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Principles and Design of the Automatic Strapping Equipment for Solid Propellants

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Abstract

To ensure the positional accuracy of the product after assembly, grouped rod-like solid propellants must be pre-strapped with cotton thread. The current manual operation involves operators being exposed to hazardous and explosive materials over long periods, suffers from limited efficiency, and presents high operational difficulty. To address these issues, an automatic strapping equipment for solid propellants was designed. This equipment employs a PLC as the control core and utilizes hardware components such as servo motors, cams, and cylinders to achieve an automatic strapping speed of 4 minutes per bundle. This significantly improves strapping efficiency and consistency while reducing operational difficulty.

Keywords

Solid Propellant, Strapping Equipment, Automatic Production

1. Introduction

Solid propellants can rapidly release large amounts of energy through chemical reactions and are widely used as core power sources in aerospace, aviation, and military fields. To ensure range, accuracy, and response speed, the grouped rod-like solid propellant inside the product must maintain precise and stable relative positioning. A conventional approach involves manually strapping the grouped rod-like solid propellant with cotton thread prior to product assembly. However, this manual strapping method has long posed challenges, including:

Safety Risks: Operators must handle hazardous explosive materials for extended periods, creating potential safety hazards.

Limited Efficiency: The strapping process is time-consuming and labor-intensive.

Inconsistent Quality: The tightness of the cotton thread arrangement and the robustness of the knots are heavily influenced by the operator's skill level.

As production safety requirements become increasingly stringent and capacity demands continue to grow, this traditional production method is increasingly constraining industry development.

In the fields of agriculture, packaging, and metallurgy, a significant number of semi-automated or fully automated strapping devices have been developed and applied [1]-[6]. These systems have established widely applicable strapping methods, such as: Rotational winding with axial rotation [7], Helical winding with knotting [8], Twisting-based knotting [9], Knotting mechanisms [10] [11]. The core principle of these methods involves using strapping material to constrain the bundled material and applying compressive forces to induce controlled deformation in the material. This deformation compensates for the excess length between the strapping mechanism and the material after knotting, ensuring secure strapping. Alternatively, high-elasticity strapping materials are employed, where the stretching deformation during winding compensates for the excess length.

However, solid propellants are viscoelastic materials, and under significant constraint forces, they undergo creep deformation and permanent structural changes [12] [13], which negatively impact product performance. Additionally, the cotton thread used for strapping has low breaking strength and limited elongation at break, making it ineffective to compensate for excess length through elasticity. As a result, industrial-grade automated strapping equipment or mechanisms cannot be directly applied to solid propellant strapping.

This paper presents the principles and design of an automated strapping equipment that utilizes specialized industrial thread to wind and knot grouped rod-like solid propellant. The equipment introduces physical constraints during the knotting process to prevent the knot from loosening, eliminating the need to induce deformation in the material to compensate for excess thread length between the strapping mechanism and the material. Additionally, it achieves precise control of the knot's position, fulfilling the automated strapping requirements for solid propellants in aerospace applications.

2. Strapping Requirements for Solid Propellant

The strapping requirements for solid propellant stipulate that seven rod-like solid propellant rods per product unit must be positioned according to predefined relative positions during assembly. Subsequently, cotton thread is used to strap the rods at three specific locations: two locations 20 mm from each end, and the middle of the assembly (as shown in **Figure 1**). At each strapping location, the cotton thread is wrapped around the rods with a 5 mm width. Additionally, the knot must be positioned outside the area where the solid propellant and cotton thread are in contact to avoid interference. The diameter of the cotton thread used is 0.3 mm.

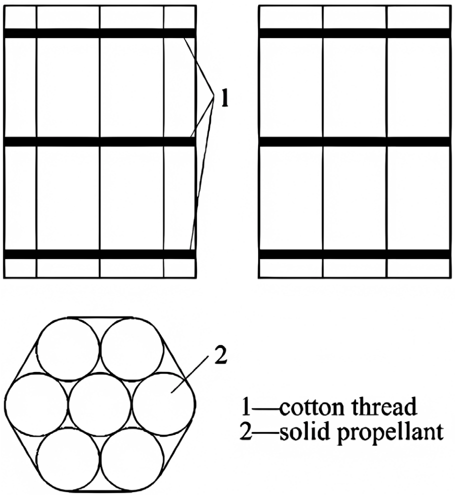

Figure 1. Diagram of solid propellant strapping requirements.

