

# Design of automatic packaging tape reeling machine based on equal area model

Chen Jin

HD Ningbo School, Ningbo, 315000, China;

**Abstract.** An automated packaging tape reeling machine was designed and implemented, simplifying the traditional three-step process of "measuring length, cutting, and reeling" to a two-step process of "reeling and cutting." A relationship between reel length and number of turns was established based on an equal-area model, and Hall sensors were used to count the number of turns. Experiments confirmed that the packaging error was 6% at a target length of 400 mm. Compared with traditional processes, the automated reeling machine reduces time, eliminates human error, and mitigates safety hazards. The research identified rounding up of the number of revolutions as a primary error factor and proposed designing product specifications based on integer revolutions or introducing half-turn detection to reduce errors and lower costs. The prototype developed by the research institute provides a feasible technical route for automated packaging of packaging tape.

**Keywords:** Packaging engineering; packaging tape reel; Hall effect sensor; equal area model.

## 1. Introduction

Robotics is undergoing a major transformation. Leveraging the rapid development of related industries such as artificial intelligence, machine learning, and sensors, traditional single-purpose robots have evolved into highly adaptive intelligent technologies. Today, robots are able to perform complex tasks with greater autonomy and efficiency. Furthermore, the growing demand for automation across various industries has accelerated this transformation, resulting in increased productivity, reduced costs, and enhanced adaptability of robots in unstructured environments[1][2]. On the other hand, packaging engineering remains a labor-intensive industry, with a large number of workers employed in factories. With the aging global population, labor will become a scarce resource in the future. Therefore, achieving automation in packaging engineering has become a pressing issue for small and medium-sized enterprises. The rise of Industry 4.0 and smart manufacturing has further strengthened the role of robotics in industrial settings. Companies are increasingly integrating robotic solutions to optimize production processes, alleviate labor shortages, and increase operational flexibility in a rapidly evolving global market. Beyond traditional manufacturing, industrial robots are expanding into sectors such as healthcare, logistics, and agriculture, where automation is bringing transformative benefits [3-7]. While early systems, such as the Unimate robot introduced in the 1960s, revolutionized the automotive industry with tasks such as spot welding[8], their rigidity limited their broader applicability. In the decades that followed, driven by artificial intelligence and machine learning, robots underwent a paradigm shift, becoming dynamic collaborators capable of real-time optimization through reinforcement learning and perception through technologies such as laser imaging detection and ranging (LiDAR) and computer vision[9][10]. Driven by initiatives such as Germany's Industry 4.0 initiative and China's Made-in-China 2025 strategy, the global annual installation of robots has surged, exceeding 500,000 units per year since 2020 [11][12].

With the rapid development of the packaging industry, the automated design of packaging production lines has become a key technical means to improve production efficiency, reduce costs, and ensure product quality. Automation refers to the use of control systems to handle different processes and items of machinery so as to replace manual labor. Today, more and more companies are turning to automation. The implementation of advanced automatic control systems based on industrial controllers makes it possible to effectively execute major processing systems in a programmable manner. Hnin Yu Lwin et al. proposed a "modular + distributed I/O" packaging machine control framework with a programmable logic controller (PLC) as the core. Through the

ladder diagram sequential function chart (SFC), the three stations of boxing, sealing, and labeling are synchronized, the changeover time is shortened from 45 minutes to 9 minutes, and the throughput reaches 120 packages per minute[13]. Verma used a low-cost LDR sensor on a small, simple conveyor belt to automatically package small wooden blocks into small paper boxes[14]. Compared to traditional manual systems, this system shortens product packaging time and improves product packaging rates.

As can be seen from the above research, there are two main approaches to automation design in the field of robotics and packaging engineering: one is to optimize the time consumption of a single workstation; the other is to improve production efficiency by reducing the number of workstations and implementing multi-workstation parallel production.

In the field of packaging tape packaging, the current production process first measures the target packaging length, then cuts the desired length, and finally rolls up the cut packaging tape to complete the packaging. However, the current process has the following problems:

- ① Manual length measurement is inefficient and can lead to measurement errors due to fatigue;
- ② The cutting tool used to cut the packaging tape can cause worker injuries.

