supply parameters and external conditions.

Methods and Materials. For the research, a Nema 17 stepper motor was used, controlled by a Raspberry Pi single-board computer via a TB6600 driver. The motor was powered by a battery pack with a 10S 6P configuration and a capacity of 21 Ah, connected through a DC/DC converter to stabilize the required voltage.

Remote control of the motor was implemented using the CRSF protocol, allowing for control at distances up to 5000 meters. The terrain in which the motor is intended to operate varies in the range of -10 to 15 meters relative to a conditional zero height.

As part of the study, a dynamic model was developed to simulate the loss of control signal at four different frequencies: 433 MHz, 915 MHz, 2.4 GHz, and 5.8 GHz. The model takes into account the total losses, consisting of Free Space Path Loss and additional losses due to knife-edge diffraction when radio waves pass over terrain obstacles. In the process of modeling the influence of terrain on radio wave propagation, the knife-edge diffraction model [10] was used, which is a generally accepted method for estimating signal loss in the presence of obstacles. The total range of modeled signal loss was limited to values from 50 to 150 dB (np.clip(L_total, 50, 150)). Additionally, aspects of modeling the influence of physical barriers on signal propagation in the conditions of the studied terrain were investigated.

To analyze the influence of torque, heat dissipation, and positioning accuracy of the Nema 17 stepper motor, a series of model experiments were conducted at fixed power supply parameters: a voltage of 12V and a current of 1.1A. The motor step was 1.8 degrees (200 steps per revolution). The results of these studies are aimed at determining the operational characteristics of the motor under various load and environmental conditions.

Research results. Stepper Motor Control Based on Raspberry Pi/ESP/JETSON. The process of controlling stepper motors using the Raspberry Pi, ESP, and JETSON platforms is fundamentally similar; however, it is implemented using different software libraries. Specifically, for Raspberry Pi [11] and JETSON, the gpiozero and Jetson.GPIO libraries are used, respectively [12]. Control on the ESP platform involves using low-level pin access via machine.Pin or employing the specialized Stepper library.

The developed hardware circuit was used to control the stepper motor in various modes, including remote control. To analyze the quality of the control signal and identify the factors influencing the stepper motor's operation under remote control conditions, theoretical modeling was performed, the methodology of which is described in detail in the corresponding section.

The results of the dynamic model simulating the loss of control signal at the studied frequencies (433 MHz, 915 MHz, 2.4 GHz, and 5.8 GHz) are presented in Figure 1.