3. Overall Plan

3.1. System Overview

The equipment shown in **Figure 2** is designed with integrated mechanisms, including a material clamping and feeding unit, a cotton clamping and cutting unit, a winding unit, a cotton blocking unit, a pinning unit, a threading unit, and a cotton control unit. The system's main technical parameters are as follows: an overall size of 2000 mm × 1150 mm × 1900 mm, a total power consumption of 2 kW, a supply voltage of 220 V AC, a supply air pressure range of 0.5 - 0.7 MPa, and a production efficiency of 120 bundles per day (calculated based on an 8-hour daily operation). The entire strapping process of solid propellants is fully automated by the equipment, requiring operators to only perform material loading and unloading tasks, thereby achieving a high level of automation.

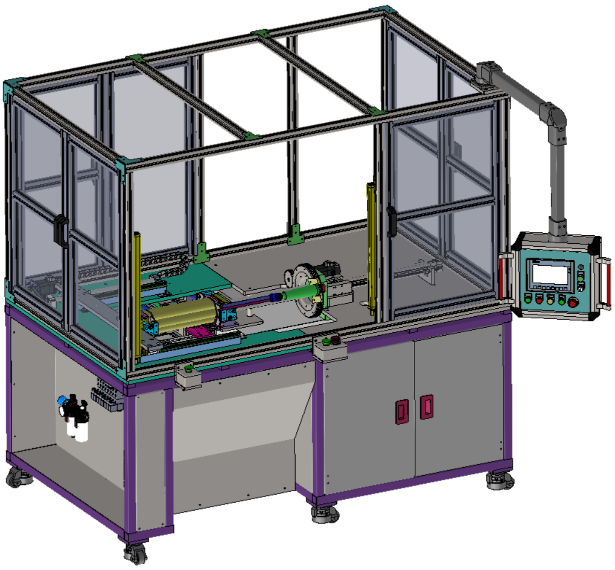

Figure 2. The automated solid propellant strapping equipment.

As shown in **Figure 3**, after manual loading, the material clamping and feeding mechanism clamps the grouped solid propellants together and moves them to the winding position. Through the coordinated movement of the material clamping and feeding mechanism and the winding mechanism, the solid propellants are wound. The cutting mechanism then cuts the cotton thread, followed by the completion of tying knots using the line blocking mechanism, pinning mechanism, threading mechanism, and line control mechanism. This completes the first binding. The process repeats until three bindings are finished. Finally, the material clamping and feeding mechanism moves the solid propellants to the loading and unloading positions for manual unloading.

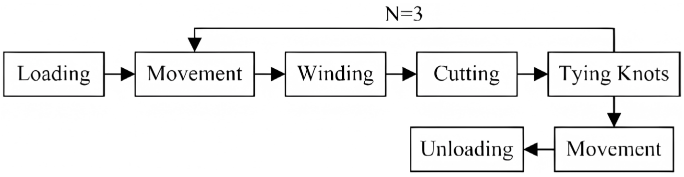

Figure 3. The automatic strapping process for solid propellants.

3.2. Control System

PLC (Programmable Logic Controller) is widely used in various industrial equipment due to its ability to operate stably in harsh industrial environments, its rich Input/Output (I/O) interfaces for convenient integration with industrial sensors and actuators, and its support for multiple communication protocols. As shown in **Figure 4**, the control system topology of the solid propellant automatic strapping

