DESIGN OF SEMI-PHYSICAL SIMULATION PLATFORM FOR GRAIN CLEANING AND REGULATING SYSTEM
/
谷物清选调控系统半实物仿真平台设计

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ABSTRACT
To address the long development cycle of the grain air-screen cleaning device, a semi-physical simulation platform for the grain cleaning control system was designed. The platform was used to simulate the actual operational process, conducting both open-loop and closed-loop tests, with results compared to actual tests. In the open-loop test, the speed error had a mathematical expectation of 0.8387 rpm, with a standard deviation of 2.75 rpm, and the fish-scale sieve opening error had a mathematical expectation of -0.0117 mm, with a standard deviation of 0.038 mm. In the closed-loop test, the speed error had a mathematical expectation of 0.679 rpm, with a standard deviation of 1.815 rpm. The experimental results demonstrate that the simulation platform can effectively replicate the actual operating conditions of the grain cleaning device and validate the effectiveness of the TC377 controller's control algorithm, thereby improving the development efficiency.

摘要
针对谷物风筛式清选装置开发周期长的问题，设计出一套谷物清选调控系统半实物仿真平台。利用半实物仿真平台模拟实际作业过程，进行开环与闭环测试，与实际测试进行对比。其中，开环测试转速误差数学期望为 0.8387rpm，标准差为 2.75rpm，鱼鳞筛开度误差数学期望为-0.0117mm，标准差为 0.038mm。闭环测试转速误差数学期望为 0.679rpm，标准差为 1.815rpm，试验结果表明了该仿真平台能够模拟谷物清选装置的实际工况以及 TC377 作为控制器控制算法的有效性，能够提高开发效率。

INTRODUCTION
China, as a major agricultural country, has high demands on the quality and efficiency of grain production due to its socio-economic context. During the processes of growth, harvesting, transportation, and storage, grains are susceptible to various adverse factors, leading to the presence of impurities, damaged kernels, and certain harmful substances. These factors not only impact the quality and nutritional value of the grains but may also pose potential health risks to consumers. Therefore, grain cleaning and sorting equipment plays an indispensable role in agricultural production (*Qu et al., 2024; Wang et al., 2022*).

The wind-sifting cleaning and sorting device is the primary equipment used by combine harvesters for grain cleaning operations. It offers advantages such as high cleaning efficiency and a high kernel cleaning rate. During operation, the wind-sifting cleaning device has multiple adjustable working parameters. The precision and automation of these adjustments are key factors that influence its cleaning efficiency and performance in field operations (*Ning et al., 2018)*.

In the practical development of harvesting machine cleaning devices, limitations such as harvest season and test field conditions make it difficult to conduct extensive field trials under various operational conditions. Before conducting real-world vehicle tests, extensive iterative experimental research is required to obtain optimal test results, which, to some extent, impacts the development process of cleaning devices. Many research institutions have designed and manufactured various testing rigs, but these rigs are expensive, and the testing process requires large amounts of crops, which still presents certain constraints. Under these conditions, the concept of semi-physical simulation technology has been proposed (*Jiang et al., 2022; Xu et al., 2024; Liu et al., 2018*).

Semi-physical simulation technology is an important simulation technique, currently widely used in various fields such as aerospace engineering, military applications, automotive engineering, diesel engine electronic control systems, and medical applications (*Cheng et al., 2022*).

Hardware-in-the-loop simulation is a simulation method targeting specific research objects. Its core lies in introducing a portion of the simulation object system into the simulation environment in the form of a physical model, while the remaining components are described through mathematical modeling methods and further developed into corresponding simulation computation models. Based on this, leveraging the actual effects generated by the physical model, real-time joint simulation tests can be conducted, integrating the collaborative work of mathematical and physical models. At present, the semi-physical simulation technology is not widely used in the field of agricultural machinery, and it is mainly used for the steering control and gear shift simulation of tractors (*Wu et al., 2023; Wu et al., 2019; Li et al., 2024*). Semi-physical simulation technology provides strong support for the integration of control systems in the development of agricultural machinery. By combining virtual models with actual hardware, it allows for the validation of the system's overall performance at an early stage of agricultural machinery development, enabling the timely identification of potential issues and optimization of system design. Furthermore, this simulation technology can real-time simulate the performance of agricultural machinery during actual operation. Through interaction with physical hardware, developers can more precisely adjust control system parameters, thus optimizing the performance of the grain cleaning device and ensuring that the machinery operates efficiently and stably (*Zhu et al., 2022*).

Zhu Xiaolong et al. in China developed a semi-physical simulation platform for a low-loss threshing intelligent control system. Through signal simulation testing and automatic control strategy simulations, they demonstrated that the platform can be used for the development of intelligent control systems for corn grain harvesters. This platform has provided an experimental foundation for the development of intelligent control systems for corn grain harvesters. Through a comparison of simulation and experimental tests, the semi-physical simulation platform was successfully validated for the development of the intelligent control system, shortening the development cycle (*Zhu et al., 2022*). Xie Bin et al. designed the mechanical structure of the electric tractor's drive system and built a prototype, which was then downloaded to the controller for hardware-in-the-loop (HIL) experiments. Actual data from previous field tests on plowing and rotary tilling were used as the load for the HIL experiments, which were conducted on a personal computer. Through multiple simulations and experiments on the semi-physical simulation platform, the traditional drive system was successfully improved, enhancing ploughing and rotary tilling efficiency (*Xie et al., 2022*).

Therefore, this paper focuses on the development of a grain cleaning test bench and designs a semi-physical simulation platform, applying semi-physical simulation technology to the grain cleaning device. The aim is to address the issues of long development cycles and high development costs. By reviewing relevant literature and utilizing appropriate software, mathematical models of the key operating components of the grain cleaning system were established. The platform was equipped with various components that generated the necessary signals for the testing process, achieving the conversion between physical values and signal values, thereby enabling successful signal transmission between different circuit boards. Finally, before conducting actual experiments, the control effects were verified through simulation testing of the controller.