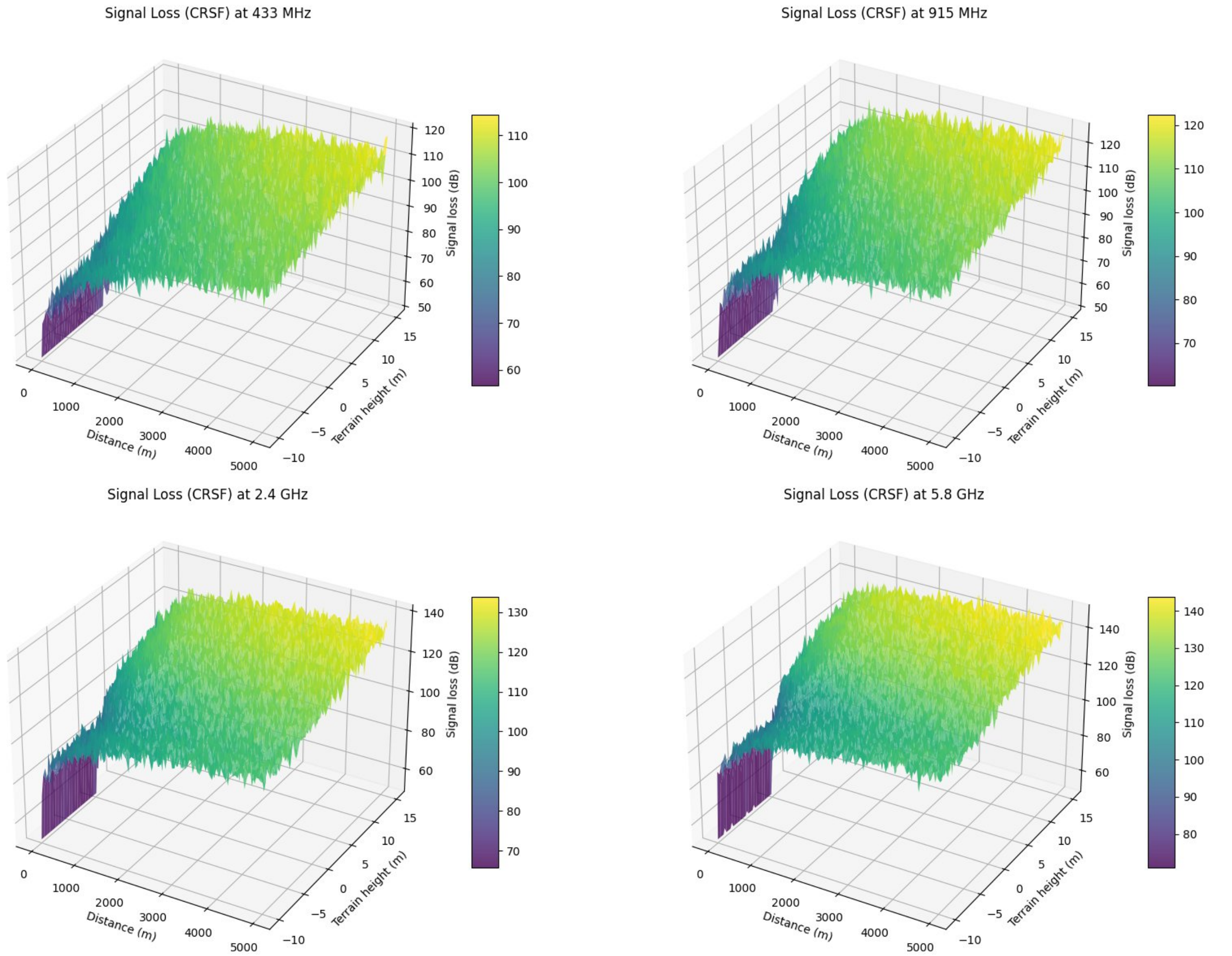

Fig. 1. CRSF signal loss with knife-edge diffraction depending on distance and terrain
Рис. 1. Втрата сигналу CRSF з дифракцією на кромці ножа залежно від відстані та рельєфу

Analysis of Figure 1 demonstrates a clear trend of increasing signal loss with increasing distance between the transmitter and receiver, as well as in the presence of terrain depressions, for all investigated frequency ranges.

To study the influence of torque, heat dissipation, and positioning accuracy on the Nema 17 stepper motor with the TB6600 driver, a separate model was developed and analyzed, the results of which are shown in Figure 2.

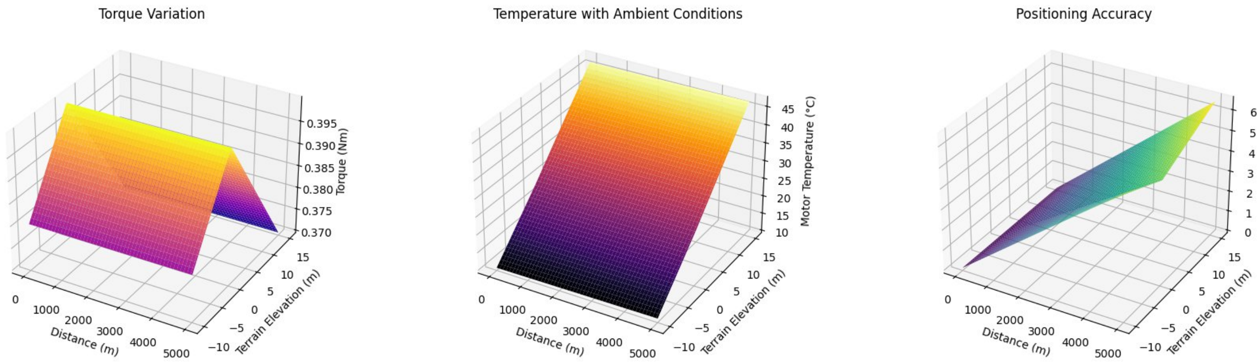

Fig. 2. Influence of torque, heat dissipation, positioning accuracy on Nema 17 stepper motor with TB6600 driver
Рис. 2. Вплив крутного моменту, нагріву, точності позиціонування на кроковий двигун Nema 17 із драйвером TB6600

According to the data presented in Figure 2, an increase in motor temperature is observed with increasing altitude (as a representative of certain changes in external conditions). Positioning accuracy and the magnitude of the torque demonstrate a dependence on the modeled terrain relief.

The process of manufacturing the housing elements for the developed system was carried out using a P1P 3D printer with PETg LBL plastic (see Fig. 3).