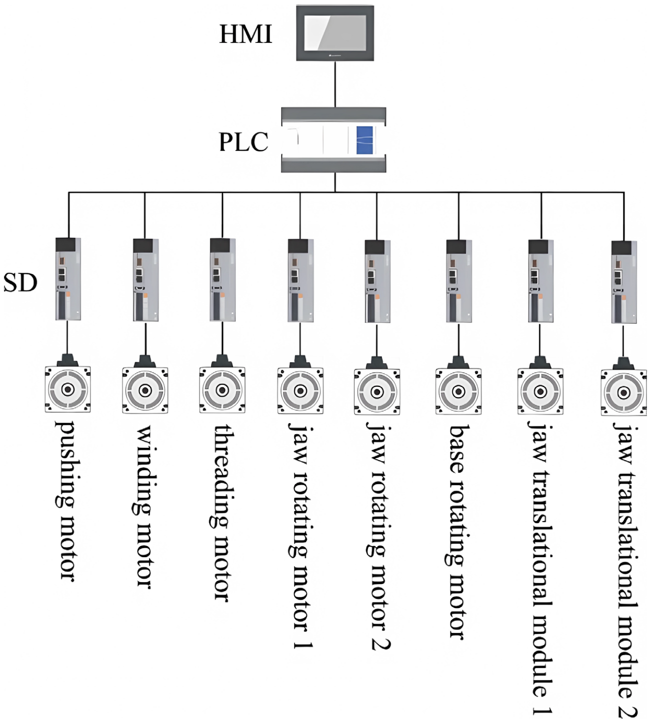

Figure 4. System topology diagram

equipment is designed with a Siemens PLC as the core controller. Operators use a touchscreen HMI (Human-Machine Interface) to start or stop the equipment. The PLC receives signals such as “material in-position” and “compartment door closed” from sensors, and under the condition that no alarm signals are triggered by any mechanisms, it sequentially controls the operation of each mechanism according to the predefined workflow to complete the automatic strapping of solid propellants.

4. Hardware Design

Due to the physical constraints of solid propellants and the cotton thread used for strapping, the automatic strapping equipment must be ingeniously designed to mimic the intricate and delicate movements of human hands while maintaining efficiency and stability. As shown in **Figure 5**, the main mechanisms of the automatic strapping equipment include the cotton control mechanism, which is positioned beneath other structural components. This mechanism is secured to the base structural components of the equipment to maintain a fixed position. Other mechanisms are installed on the equipment’s platform and fastened with bolts.

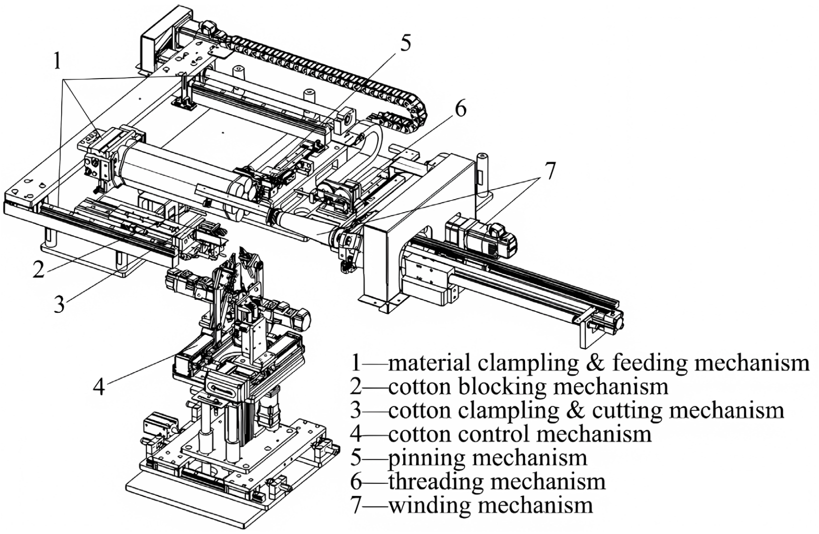

Figure 5. Main mechanisms of the automatic strapping equipment for solid propellant.

4.1. Design of the Material Clamping & Feeding Mechanism

Figure 6 illustrates the material clamping & feeding mechanism of the equipment. The mechanism includes a gripping base, spring-loaded gripper blades, quick-change tooling, finger cylinders, a pushing motor, linear guides, and follower cylinders. The clamping process operates as follows: First, adjust the position of the spring-loaded gripper blades according to the diameter specifications of the solid propellant and install the corresponding quick-change tooling on both sides of the finger cylinders. Then, place seven solid propellants onto the gripping base. At this stage, the two lower solid propellants are constrained by the base and the spring-loaded blades to maintain their correct positions, while the remaining five are held in place by gravity and the lower propellants. Finally, the finger cylinders retract, driving the quick-change tooling to clamp the sides of the grouped solid propellants. The resulting constraints on the grouped propellants are illustrated in **Figure 7**.

The feeding mechanism operates as follows: When the pushing motor rotates forward, the clamping & feeding mechanism drives the solid propellant toward the winding mechanism. At this point, the follower cylinder installed on the side of the winding mechanism retracts under applied force. When the pushing motor reverses, the clamping & feeding mechanism moves the solid propellant away from the winding mechanism. After the follower cylinder's constraint is released, it extends outward, ensuring the solid propellant remains securely constrained at both ends and moves with the clamping & feeding mechanism away from the winding mechanism.