This article presents the implementation of an automated packaging-tape reeling machine. Our research aims to build an automated winding system. A DC motor drives the winding spindle, while an encoder measures the tape length from the spindle speed, and a sensor determines the length of the packaging tape based on the main shaft's rotational speed. Through automated design, the original three-step process of "measuring, cutting, and rolling packaging tape" has been optimized to two steps: "rolling packaging tape and cutting." This automated system reduces labor costs, shortens production time, and improves product packaging quality. The following chapter provides an introduction; Chapter 2 introduces the basic theory, including the mathematical model of packaging tape dispensing, the operating principles of sensors, and the structural components of the automated packaging machine; Chapter 3 describes experiments that verify the mathematical model and measure the efficiency of the automated dispensing machine; and Chapter 4 provides a discussion and conclusion.

## 2. Methods

The original three steps of "measuring length - cutting - rolling packaging tape" have been optimized into two steps of "rolling packaging tape - cutting". The core of the optimization is to calculate the length of the packaging tape. During the packaging taping process, the rotation radius increases uniformly with the increase of the rotation angle, which is mathematically called an Archimedean spiral. The precise calculation of the arc length of the spiral is relatively complicated [15]. This paper uses the equal area model to calculate the length of the packaging tape.

The basic assumptions of the equal area model are:

- (1) The thickness  $h$  of the roll is constant and incompressible;
- (2) During the winding process, each layer fits tightly without sliding and gaps;
- (3) The lateral area of the roll after unfolding is equal to the lateral area of the annular area between the outer surface of the core and the outermost layer.

## 3. Packaging tape length calculation model

The geometric parameters of the packaging tape are shown in Figure 1, where  $r$  is the inner circle radius and  $R$  is the outer circle radius.  $L$  is the total length of the packaging tape in the  $l$  direction and  $h$  is the thickness of a layer of packaging tape. The number of rolls  $n$  can be expressed as  $n = (R - r)/h$ .

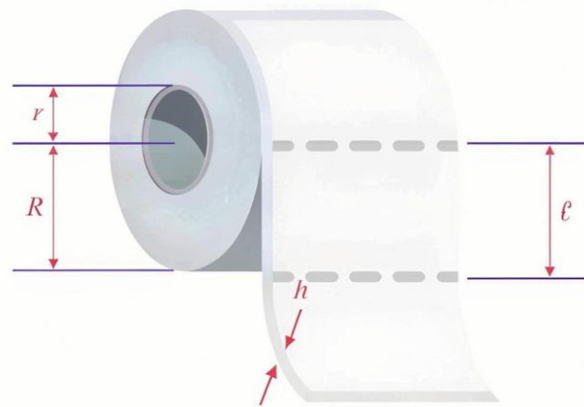


Figure 1 Geometric parameters of the packaging tape

The equal-area model assumes that the lateral area  $A$  of the unrolled packaging tape is equal before and after it is unrolled. As shown in Figure 2, the unrolled side of the packaging tape is considered a ring with an outer radius of  $R$  and an inner radius of  $r$ . The area is:

$$A = \pi(R^2 - r^2) \tag{1}$$

After the roll is unrolled, the circular ring on the side becomes a rectangle with a length of  $L$  and a width of  $h$ , where the width is the thickness of the roll. The area is:

$$A = Lh \tag{2}$$

By combining Formula 1 and Formula 2,  $L$  can be solved as Formula 3:

$$L = \frac{\pi(R^2 - r^2)}{h} = \pi \frac{(R + r)(R - r)}{h} = \pi n(R + r) = 2n\pi r + n^2\pi h \tag{3}$$

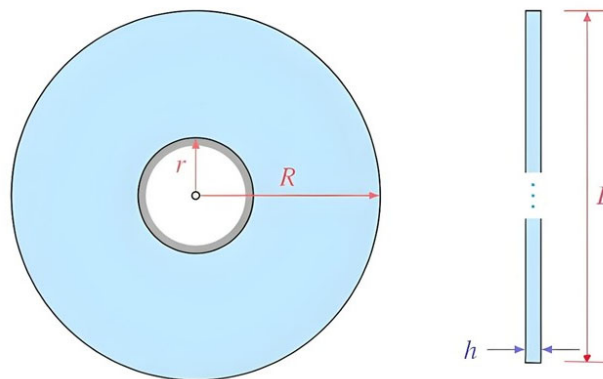


Figure 2 Equal area calculation model

In engineering applications, the total length  $L$  is known, and the number of rolls  $n$  can be measured by a sensor to achieve automated packaging tape winding. Therefore, the relationship between  $n$  and  $L$  needs to be understood. Therefore, Formula 3 can be rewritten as:

$$n = \frac{\sqrt{r^2 + \frac{Lh}{\pi}} - r}{h} \tag{4}$$

Since only integer numbers of revolutions can be counted, round up is used when calculating  $n$ . This ensures that the length of the packaging tape always meets the minimum length requirement.