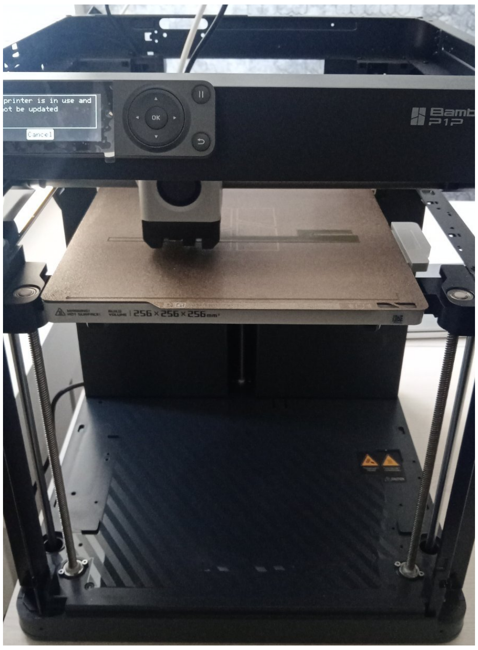

Fig. 3. Housing manufacturing process using P1P with PETg LBL plastic
Рис. 3. Процес виготовлення корпусу засобами P1P з використанням пластику PETg LBL

A key aspect in the manufacturing of housings is the careful adjustment of printing parameters, particularly the bed temperature. The application of these additive manufacturing technologies has significantly accelerated the prototyping and fabrication process of the necessary components.

Discussion. The development of the presented dynamic models for stepper motor control opens new possibilities for a deep understanding of the specifics of its operation under various operating conditions. The analysis of the influence of signal quality, external factors such as terrain relief, on control characteristics allows for a transition from simple motor activation to a more complex and adaptive approach. Stepper motor control should not be considered as a separate process but as a component of a global system that encompasses not only different activation methods but also detailed modeling of its behavior at both theoretical and experimental levels.

This comprehensive approach makes it possible to consider potential situations that may arise during the actual operation of the motor and the entire control system already at the initial stages of design and research. This includes predicting possible control signal losses depending on distance and obstacles, assessing the impact of load and external conditions on positioning accuracy and the motor's thermal regime.

In this context, a modern stepper motor control system should be equipped with various sensors that provide constant monitoring of key parameters such as communication signal quality, motor temperature, its current position, consumed current, and other important indicators. The data obtained from these sensors is critical not only for detecting current deviations from the normal operating mode but also for predicting possible malfunctions or the occurrence of critical situations.

Furthermore, the results of the developed dynamic models and the data collected from the sensors should be integrated into an intelligent decision-making system. Such a system will be able to automatically adapt the motor control parameters depending on the current conditions, select optimal operating modes, and, in the event of abnormal situations, make informed decisions to ensure the stable and safe operation of the entire system. For example, with a significant deterioration in signal quality, the system can automatically switch to a backup communication channel or notify the operator of the need for intervention. Similarly, upon detecting critical motor heating, the system can reduce the load or change the operating mode to prevent failure.

Thus, the combination of deep modeling of stepper motor control dynamics with the use of modern sensor technologies and intelligent decision-making systems is a key direction in the development of efficient and reliable control systems in various fields of application.

Conclusions. In the course of the conducted research, a successful analysis and comparison of various approaches to controlling stepper motors based on Jetson, ESP, and Raspberry Pi 5 computing platforms was carried out. The key advantages and disadvantages of each of the considered methods were identified in terms of configuration complexity, remote control implementation possibilities, integration potential with other components of robotic systems, and their energy efficiency.

One of the important achievements was the development and successful implementation of dynamic models that simulate the behavior of a stepper motor under control signal loss conditions at different frequencies, as well as model the influence of critical operational parameters such as torque, thermal regime, and positioning accuracy of the Nema 17 motor with the TB6600 driver. The developed models are a valuable tool for predicting the behavior of the control system under real operating conditions and developing appropriate action recommendations for various scenarios, including the optimization of control parameters depending on signal quality and external conditions.

In addition, the research demonstrated the effectiveness of using additive technologies, specifically 3D printing with a P1P printer and PETg LBL plastic, for the rapid prototyping and fabrication of housing elements for robotic modules. This confirms the potential of using modern manufacturing technologies to accelerate the development cycle and reduce the cost of creating components for robotic systems.

The results obtained during the research are an important step towards increasing the efficiency of development and improvement of stepper motor control systems for robotic platforms. The developed dynamic models and practical recommendations create a solid foundation for further scientific research in the direction of adaptive control, failure prediction, and the expansion of the functional capabilities of robotic complexes, particularly in the context of their application in complex operating conditions and with remote control. Further research may be aimed at validating the developed models with experimental data and developing intelligent control algorithms based on them.

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