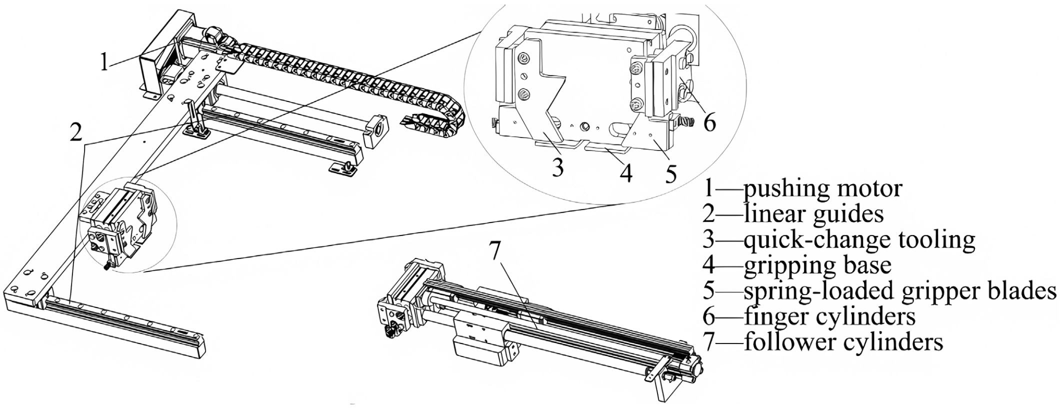

Figure 6. Structure of the material clamping & feeding mechanism.

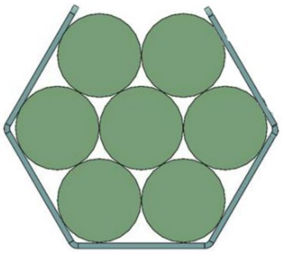

Figure 7. Schematic diagram of bundled solid propellant held in place.

4.2. Design of the Cotton Clamping & Cutting Mechanism

Figure 8 illustrates the cotton clamping & cutting mechanism of the equipment, which includes a telescoping cylinder, a clamping cylinder, a cutting cylinder, and a blade. The operational sequence is as follows: Before the operation begins, the clamping cylinder grips the cotton thread end of the spool. Prior to winding, the telescoping cylinder extends, the clamping cylinder opens, and the cotton thread end is transferred to the cotton control mechanism at the base of the equipment, after which the telescoping cylinder retracts. After winding, the telescoping cylinder extends again, and the clamping cylinder grips the cotton thread at one end of the spool. Once the cotton control mechanism's claw securely holds the cotton thread, the cutting cylinder extends, driving the blade to cut the thread between the clamping cylinder and the cotton control mechanism's claw. Subsequently, the cutting cylinder retracts, and the telescoping cylinder retracts, returning the mechanism to its initial position. At this point, the two ends of the cut cotton thread are gripped by the two claws of the cotton control mechanism, while the spool's cotton thread end remains clamped by the clamping cylinder.

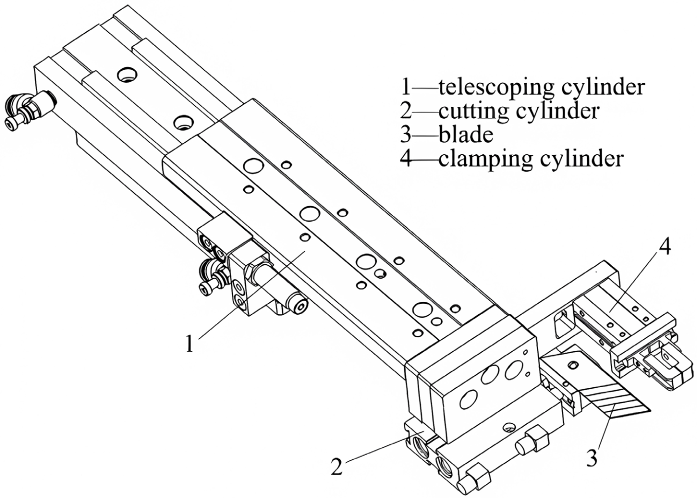

Figure 8. Structure of the cotton clamping & cutting mechanism.