MATERIALS AND METHODS

The overall structure of the hardware-in-the-loop simulation platform is shown in Fig. 1. Its structure is mainly divided into three parts: the hardware platform, the up-per-level computer software, and the real-time simulation model.

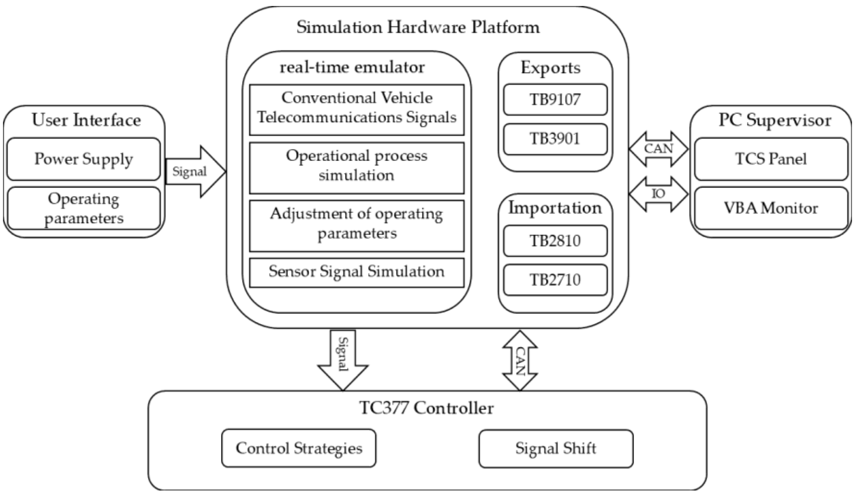


Fig. 1 - Overall Flow Chart

The specific requirements are as follows: (1) Simulate the electrical signals generated during the operation of the grain cleaning test bench, as well as the signals transmitted by the sensors. These signals are received through various boards located within the cabinet and transmitted to the controller via the ODU port. (2) It should be capable of simulating the actual working conditions, detecting variations in signals such as voltage and current during the control process, and performing data processing and transmission via hard-wire I/O signals and CAN communication. (3) Develop a model of the grain cleaning test bench and construct the mathematical model using the Simulink simulation platform. The controlled object receives the control signals from the controller and generates corresponding feedback signals to return to the controller, thus forming a complete closed-loop system. (4) The system is equipped with a human-machine interface, allowing for more intuitive and convenient adjustment and monitoring of the frequency variations of the inverter control cabinet, motor speed, fan speed, and other key components. The working status is monitored in real-time through CAN messages.

The components of the cabinet used for testing include devices such as PDU, programmable power supplies, regulated power supplies, PSM, function boards, general-purpose IO boards, and real-time processing systems, as shown in Fig. 2. The PDU primarily performs AC power control, distribution, and equipment protection functions. The real-time simulator ensures the simulation model operates in real-time, facilitates data interaction with the host-computer test software, and enables online parameter adjustment and monitoring. It also transmits the signals required by the controller through various IO boards and collects all signals transmitted by the controller.

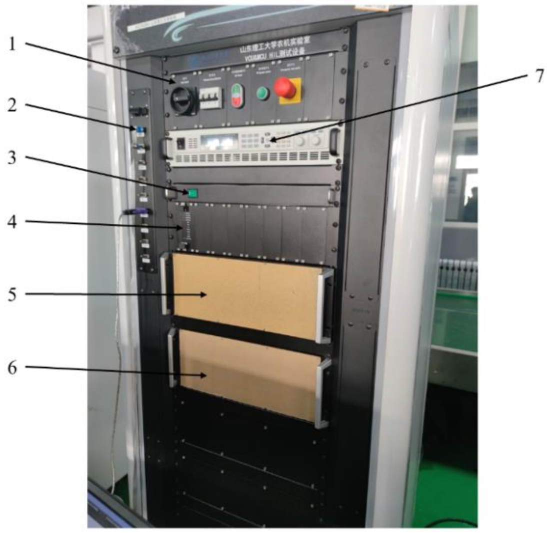


Fig. 2 - Cabinet Composition

1 - PDU Power Management, 2 - CAN interface, 3 - Signal conditioning power supply, 4 - Power switching, 5 - ODU connection draw box, 6 - Load draw box, 7 - Programmable power supply

The host computer software primarily includes Real-time Simulation Test Management Software (TCS), Automated Testing Software (TAE), Bus Monitoring Software (VBA), IO Model Generation Software (TB_IOModel_Gen), and Fault Injection Software (TB_EFI). The experimental management software oversees the management of model files and hardware resources. The bus monitoring software directly monitors messages on the CAN bus and functions as the bus monitor during the interaction between the HIL device and the controller. The fault injection software directly controls the fault injection board to introduce faults, thereby simulating real-world scenarios. The automation management software facilitates the invocation of the aforementioned software via the corresponding software interfaces, setting the execution sequence to achieve an automated testing process.

The drive motor selected is a squirrel-cage three-phase asynchronous motor, which drives the corresponding components through belt transmission. The motor speed is adjusted by varying the frequency using a frequency converter. A simulation model is built to simulate the corresponding frequency-controlled speed regulation system and output the corresponding motor speed. The motor speeds of the driving and driven wheels are detected by the VEMSEE speed sensor. Wind speed is measured by installing a wind speed sensor at the fan outlet and inside the sieve box. An impact plate sensor is used behind the sieve box to record the number of grains lost at the impurity discharge outlet during the grain cleaning process.

