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A Review of Mechanical Transmission Structures and Their Applications in Automated Assembly Lines

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Abstract. In this paper, we conduct a comprehensive literature review on the working principle and main features of four common mechanical transmission structures applied in automated production lines (gears, synchronous belts, chains, ball screws). Based on their transmission efficiency, precision, load-bearing capacity, and environmental adaptability, we analyze the advantages, disadvantages, and typical applications of different transmission mechanisms. In order to overcome inherent physical bottlenecks such as thermal deformation and contact fatigue in rigid transmissions or the polygon effect in flexible transmissions, we discuss advanced optimization methods based on surface engineering, direct drive technology, and digital twins. We also present a comprehensive overview of the mainstream multi-stage composite transmission configurations. For example, it highlights a configuration combining a servo motor, planetary reducer, and synchronous belt, as well as another configuration combining a servo motor with a ball screw and linear guide. It provides a solid theoretical basis for the selection and system integration of automated equipment. Finally, our review stresses that the future development direction of mechanical transmissions is determined by the use of advanced materials, digital condition monitoring, and intelligent maintenance.

Keywords: Mechanical Engineering, Mechanical Transmission Structures, Performance Comparison and Selection, Technical Optimization

1. Introduction

With the advancement of high-end manufacturing and automated production, diverse operating conditions impose differentiated performance requirements on mechanical equipment. Gear drives, synchronous belt drives, ball screw drives, and chain drives are currently the four most widely adopted transmission structures, with extensive applications in typical automated assembly lines [1-7]. Previous research has yielded remarkable achievements in multiple directions: in-depth studies on gear transmission mechanisms, investigations into the dynamic characteristics and control strategies of synchronous belts, and applied research on high-precision ball screw arrays and chain transmission structures. Furthermore, through material improvement and structural optimization, scholars have carried out further research on mechanical system integration theories and high-performance transmission mechanisms such as harmonic reducers, planetary gears, and planetary ball screws [1-3, 5, 6, 8-11]. To achieve higher manufacturing precision and reduce mechanical

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wear, cutting-edge technologies including magnetic gear composite motors, direct-drive technology, and digital twins have also been introduced into transmission system research [12-14].

However, most existing literature focuses on a single transmission technology or the optimization of individual components, and there is a lack of comprehensive performance comparison across the four mainstream transmission types, systematic sorting of integrated transmission solutions, and a summarized review of cutting-edge technological evolution [1-6, 9-12]. Although some frontier transmission technologies have not been widely deployed in conventional automated production lines, their development directions carry important guiding significance for the upgrading of intelligent manufacturing equipment in the future. To address the existing gaps in transmission scheme selection and system integration, this paper adopts a literature review method to clarify the technical connotations of the four mainstream transmission structures. It comparatively analyzes their working principles and core performance characteristics including transmission efficiency, motion accuracy, and load-bearing capacity, and provides a detailed overview of prevailing multi-drive integrated configurations with corresponding analysis of their advantages and limitations. On this basis, the paper summarizes the strengths, weaknesses, and future development trends of various transmission systems, and provides practical guidance for the selection of transmission schemes in automated assembly line equipment.

2. Comparison of principles and performance of four typical mechanical transmission structures

In order to visualize the difference between these four mainstream transmission structures and understand the corresponding limits when applied in engineering applications, we conduct a comparative study from five aspects including transmission accuracy, load-bearing capacity, transmission efficiency, maintenance requirement, and environmental adaptability. The main advantages and disadvantages are summarized to provide a clear reference for selecting automation equipment and designing composite mechanisms. Specific performance comparison can be seen in Table 1 below.

Table 1. Comparison of core performance characteristics of four typical mechanical transmission structures

Transmission Type	Transmission Accuracy	Load-Carrying Capacity	Transmission Efficiency	Maintenance Costs	Environmental Adaptability	Key Advantages and Limitations
Gear Transmission	High (rigid meshing with no slippage)	Extremely high, with high resistance to shock torque	≈98%	High (requires specialized lubrication, damaged units must be replaced in pairs)	Fair (requires a sealed housing to isolate external contaminants)	Advantages: Long service life, compact design Limitations: High manufacturing costs, hidden failures
Synchronous belt drive	High (no slippage due to tooth-to-hole meshing)	Weak, poor overload protection	>98%	Low (lubrication-free, easy to replace)	Poor (not resistant to high temperatures, oil contamination, or strong acids and alkalis)	Advantages: High speed, low noise, maintenance-free. Limitations: Prone to tooth shearing and belt breakage, requires precise alignment

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Table 1. (continued)

Chain Drive	Low (polygon effect present)	Strong, with good tensile strength	≈95%	Moderate (requires periodic lubrication and tension adjustment)	Extremely strong (resistant to high temperatures, dust, oil, and moisture)	Advantages: Flexible span, wide range of operating conditions Limitations: High vibration and noise, wear can cause elongation
Ball Screw Drive	Extremely high (micrometer-level positioning)	High (excellent axial rigidity)	90%–95%	Extremely high (extremely stringent requirements for guideways and protective covers)	Very poor (extremely sensitive to dust and metal chips)	Advantages: High-precision linear motion, no vibration Limitations: No self-locking capability, limited by critical speed

3. Typical application scenarios and suitability for automated assembly lines

3.1. Summary of scenario-based selection logic

When selecting drive mechanisms for automated assembly lines, the primary consideration is how to choose the appropriate drive method based on specific operating conditions and precision requirements, while summarizing the logical relationships between various typical drive methods and different application scenarios.