4.3. Design of the Winding Mechanism

Figure 9 illustrates the winding mechanism of the equipment, which includes a winding motor, winding gear set, tension rod, spool holder, and protective cover. The winding operation works as follows: The spool is installed on the spool holder, and the cotton thread is passed through the spring-loaded tension clamp on the

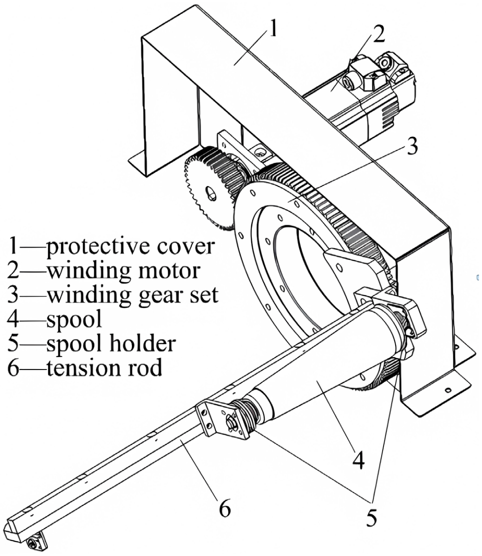

Figure 9. Structure of the winding mechanism.

tension rod, ultimately being clamped by the clamping cylinder of the cotton clamping and cutting mechanism. After the cotton control mechanism's claw grasps the cotton thread from the clamping cylinder, the winding motor rotates forward, driving the winding gear set to move the tension rod and spool in a circular motion around the solid propellant. By coordinating the speed of the winding motor with that of the feed motor, precise alignment of the cotton thread is achieved.

4.4. Design of the Cotton Blocking Mechanism

Figure 10 illustrates the cotton blocking mechanism of the equipment, which includes cotton cylinder 1, cotton cylinder 2, cotton rod 1, and cotton rod 2. The function of the cotton blocking mechanism is as follows: When the winding mechanism reaches the last turn, cotton cylinder 1 and cotton cylinder 2 extend, moving cotton rod 1 and cotton rod 2 to the center between the winding mechanism and the solid propellant. This action increases the length of the cotton thread end after winding, facilitating the subsequent knotting process.

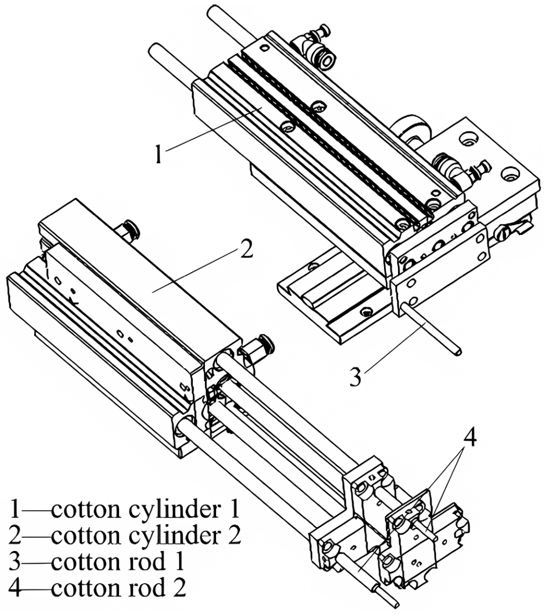

Figure 10. Structure of the cotton blocking mechanism.

4.5. Design of the Pinning Mechanism

Figure 11 illustrates the pinning mechanism of the equipment, which includes an overall telescopic cylinder, linear guide, needle punch, needle telescopic cylinder, needle lifting cylinder, threading assist cylinder, and threading stopper. The mechanism serves two primary functions:

Knotting Support: When the two ends of the cotton thread are gripped by the cotton control mechanism's claws and prepared for knotting, the overall telescopic cylinder extends, moving the entire pinning mechanism along the linear guide. Subsequently, the needle telescopic cylinder and needle lifting cylinder extend, causing the needle punch to press down on the cotton thread between the two lowermost solid propellant rods. This action prevents the thread from loosening during knotting and ensures the knot is precisely constrained at the needle punch location when the thread ends are tightened.

Threading Assistance: Before threading, the threading assist cylinder extends, driving the threading stopper outward. This motion, combined with the rotational movement of the line control mechanism, creates a diamond-shaped area in the cotton thread, facilitating the subsequent threading operation by the threading mechanism.