In actual operation, the size of the motor-driven load also affects the variation in motor speed. Therefore, to simplify the process, it is assumed that the motor's speed transmission is ideal. Mathematical models for the centrifugal fan, fish-scale sieve opening, spiral drill, and other components were established based on the agricultural machinery manual and relevant literature. The mathematical models were not optimized in this paper but are used to simulate the adjustment process of the test bench during actual operation. The physical values obtained during operation are converted into signal values and output through the circuit boards. The simulation of vehicle electrical signals and sensor signals is achieved through the IO conversion board and CAN communication board integrated into the simulation platform.

Table 1

The Main Technical Parameters of the Grain Cleaning Device

Item	Parameter
Belt width	1000 mm
Feed motor speed	0～100 rpm
Fan speed	400～1200 rpm
Vibrating screen crank speed	0～280 rpm
Fish scale sieve opening	7～22mm
Rotating speed of the elevator	0～500rpm

This paper takes the air-screen grain cleaning device as the development object. The tuning ranges for the working components are based on the equipment settings provided by the grain cleaning device manufacturer, as well as the professional instructions from the training personnel. The tuning ranges comply with the manufacturer's technical specifications and usage recommendations, ensuring standardization and consistency during the experimental process. Additionally, the device was delivered at the end of last year and, under the guidance of trained personnel, the operational ranges for each component parameter were confirmed, thereby enhancing the reliability of the experiment.

The wind separation system of the grain cleaning device employs a volute centrifugal fan, consisting primarily of components such as the fan casing, air regulation plate, fan shaft, blade connection plate, and blades. This centrifugal fan features a relatively wide design, provides adequate airflow, and ensures a uniform distribution of air within the screening box, thereby meeting the cleaning and selection requirements. The airflow speed and direction within the system can be adjusted through the air regulation plate based on actual conditions, enabling the attainment of the desired cleaning and selection effect.

The cleaning airflow V is given by Equation (1).

$$V = \frac{\beta\, Q}{\mu\, \rho} \tag{1}$$

where: β is the proportion of impurities in the mixture, taken as β=16%, for full feeding, the typical values for wheat range from 0.15 to 0.2, and for rice, from 0.1 to 0.15; for partial feeding, wheat typically ranges from 0.1 to 0.15, and rice from 0.08 to 0.12; Q is the machine's feeding rate, with a minimum value of 10 kg/s; μ is the concentration ratio of the airflow carrying impurities, taken as 0.25; ρ is the air density, taken as 1.29 kg/m^3.

Outlet air velocity, v, is given by Equation (2).

$$v = \frac{V}{B\, H} \tag{2}$$

where B is the outlet width, mm; H is the outlet height, mm.

The variation in the fish-scale sieve opening corresponds to the vertical spacing between adjacent sieve plates is given by Equation (3). The airflow through the cross-sectional gap between adjacent sieve plates per unit time is given by Equation (4).

$$S_1 = l \cdot l_1 = l_0 \sin\alpha l_1 \tag{3}$$

$$N = 3600\, S_1 v = 3600\, l_0 \sin\alpha\, l_1\, v \tag{4}$$

where: N is the airflow through the cross-sectional area of the gap between adjacent sieve plates per unit time, in m^3/s; v is the airflow velocity, in m/s; S_1 is the cross-sectional area of the gap between adjacent sieve plates, in m^2; l_0 is the length of the connecting plate between adjacent sieve plates, in m; l_1 is the width of the sieve plate, in m; l is the opening of the fish-scale sieve, in m.

v, l_0, l_1 is a fixed value, therefore, the change angle α of the sieve sheet determines the cross sectional ventilation N of the adjacent sieve sheet gap per unit time. From $l=l_0 \sin\alpha$, it follows that 0°≤α≤90°, so 0≤sinα≤1, when α =90°, sinα=1, at this point, the opening l of the fish scale sieve is at its maximum value and equal to l_0.

The horizontal winch seed conveying speed is given by Equation (5).

$$v_{d1} = \frac{p_1 w_{d1}}{60\Pi} \tag{5}$$

where v_{d1} is the axial conveying speed of the material, in m/s; p_1 represents the pitch of the helical blade, full−face blade p_1=0.8D_1, in m; D_1 represents the diameter of the helical blade, in m; w_{d1} represents the rotational speed of the screw shaft, in rpm.

Vertical winch seed conveying speed is given by Equation (6).

$$v_{d2} = \frac{w_{d2} R_{d2} \sin\alpha \sin\beta}{30 \sin(\alpha+\beta)} \tag{6}$$

where w_{d2} is the rotational speed of the screw shaft, in rpm; R_{d2} is the radius of the auger, in m; β represents the angle between the direction of grain movement and the horizontal, in degrees (°); α a represents the helical angle of the blade, in degrees (°).

The simulation model built in MATLAB/Simulink consists of multiple modules. TestBaseIO: Cabinet Basic Control Module. This section primarily controls the output of the programmable power supply and its feedback. The programmable power supply is turned off by adjusting the high or low level of DO1. Additionally, the output voltage values of AO1 and AO2 are used to achieve the specified voltage and current settings in the model.

The IO model serves as the interface between the simulation model and external hardware. As shown in Fig. 3, the left-side module, MDL Data to Controller, transmits hard-wired signals from the model to the cabinet board, which are then sent to the controller. Conversely, the right-side module, Controller Data To MDL, collects hard-wired signals from the controller via the cabinet board and delivers them to the model.

In particular, the MDL Soft ECU Data to Bus module categorizes various messages, as shown in Fig. 4, which are centrally monitored and managed by VBA. Each signal is ultimately transmitted to the RTSE output interface, then forwarded to the CAN communication board, and finally sent to the controller under test.