### 3.1 Sensor

Using the mathematical relationship established in Section 2.1, the target packaging tape length can be determined by counting the number of turns of the automatic tape reeling. This achieves the design goal of the automatic packaging tape reeling machine. A sensor can be used to measure the number of revolutions. In fact, many types of sensors can achieve this. Considering structural cost, system accuracy, and robustness, this article uses a Hall effect sensor for revolution measurement.

### 3.1.1 Basic Principles of the Hall Effect

When a conductor or semiconductor sheet with current flowing through it is placed in a magnetic field perpendicular to the current, the positive and negative electrons in the magnetic field are offset laterally due to the Lorentz force, forming an electric field on both sides of the sheet; when the electric field force of the Hall electric field on the electrons is equal to the Lorentz force and in the opposite direction, the lateral resultant force is zero, and the system reaches a steady state. At this time, a lateral potential difference will appear between the two sheets, which is proportional to the current and magnetic induction intensity and inversely proportional to the distance between them. This is called the Hall voltage; by measuring the size of the Hall voltage, the change in the external magnetic field or current can be converted into a measurable electrical signal. The size of the Hall voltage can be calculated using Formula 5.

$$V_H = \frac{R_H \cdot B \cdot I}{d} \quad (5)$$

Where  $V_H$  is the Hall voltage,  $I$  is the conductor current,  $B$  is the magnetic field strength,  $d$  is the conductor thickness, and  $R_H$  is the Hall coefficient.

### 3.1.2 Working Process of a Hall-Effect Counter

A Hall-effect counter consists of a Hall sensor, a magnet, an op amp, and a counter. When a magnet approaches or moves away from the Hall sensor, the sensor's output voltage changes. The op amp amplifies the electrical signal output by the Hall sensor and converts the change in the sensor's output voltage into a pulse signal; each change in the magnetic field caused by the passage of the magnet generates a pulse. When the counter receives a pulse signal, it accumulates counts on each pulse edge and dynamically updates the result through the clock signal, displaying the count result in real time, thereby realizing the counting of the number of rotations.

## 3.2 Automatic packaging tape reeling machine design

This section describes the structural design of a packaging tape reeling machine. The prototype is shown in Figure 3. The dimensions of the prototype are 150 mm × 78 mm × 80 mm. The bracket is processed by 3D printing. The packaging tape to be packaged is placed above a support. An electric motor drives the copper shaft of the driving wheel through a coupling, causing the driving wheel to rotate. A magnet is placed in the side baffle of the driving wheel's copper shaft. As the driving wheel rotates, the magnet rotates, and

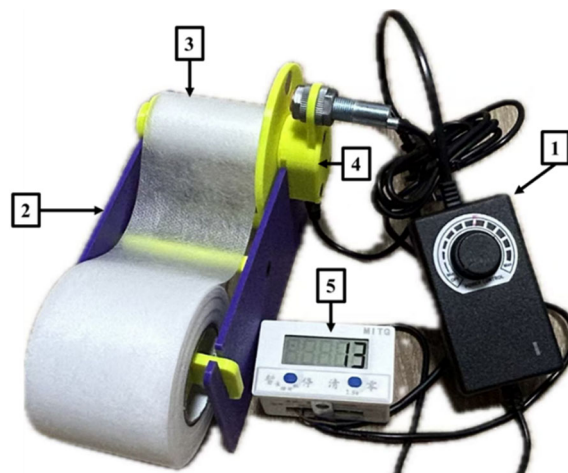


Figure 3 Automatic packaging tape reeling machine prototype

each time it passes through a Hall effect sensor, a count is generated. This records the number of revolutions  $n$ . The number of revolutions is displayed in real time on a digital display. The names of the packaging tape reeling machine components are listed in Table 1.