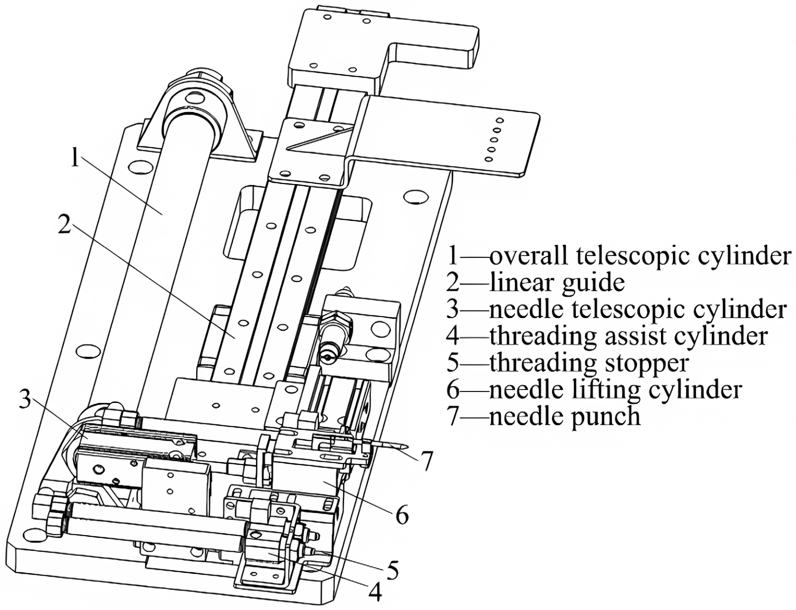

Figure 11. Structure of the pinning mechanism.

4.6. Design of the Threading Mechanism

Figure 12 illustrates the threading mechanism of the equipment, which includes an overall telescopic cylinder, linear guide, threading motor, threading rod, and threading rod telescopic cylinder. The threading mechanism operates as follows: Under the coordination of the pinning mechanism and the cotton control mechanism, the cotton thread forms a diamond-shaped threading area. The overall telescopic cylinder extends, moving the entire threading mechanism along the linear guide. The threading motor reverses direction, while the threading rod remains horizontal and rotates clockwise towards the cotton control mechanism's claws. The threading rod telescopic cylinder retracts, closing the gripping claws at the end of the threading rod to retrieve the cotton thread from the cotton control mechanism's claws. Then, the threading motor rotates forward, keeping the threading rod horizontal and rotating counterclockwise through the upper diamond-shaped threading area. After the cotton control mechanism's claws grip the cotton thread, the threading rod telescopic cylinder extends again, opening the gripping claws at the end of the threading rod to pass the cotton thread to the line control mechanism's claws. Finally, the threading motor reverses direction, returning the threading rod to its initial position. The overall telescopic cylinder retracts, and the threading mechanism returns to its initial position along the linear guide.

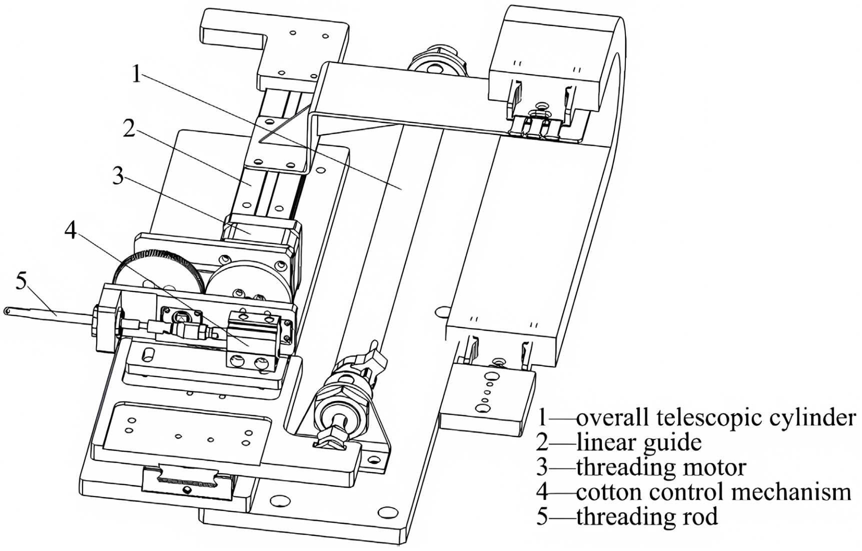

Figure 12. Structure of the threading mechanism.

4.7. Design of the Cotton Control Mechanism

Figure 13 illustrates the cotton control mechanism of the equipment, which includes jaw 1, jaw 2, jaw cylinder 1, jaw cylinder 2, jaw lifting cylinder 1, jaw lifting cylinder 2, jaw rotating motor 1, jaw rotating motor 2, jaw translational module 1, jaw translational module 2, base telescopic cylinder, base rotating motor, and base translational cylinder. The action flow of the cotton control mechanism is as follows:

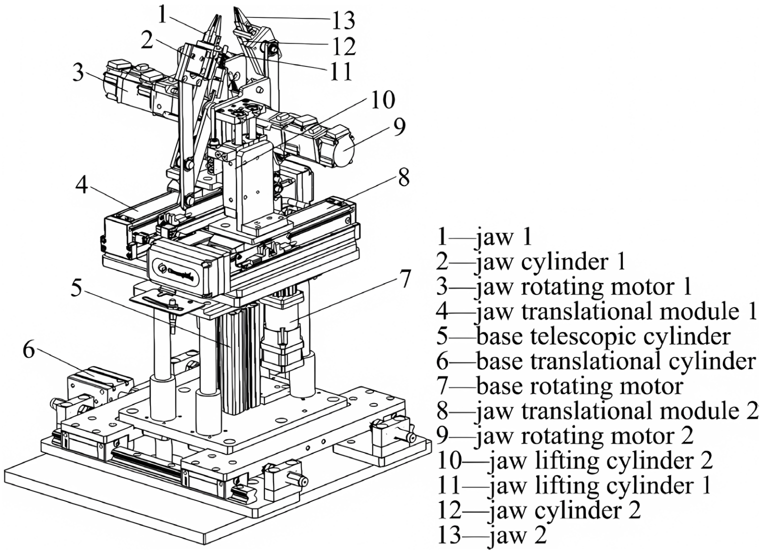

Figure 13. Structure of the cotton control mechanism.

Before threading, jaw lifting cylinder 1 extends, jaw rotating motor 1 rotates forward, jaw translational module 1 moves outward, and base telescopic cylinder extends. Jaw cylinder 1 closes, gripping the end of the cotton thread at the thread cutting cylinder of the cotton cutting mechanism, then returns to its initial position. The base rotating motor rotates the entire cotton control mechanism 180˚, initiating the threading process.

After threading, jaw lifting cylinder 2 extends, jaw rotating motor 2 rotates forward, jaw translational module 2 moves outward, and base telescopic cylinder extends. Jaw cylinder 2 closes, gripping the cotton thread at the thread cutting cylinder of the cotton cutting mechanism. After the blade of the cotton cutting mechanism cuts the cotton thread, jaw cylinder 2 returns to its initial position, with both ends of the cotton thread held by jaw 1 and jaw 2.

When the pinning mechanism's threading stopper extends, the base rotating motor rotates the cotton control mechanism 180˚, forming a diamond-shaped threading area. After the threading rod of the threading mechanism grips the cotton thread at jaw 1, jaw 1 releases.

Once the threading rod passes through the diamond-shaped area, the base translational cylinder retracts, jaw lifting cylinder 1 extends, jaw translational module 1 moves outward, and base telescopic cylinder extends. Jaw cylinder 1 closes, gripping the cotton thread at the threading rod, then returns to its initial position.

Finally, jaw lifting cylinder 1 and 2 extend, jaw rotating motors 1 and 2 rotate forward, and jaw translational modules 1 and 2 move outward. The jaws pull the thread ends sideways to form a knot at the needle punch location. After the needle telescopic cylinder retracts the needle, the motors continue rotating forward to position the final knot between the two lowest solid propellant rods. Jaw cylinders 1 and 2 open, and the line control mechanism returns to its initial position.

5. Electrical Control System Design

The controller employs the Siemens S1200 system, which offers high reliability, low power consumption, strong anti-interference capabilities, and convenient maintenance for future equipment servicing. After the equipment power is turned on, the PLC control system initializes, including the initialization of relevant variables, interrupt settings, and clearing alarm messages. Once the system initialization is complete, it waits for the operator to select the corresponding program based on the solid propellant specifications and return to the original position. After startup, the primary operational sequence is illustrated in Figure 14.

6. Practical Application

The entire system uses a PLC as the control core. Through hardware design and motion control workflows, the system achieves automatic bundling of solid propellants. The physical equipment is shown in Figure 15. After deployment, the system operated smoothly. Based on recording the time taken by a single operator