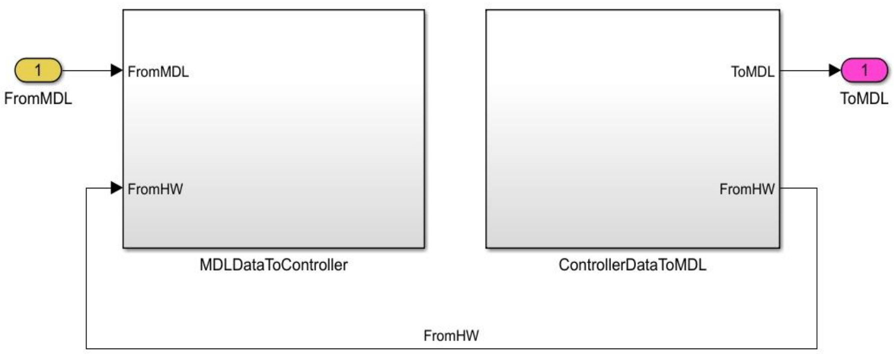


Fig. 3 - I/O model

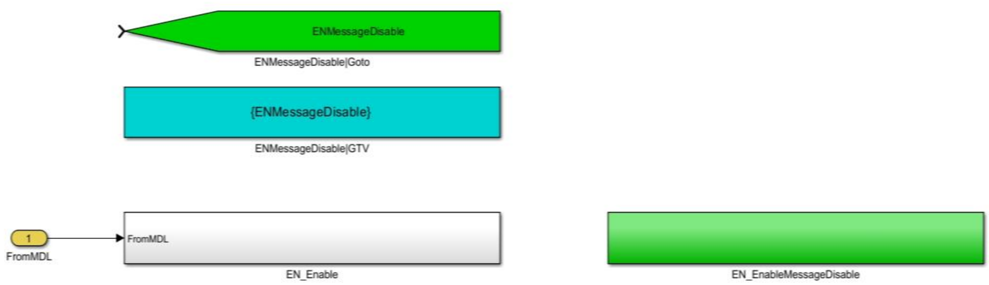


Fig. 4 - MDL Soft ECU Data to Bus

Test Bench Model: This model is used to simulate the virtual controlled object of the controller under test. The model is divided into three parts: the control cabinet, virtual controller, and test bench. The input to the model comes from signals transmitted by the IO model. The Maneuver module replaces the control cabinet and is primarily responsible for starting and stopping the test bench as well as regulating the motor speed. The virtual controller is not used in this model. The test bench model includes the motor model and the working components model. The specific setup is shown in Fig. 5.

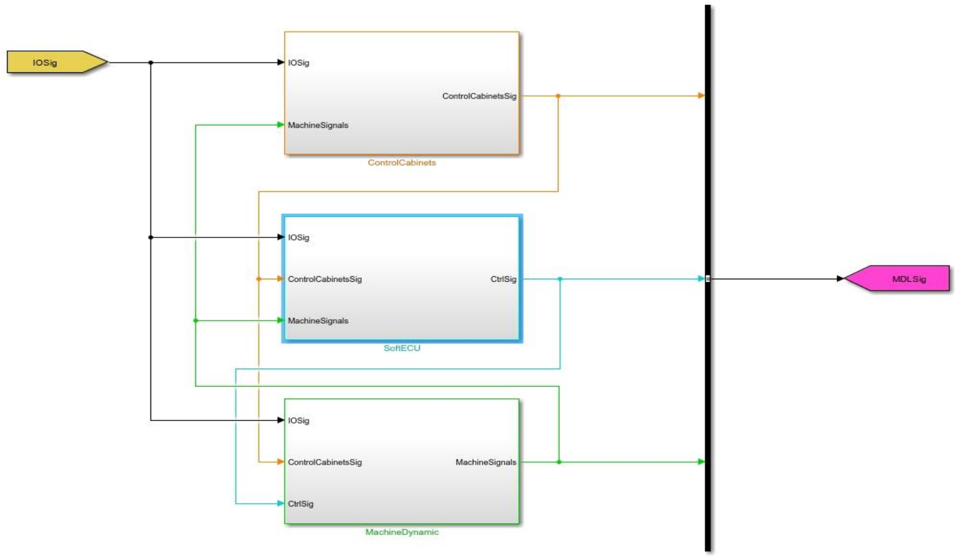


Fig. 5 - Test Bench Model

A 3D model of the grain cleaning test bench was built using SolidWorks software, based on the geometric and mass parameters of the working mechanism, as shown in Fig. 6 and Fig. 7. The model primarily includes components such as the shaker plate, vibrating screen, fan, and screw conveyor. The mass, moment of inertia, and connection parameters for each component are carefully set to ensure accuracy.