Table 1 List of packaging tape reeling machine components

Label	Component Name
1	Controller Assembly
2	Bracket Assembly
3	Pulley Assembly
4	Drive System Assembly
5	Hall Effect Counter Assembly

## 4. Experiment

This chapter uses three experiments to verify the effectiveness of the designed automatic packaging tape reeling machine model in practice. The first experiment verifies the accuracy of the equal-area model proposed in Section 2.1. The second experiment examines the relationship between target package lengths and actual package lengths for different specifications. The experiment also discusses the impact of rounding up on actual package lengths. The third experiment verifies the effectiveness of automatic packaging tape reeling machine optimization. By measuring the time consumption of the length measurement process in traditional processing steps, the time reduction effect achieved by reducing process consumption is quantified, providing data support for subsequent production line cycle optimization.

### 4.1 Validation Experiment

First, the accuracy of the equal-area model was verified experimentally. The 20-layer packaging tape stack was measured to be 0.1 mm thick, giving a single-layer thickness of 0.005 mm; the radius of the driving shaft was 12.5 mm. With the target package length set at 300 mm, these values were substituted into formula 4. The resulting  $n$  was 4.

The experimental verification showed that after four rotations of the packaging tape reel's driving wheel, the package length was 334 mm, an 11.33% deviation from the target length. This is within the 10% error range, confirming the feasibility of the equal-area model.

### 4.2 Experiments with Different Package Lengths

In practical applications, packaging tapes of varying lengths must be produced based on demand. An experiment was therefore designed to determine the machine revolutions and actual lengths required for different targets. Parameters were calculated as described in Experiment 3.1. The target packaging length, the corresponding automatic packaging machine revolutions, and the actual packaging length are listed in Table 2.

Table 2 Target packaging length and actual packaging length

No.	Target Length (mm)	Number of Revolutions (rounded)	Package Length (mm)	Error
1	200	2.4(3)	24.32cm	21.6%
2	300	4(4)	33.4cm	11.33%
3	400	5(5)	42.4cm	6%

From the experimental results, it can be seen that when the target length is 200mm, the deviation is as large as 21%, which is significantly larger than the deviation in the verification experiment. The reason for the deviation here is the rounding error when the number of revolutions  $n$  is rounded up. It can be seen that in experiment 3, the number of revolutions is 5 and no rounding is required. At the

same time, the deviation between the actual package length and the theoretical target length was only 6%, confirming that the prototype can achieve packaging within a relatively low deviation. Based on these conclusions, it can be cautiously speculated that the longer the target length, and the closer the number of revolutions corresponding to the length is to an integer, the smaller the package deviation can be achieved.

### 4.3 Automation application

In practice, the traditional three-step process of "measuring length - cutting - rolling packaging tape" is optimized to two steps: "rolling packaging tape - cutting." This section assumes that the tape rolling speed is the same in both the traditional and optimized methods. Therefore, by measuring the time required for target length measurement in conventional first process, the time optimization amount can be obtained. The measurement results for target packaging length and time consumption are shown in Table 3. Each experiment was conducted three times, with time t being the average of the three times.

Table 3 Target Packaging Length and Time Consumption

No.	Target Length (mm)	Time Consumption
1	200	4.51
2	300	4.68
3	400	5.29

The experimental results show that the longer the target length, the longer the measurement time. This is consistent with common sense, as length measurement involves two steps: first, unrolling the target length from the packaging tape, and then measuring it using the tooling. The longer the target length, the longer the unrolling time.

## 5. Conclusions and Discussion

This study developed an automatic packaging tape reeling machine model and optimized the traditional three-step process of "measuring length - cutting - reeling" into two steps: "reeling - cutting." Experiments verified the accuracy of the equal-area model. The experiments concluded that when the automatic packaging tape reeling machine model dispenses packaging tape with a target length of 400 mm, the deviation is minimal, at only 6%. However, rounding error when rounding up the number of revolutions  $n$  leads to larger deviations, with the maximum deviation reaching 6% in the experiment. Compared with the traditional three-step process, the optimized two-step process reduces the time required for length measurement. The experiments show that the longer the target length, the longer the measurement time, which is consistent with basic knowledge. This provides design recommendations for packaging tape reels: the length of the dispensed packaging tape should be as long as possible, and the corresponding number of revolutions should be close to the number of revolutions. This requires customized development and design based on the parameters of the packaging tape and the packaging tape reeling machine. This approach can shorten process time, improve packaging efficiency, and simultaneously reduce material costs during production.