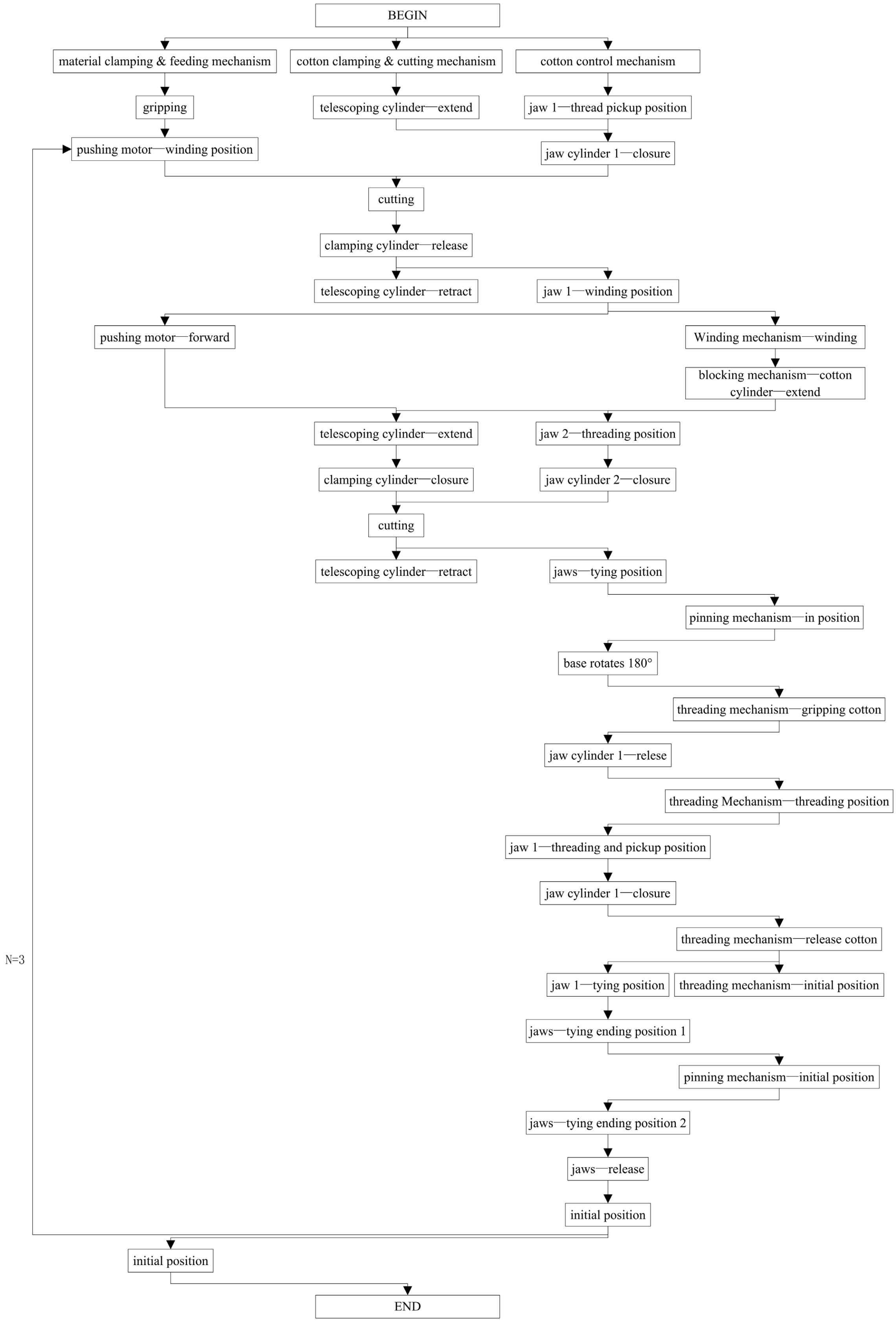

Figure 14. Primary operational sequence.

Figure 15. Physical equipment for automated strapping of solid propellant.

to complete the bundling of 95 units of product, the calculated average time per bundle was 4 minutes. In comparison, manual operation takes 8-12 minutes per bundle, resulting in a production efficiency increase of over 100%.

Through practical verification, the solid propellant automatic bundling equipment is suitable for bundling solid propellant grains with a single diameter of Φ20 - 50 mm and a length of 100 - 400 mm. **Figure 16** shows plastic rods of the same specifications bundled using the equipment. The winding is tightly secured with small and strong knots, the three bundling winding patterns and knot positions are consistent, the winding width error is within ±0.3 mm, the winding position error is within ±0.1 mm, and the knot position error is within ±1 mm. This significantly improves the uniformity and consistency of product quality.

Figure 16. Bundled solid propellant plastic rods of the same specifications.

7. Conclusion

In the context of frequent production safety accidents in recent years and the growing demand for increased production capacity driven by industry development, reducing safety risks, improving production efficiency, and ensuring consistent product quality have become critical challenges for enterprises. The automatic strapping system for solid propellants can replace manual operations such as winding and knot-tying. During loading and unloading, workers can minimize direct contact with solid propellants by wearing protective gear like gloves and masks, effectively reducing operator exposure and operational risk. This system simultaneously enhances production efficiency and quality, offering valuable insights for the automation of similar production scenarios.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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