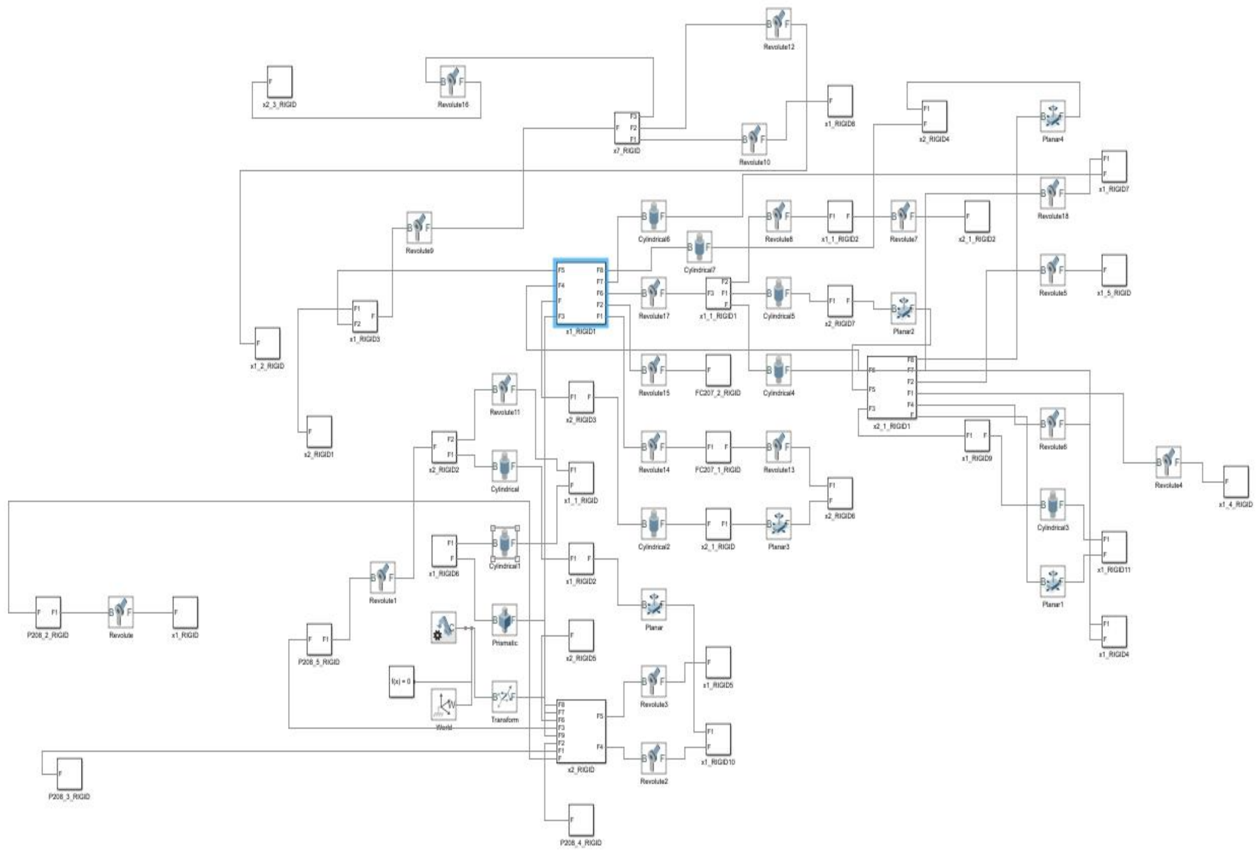


Fig 6 - Models in Simulink

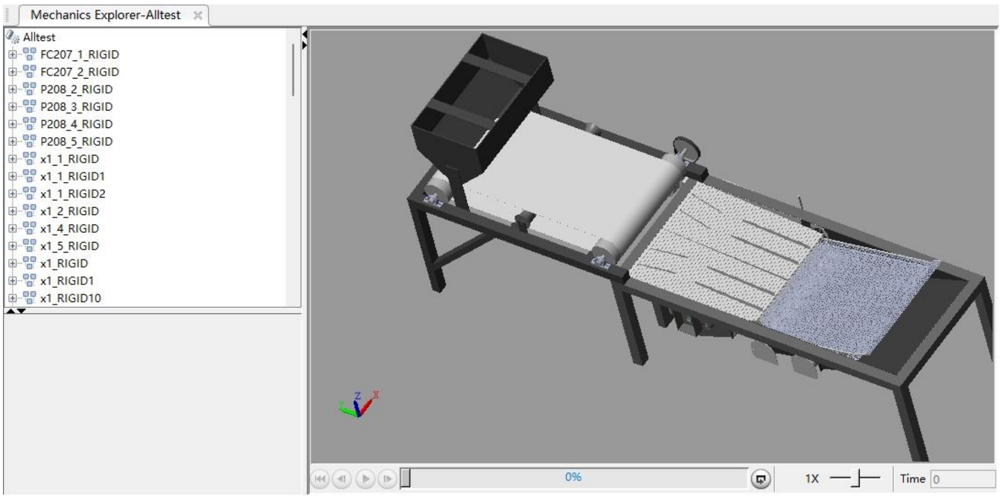


Fig. 7 - The mechanical operation diagram generated by Simscape

The TCS software control interface is shown in Fig. 8. The left side is configured for controlling the PDU and programmable power supply, enabling power cycling of the cabinet and controller as well as the corresponding voltage and current variations. The right side displays the operating parameters of each component, which need to be manually set. The basic control elements in the layout are connected to the relevant signals, reflecting the values detected by the sensors.

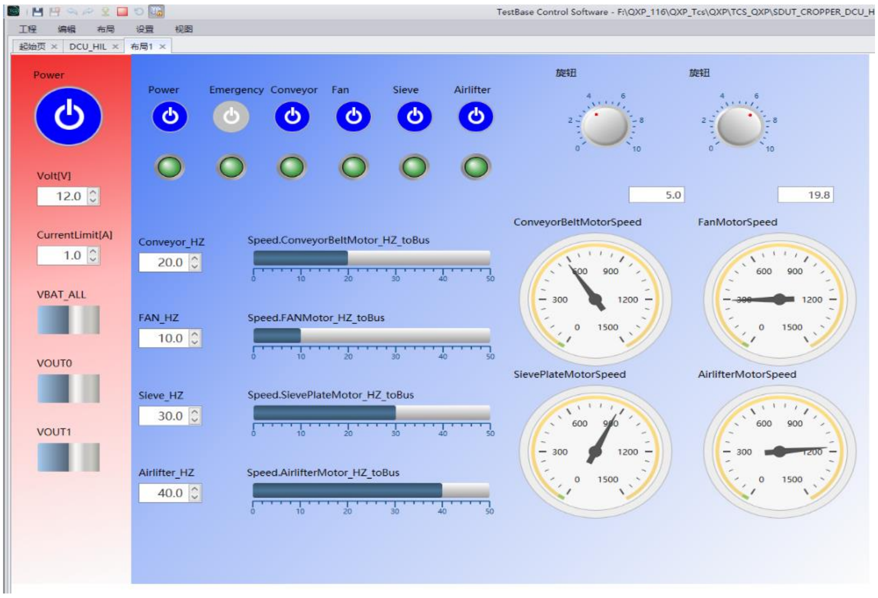


Fig. 8 - TCS Operator Interface

The VBA monitoring software is shown in Fig. 9. The cabinet is connected to the controller and successfully powered on. After running via TCS, the software reads the DBC file and displays multiple messages on the CAN bus. It intuitively shows whether the current components have started operating and the current operating frequency of the motor. The names assigned to these messages in the software provide a clearer view of the relationship between each message. This software effectively monitors whether CAN communication is running successfully.