Inevitably, the research has the following limitations. One possible reason for the error is that the packaging tapes used in the experiment were thin, resulting in measurement errors when measuring the packaging tape thickness. In actual applications, the wrapping tape is relatively thick, which would reduce this measurement error. Furthermore, the packaging tapes used in the experiment were highly ductile, potentially causing deformation. This is also a potential source of error. Further optimization is possible in future research. It should be noted that this is still in the laboratory stage. The prototype produced can meet the requirements of optimizing the original three-step process of "measuring length-cutting-rolling packaging tape" to a two-step process of "rolling packaging tape-cutting." However, a full-scale prototype is still required for verification. Secondly, the model for the

relationship between the number of wraps and the total length of the packaging tape developed in this study uses rounding to the nearest integer to meet the product length requirement, which may result in additional production costs. There are two current approaches to reducing these costs. The first is to use more advanced sensors or develop machine vision solutions. The core goal is to achieve more accurate wrap counts, such as counting half or quarter wraps. The other option is to update the company's product parameters. Based on the mathematical model proposed in this article that relates the number of turns to the total length of the packaging tape, the company designed a total length corresponding to an integer number of turns as its product. This is a more cost-friendly optimization approach.

## References

- [1] Solanes, J.E.; Gracia, L.; Valls Miro, J. Advances in Human–Machine Interaction, Artificial Intelligence, and Robotics. *Electronics* 2024, 13, 3856.
- [2] Nagy, M.; Lăzăroiu, G.; Valaskova, K. Machine Intelligence and Autonomous Robotic Technologies in the Corporate Context of SMEs: Deep Learning and Virtual Simulation Algorithms, Cyber-Physical Production Networks, and Industry 4.0-Based Manufacturing Systems. *Appl. Sci.* 2023, 13, 1681.
- [3] Singh, R.; Mozaffari, S.; Akhshik, M.; Ahamed, M.J.; Rondeau-Gagné, S.; Alirezaee, S. Human–Robot Interaction Using Learning from Demonstrations and a Wearable Glove with Multiple Sensors. *Sensors* 2023, 23, 9780.
- [4] Barari, A.; Tsuzuki, M.S.G. Smart Manufacturing and Industry 4.0. *Appl. Sci.* 2023, 13, 1545.
- [5] Othman, U.; Yang, E. Human–Robot Collaborations in Smart Manufacturing Environments: Review and Outlook. *Sensors* 2023, 23, 5663.
- [6] Visconti, P.; Rausa, G.; Del-Valle-Soto, C.; Velázquez, R.; Cafagna, D.; De Fazio, R. Machine Learning and IoT-Based Solutions in Industrial Applications for Smart Manufacturing: A Critical Review. *Future Internet* 2024, 16, 394.
- [7] Baptista, J.; Castro, A.; Gomes, M.; Amaral, P.; Santos, V.; Silva, F.; Oliveira, M. Human–Robot Collaborative Manufacturing Cell with Learning-Based Interaction Abilities. *Robotics* 2024, 13, 107.
- [8] Grau, A.; Indri, M.; Lo Bello, L.; Sauter, T. Robots in Industry: The Past, Present, and Future of a Growing Collaboration with Humans. *IEEE Ind. Electron. Mag.* 2021, 15, 50–61.
- [9] Hu, S.; Shen, L.; Zhang, Y.; Chen, Y.; Tao, D. On Transforming Reinforcement Learning with Transformers: The Development Trajectory. *IEEE Trans. Pattern Anal. Mach. Intell.* 2024, 46, 8580–8599.
- [10] Song, Q.; Zhao, Q. Recent Advances in Robotics and Intelligent Robots Applications. *Appl. Sci.* 2024, 14, 4279.
- [11] International Federation of Robotics (IFR). World Robotics Report 2024; IFR: Frankfurt, Germany, 2024.
- [12] Li, G.; Branstetter, L.G. Does “Made in China 2025” Work for China? Evidence from Chinese Listed Firms. *Res. Policy* 2024, 53, 105009.
- [13] Lwin H Y, Htay U H M. Design and Simulation of Automated Packaging Machine Process Control by Using PLC[J]. *Int. J. Trend Sci. Res. Dev.* 2019, 3: 1423-1426.
- [14] Verma H K, Dewangan S, Thakur P K, et al. Fabrication of Automated Conveyor Systems for Material Handling Based on LDR[J]. *International Journal of Mechanical and Production Engineering*, 2017, 5: 10-15.
- [15] UT CALCULUS. Arc length of polar curves: <https://web.ma.utexas.edu/users>.