3.2. Typical applications of gear drives

Based on the principle that gear drives can withstand massive impact torque and high-intensity loads, here are some engineering examples. The first is the servo stamping assembly line for automotive white bodies. In this core first-stage process of automotive production, the main drive mechanism must deliver hundreds of metric tons of stamping force within an extremely short timeframe to form the body, while withstanding frequent vibration and impact. The second example is the joints of industrial robots. In the base and upper arm joints of six-axis industrial robots, the transmission mechanisms—such as the core RV reducer—are similarly required to deliver enormous torque within an extremely compact space.

3.3. Typical applications of synchronous belt drives

Synchronous belts offer unique advantages in terms of cleanliness and low-cost maintenance. The following are some common examples. First, this method is frequently used in automated packaging production lines for the pharmaceutical and food industries. It meets safety and hygiene standards requiring an oil-free and contamination-free environment. Second, synchronous belts are frequently used in the moving parts of high-speed Cartesian robots, as they can meet the requirements for frequent starts and stops, frequent direction changes, and high travel speeds. Third, they are also used in numerous applications that do not require extremely high precision but demand low noise and no noticeable backlash, such as the drive systems in 3D printers.

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3.4. Typical applications of chain drives

Due to their good performance at heavy loads as well as stable working conditions in harsh environments, chain drives are widely used in several typical scenarios. For instance, in automotive final assembly lines and heavy-duty pallet conveyor lines, which may be tens or even hundreds of meters long with heavy load transportation, chain drives have no problem moving loads that weigh several metric tons (or even tens of metric tons). They can also increase the transmission distance just by splicing metal chain links. Furthermore, in high-temperature baking lines in paint shops and dust-laden production lines for building materials, drive chains provide excellent resistance against high temperatures and dust, ensuring safe operation. Finally, regarding lifting mechanisms in multi-level parking garages and vertical bucket elevators, the most important thing in vertical operations is avoiding slippage. Although there is usually a need for a long transmission distance and the positioning accuracy demand is quite low, the positive engagement of chain drives ensures that physical slippage is absolutely impossible.

3.5. Typical applications of ball screw drives

Ball screw drives are often employed for accurate motion control in several key areas. For example, in CNC machine tools, ball screw drives help minimize error and increase accuracy in order to produce precision components like aircraft engines and military parts. Furthermore, they are utilized in the semiconductor manufacturing industry, where processes such as chip lithography, wafer handling, or placing microscopic electronic components on circuit boards require extreme precision. Additionally, they are applied in all-electric injection molding machines and servo-driven precision press-fitting units. For manufacturing precision plastic parts (like cell phone lenses and medical catheters), molten plastic at high temperatures needs to be forced into a mold under immense pressure. Today, heavy-duty ball screws with a large lead and high load capacity are frequently coupled with servo motors, which generate tens of metric tons of axial thrust while allowing precise control of insertion depth and force.

4. Technical bottlenecks and recent optimization solutions

4.1. Technical bottlenecks and optimization pathways for rigid transmission

In heavy-load and high-speed operations, gears experience high-frequency stresses that may easily lead to micro-crack formation just beneath the surface causing pitting because of material spalling. Under extreme pressure and high-speed sliding, local instantaneous high temperature on gear tooth surfaces will rupture the lubricating oil film, directly contacting the two metal surfaces and possibly result in adhesive wear or even adhesive failure [1]. To solve these problems, engineers have adopted micro-modification and surface engineering technologies: By optimizing contact stresses during meshing using approaches like three-dimensional crowning, tip modification, and root modification, they avoid excessive stress concentration on each tooth while at the same time adopting methods like carburizing and quenching, physical vapor deposition (such as diamond-like carbon, DLC coatings) and micro-shot peening to greatly decrease the coefficient of friction and effectively prevent oil film rupture [1, 10]. Besides the above-mentioned micro-scale surface friction and contact fatigue issues, bottlenecks for gear transmission are also caused by macro-scale material-physical limitations and thermal deformation problems.