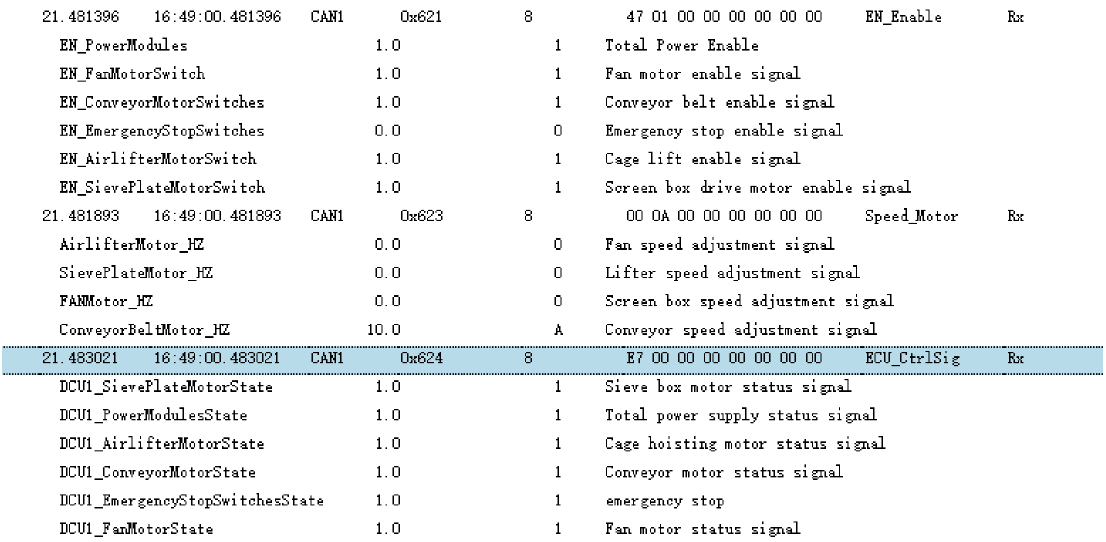


Fig. 9 - VBA Monitor Interface

Automatic Control Strategy: An automatic control strategy is built within the con-trolled object model and the TC377 controller, with predefined goals to be achieved. During simulation, the TC377 controller periodically uses data feedback from sensors to assess the current operating status. By determining the deviation between the current state and the target parameters, it sends corresponding signals to drive the controlled object further, continuing until the parameters fall within the set range.

RESULTS

Operational parameter tests are conducted on both the simulation platform and the grain cleaning test bench. Under the assumption of no load, motor speed adjustment and fish-scale sieve opening adjustment experiments are carried out. The actual adjustment process of the operational parameters is compared with the simulation adjustment process to verify the effectiveness of the controlled object model within the simulation platform. To ensure that the control processes on both the simulation platform and the grain cleaning test bench are identical, the adjustment time and steps for both should be consistent during the experiments.

(1) Open-loop control test procedure:

Actual Test: Operate the control panel on the frequency converter control cabinet to adjust the motor's operating frequency to 41 Hz within 10 seconds. After the motor speed reaches 1200 rpm, it will continue to run, with detection and recording conducted through the speed sensor installed on the motor's drive wheel.

The adjustment range of the fish-scale sieve screen piece angle α is from 15° to 40°, and the screen opening l ranges from 7 mm to 22 mm. The fish-scale sieve adjustment device measures and records every 5° adjustment. The data record of the fish-scale sieve screen piece angle variation is presented in Table 2.

Table 2

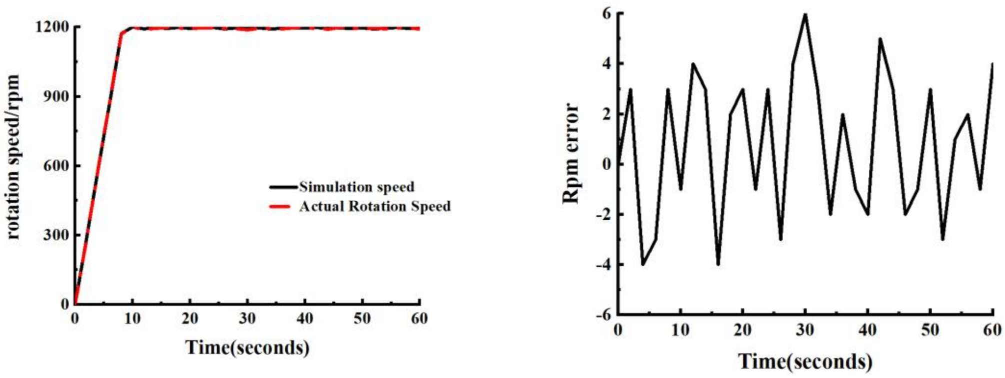
Fish-Scale Sieve Screen Piece Angle Variation

Angle of change α (°)	Fish Scale Sieve Opening l / mm	Emulate / mm	Practice / mm	Relative error / mm
15	7	7.17	7.2	-0.4167
20	10	9.56	9.6	-0.4167
25	13	11.94	11.9	0.3361
30	16	14.33	14.4	-0.4861
35	19	16.72	16.7	0.1198
40	22	19.11	19.1	0.0524

Simulation platform test: Input the same control signals as those on the test bench into the upper-level TCS control interface, complete the input of the corresponding parameters and the adjustment of control knobs, and record the data generated by the controlled object during operation.

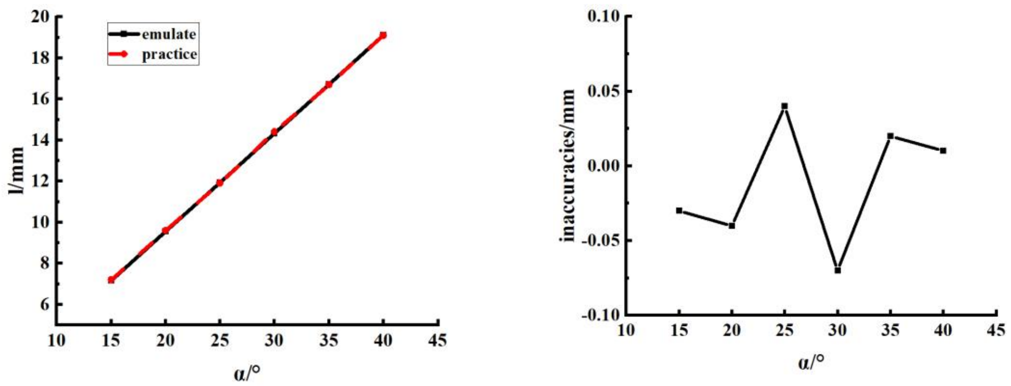
Comparison of the experimental results shown in Fig. 10 and Fig. 11 reveals that there is a discrepancy between the simulation results on the simulation platform and the actual test results of the grain cleaning machine. The main reason for this is the presence of numerous uncontrollable factors in the actual experiment, which cause deviations in the motor speed. In contrast, the simulation platform may experience voltage or current instability during transmission, leading to deviations in the simulated motor speed.

The actual measurement of the scalper screen opening contains errors due to manual measurement. The tool used was a standard vernier caliper with a precision of 0.1 mm. The mathematical expectation of the speed error is 0.8387 rpm, with a standard deviation of 2.75 rpm. The mathematical expectation of the speed error is positive, with the simulation results generally being 1 rpm higher than the actual measured results. Additionally, the motor speed does not remain completely stable at a specific value but exhibits some random fluctuations, which are caused by the instability in the actual measurements. The mathematical expectation for the fish-scale sieve is -0.0117 mm, with a standard deviation of 0.0380 mm. The measurement data shows some fluctuation, but the range of variation is small, which is within an acceptable range for the actual machine. Therefore, the controlled object model in the simulation platform can reasonably simulate the actual operating conditions of the grain cleaning test bench.



(**1**) Motor Speed Comparison (**2**) Velocity Error Comparison

Fig. 10 - Open Loop Test Comparison and Error



(**1**) Openness Comparison (**2**) Opening Error

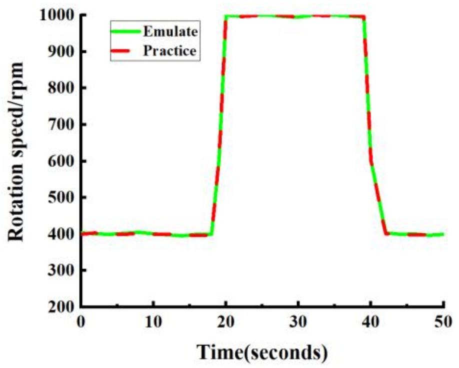
Fig. 11 - Fish Scale Sieve Opening Test Comparison

(2) Closed-loop control of the test process:

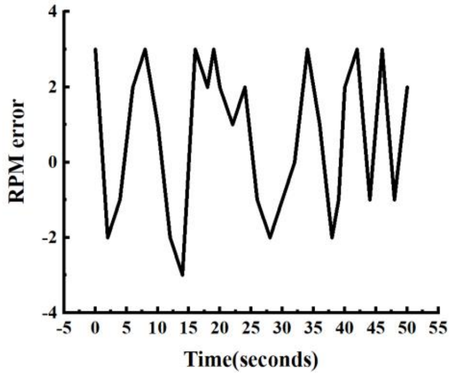
The TC377 development board, based on AutoSAR, is used as the controller. This controller is employed for both simulation and real-world experiments, with the results compared.

Actual test: Through the control panel on the frequency converter cabinet, the fan motor is stabilized to operate at around 400 rpm for a small amount of grain cleaning. After 20 seconds, the feeding rate is increased, and 20 seconds later, the initial feeding rate is restored. The experiment shows that the motor speed changes with the feeding rate. When the feeding rate suddenly increases, the controller receives the instruction for the change and sends a signal to increase the fan speed, thereby ensuring the normal operation of the cleaning process.

Simulation platform test: Design the same control signals as in the actual test. Adjust the input parameters in the initial state to stabilize the model at the corresponding speed. Then, increase the feeding rate by adjusting the control knob and restore the initial state after 20 seconds.



(**1**) Motor Speed Comparison



(**2**) Velocity Error Comparison

Fig. 12 - Closed Loop Test Comparison and Error

Due to deviations in the actual feeding weight and differences in bulk density, there is a slight error between the comparison tests. The experimental results are shown in Fig. 11. The mathematical expectation of the error during the speed adjustment process is 0.679 rpm. It can be observed that the simulation platform is capable of testing the controller and that the controller demonstrates strong control capability over the actual machine.

This paper takes the air-screen grain cleaning device, a common type of agricultural machinery, as the development object and applies semi-physical simulation technology to the grain cleaning device. By building a model on the semi-physical simulation platform, experimental results demonstrate that the simulation model can effectively replicate the actual operating conditions of the machine, with errors within an acceptable range. This provides a testing platform for the subsequent controller development, preventing potential damage to the grain cleaning device during the actual testing phase, and eliminating the need for multiple experiments, thus saving significant operational time.

CONCLUSIONS

(1) Due to the lengthy development process, cumbersome testing, and high development costs of the grain cleaning test bench, a hardware-in-the-loop simulation platform for grain cleaning control was designed. This platform is linked to the actual machine through the establishment of mathematical models for key components during operation. It provides the necessary hardware platform and corresponding upper-level control software for the development of the intelligent grain cleaning control system.

(2) Based on the practical influence of seasonal and site factors on the development of the grain cleaning device, a semi-physical simulation platform for the grain cleaning device control system was designed. This platform provides the hardware foundation and simulation test object for the development of the grain cleaning control system.

(3) The TC377 development board is used as the controller for both the actual machine and the controlled object on the simulation platform. A comparative experiment between simulation and real-world testing was conducted. The open-loop test verified the validity of the model and the successful transmission of signals, while the closed-loop test demonstrated the effectiveness of the controller algorithm and the actual control performance. This confirms that the simulation platform can significantly shorten the development cycle and reduce development costs.

(4) Hardware-in-the-loop simulation technology has achieved initial success in the field of grain cleaning. However, at present, its application objects are relatively simple, and there may be some errors in the development process. It is hoped that, in future development, improvements can be made to expand the applicability of this technology to various types of cleaning equipment.

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REFERENCES

[1] Cheng, K., Wang, Q., Yang, D., Dai, Q., Wang, M. (2022). Digital-Twins-Driven Semi-Physical Simulation for Testing and Evaluation of Industrial Software in a Smart Manufacturing System. *Machines*. *10,* 388, Guangzhou/China.

[2] Jiang, Q., Wang, R. (2022). Simulation and Experiment of an Intelligent Control Model for the Cleaning of a Rice-wheat Combine Harvester (稻麦联合收获机清选智能调控模型仿真与试验). *Journal of System Simulation. 34(11)*, 2485-2496. Anhui/China.

[3] Kaven, L., Frehn, A., Basler, M., Jassmann, U., Röttgers, H., Konrad, T., Abel, D., Monti, A. (2022). Impact of Multi-Physics HiL Test Benches on Wind Turbine Certification. *Energies. 15*, 1336, Germany.

[4] Li, Y., Zhang, X., Li, Y., Lv, L., Shi, M. (2024). Modeling and control methods of a multi-parameter system for threshing and cleaning in grain combine harvesters. *Computers and Electronics in Agriculture. 225,* 109251, Changzhou/China.

[5] Lin, Z., Wang, W., Li, Y., Zhang, X., Zhang, T., Wang, H., Wu, X., Huang, F. (2023). Design and Experimental Study of a Novel Semi-Physical Unmanned-Aerial-Vehicle Simulation Platform for Optical-Flow-Based Navigation. *Aerospace. 10(2)*:18, Fuzhou/China.

[6] Liu, L., Yu, W., Yu, Z. (2018). Active Fault-tolerant Control Design for a Submarine Semi-physical Simulation System. *International Journal of Control, Automation and Systems. 16*, 2363–2372, Xiamen/China.

[7] Ning, X., Jin, C., Yin, X., Liu, P., Li, Q. (2018). Research status and development trend of air-and-screen cleaning device for cereal combine harvesters (谷物联合收割机风筛式清选装置研究现状与发展趋势). *Journal of Chinese agricultural mechanization. 39*, 5-10, Zibo/China.

[8] Qu, Z., Lu, Q., Shao, H., Le, J., Wang, X., Zhao, H., Wang, W. (2024). Design and Test of a Grain Cleaning Loss Monitoring Device for Wheat Combine Harvester. *Agriculture, 14(5)*, 671, Zhengzhou/China.

[9] Raikwar, S., Wani, L., Kumar, S. (2019). Hardware-in-the-Loop test automation of embedded systems for agricultural tractors. *Measurement, Volume 133*, Pages 271-280, German.

[10] Wang, L., Liu, W., Li, Y., Yu, K. (2022). Research on Double-layer Jitter Plates with Holes in Large-feeding Mass Cleaning System of Maize Grain Harvester (大喂入量玉米籽粒收获机清选系统双层筛孔抖动板研究). *Transactions of the Chinese Society of Agricultural Machinery. 53.* 92-102, Heilongjiang/China.

[11] Wang, X., Zhao, H., Le, J., Liu, Q. (2024). Investigation on Structural Design and Performance Analysis of the Grain Loss Monitoring System for Wheat Combine Harvester. *Journal of Agricultural Engineering. 20(5)*, 24-35, Zhengzhou/China.

[12] Wu, J., Tang, Q., Mu, S., Yang, X., Jiang, L., Hu, Z. (2023). Design and Test of Self-Leveling System for Cleaning Screen of Grain Combine Harvester. *Agriculture. 13*, 377, Nanjing/China.

[13] Wu, Z., Xie, B., Chi, R., Ren, Z., Du, Yu., Li, Z. (2019). Driving torque management model for electric tractor in field cruise condition (电动拖拉机田间巡航作业驱动转矩管理模型). *Transactions of the Chinese Society of Agricultural Engineering, 35(4)*: 88－98. Beijing/China.

[14] Xie, B., Wang, S., Wu, X., Wen, C., Zhang, S., Zhao, X. (2022). Design and hardware-in-the-loop test of a coupled drive system for electric tractor. *Biosystems Engineering. 216*, 165-185, Beijing/China.

[15] Xu, J., Guo, Y., Liu, F., Huang, H. (2024). Development and Experiment of Semi-Physical Simulation Platform for Space Manipulator. *Sensors. 24*, 4354, Qinhuangdao/China.

[16] Zhou, J., Shen, L., Zhang, T. (2016). Modeling and HIL Simulation of Flight Conditions Simulating Control System for the Altitude Test Facility. *International Journal of Turbo & Jet-Engines. 33*, 319-328, Nanjing/China.

[17] Zhu, X., Chi, R., Du, Y., Ban, C., Ma, Y., Huang, X. (2022). Design of Hardware in Loop Simulation Platform for Intelligent Control System of Corn Kernel Harvester (玉米收获机低损脱粒智能控制系统半实物仿真平台设计). *Transactions of the Chinese Society of Agricultural Machinery, 53*, 114-122, Beijing/China.