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Material limitations have made it difficult to improve the transmission efficiency of gear mechanisms: friction-heat generated at high frequency leads to thermal expansion of the gear teeth, cancelling out the initially designed meshing clearance and causing "thermal seizure"; while unexpected impacts under different working conditions may easily lead to gear tooth fracture failure [1]; Among recent improvements, apart from predicting gear expansion due to heat via finite element analysis and removing the corresponding machining allowance when performing cold-state machining, the most important breakthrough has come with the emergence and popularization of direct-drive technology. The goal of this technology is to remove intermediate mechanical reduction mechanisms like gearboxes and use DD motors, linear motors, or direct-drive wind turbines to directly drive the load, thus partly solving problems related to mechanical wear and material efficiency; however, without the physical buffering effect of the gearbox, its stability depends solely on power electronic converters, which can easily trigger new problems such as subsynchronous oscillations (SSO), resulting from an interaction between direct-drive wind farms and the AC grid, requiring coordination suppression based on advanced power electronic control algorithms [13]. The introduction of magnetic gears provides the industry with another way forward. Using magnetic field coupling to realize contactless power transmission through space, they totally avoid mechanical contact and frictional wear. Though not yet fully developed, it is still a cutting edge area for breaking through the traditional physical limits in extreme environment [12]. Ball screw drives are also part of the same family of rigid transmission systems facing their own technical challenges brought about by thermal deformation and mechanical wear in applications demanding extreme precision.

The main technical bottlenecks of ball screw drives mainly include: the loss of precision induced by thermal deformation under high-frequency friction, limitation of critical rotational speed when operating at high speed, and cumulative backlash error generated with long-term reciprocating motion. Under high-frequency, high-load motion, intensive friction occurs among the balls and the raceway, generating much heat that causes micro thermal elongation of the lead screw, thus deteriorating the micrometer-level positioning accuracy of machine tools or semiconductor equipment. Long-term wear reduces the system's preload leading to backlash. Moreover, slender lead screws are very susceptible to reaching their critical rotational speed when ultra-high-speed rotation triggers severe resonance or even bending deformation [5]. In order to solve these physical problems, engineers initially advocated using hollow-screw forced cooling technology and nut cooling technology. Forcibly circulating coolant inside the lead screw to dissipate heat in real-time can effectively control the thermal deformation to an extremely low level. Methods like dual-nut preload configuration or intelligent compensation for axial displacement are commonly used to deal with backlash. Large-lead lead screws and rotating-nut lead screws were widely adopted to overcome the resonance problem at high speeds, greatly expanding the upper limit of feed rates. In the extremely demanding field of high-end semiconductors, traditional ball screws are gradually replaced by linear motors. The electromagnetic direct-push method (zero mechanical contact) completely eliminates backlash, mechanical wear and the effect of thermal deformation, making a quantum leap in nanometer-level precision [11]. Although the aforementioned rigid drives prevail in the heavy-duty and precision control fields, flexible drives need to be applied in long-distance flexible conveyance scenarios, but flexible drives also suffer from serious common challenges in their underlying physical mechanisms.

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4.2. Common physical bottlenecks and mitigation strategies for flexible meshing drives

Both synchronous belt drives and chain drives fall under the category of flexible meshing drives. Since both rely on flexible elements with specific pitch to physically engage with the teeth of the drive wheels, they share two inherent physical bottlenecks in their underlying kinematic and dynamic mechanisms. One of the primary issues is the polygon effect. When the flexible element wraps around the drive pulley, its pitch line cannot form a perfect arc but instead takes the form of a polygonal polyline composed of several pitch line segments. This causes the effective radius of action of the flexible element—as it enters and exits the engagement point—to oscillate periodically between the vertices of the polygon and the midpoints of its sides, thereby inducing severe vertical oscillations and speed pulsations. Due to geometric constraints, this issue can currently only be mitigated but not completely eliminated. The primary solutions include: selecting pulleys with as small a pitch and as many teeth as possible within design tolerances to reduce the amplitude of speed pulsations to a microscopic level; or optimizing the tooth profile—for example, using involute or arc-modified tooth profiles to smooth the meshing transition points—thereby effectively alleviating the periodic impacts and NVH vibrations triggered by the polygon effect [8]. In addition to mesoscopic meshing jitter defects, a common bottleneck for this type of flexible transmission at the macroscopic scale during long-distance operation lies in tension decay and resonance control.

On long-distance transport applications, due to matrix stress relaxation (in synchronous belts) or hinge wear (in chains), the initial tension of the flexible system spontaneously decays over time, leading to severe slack and whiplash effects; This leads to a sudden decline in transmission smoothness and, in severe cases, can cause tooth disengagement, tooth skipping, or even fatigue fracture of the flexible member. To address this common challenge, the engineering community's primary solution is to adopt adaptive intelligent tensioning mechanisms—such as spring-based self-adjustment, pneumatic, or hydraulic adaptive tensioning pulleys—to compensate in real time for the dynamic decay of tension. At the same time, with the advancement of digital technology, the use of digital twin-based online monitoring has emerged as a new preventive trend—combining tension sensors with IoT algorithms to monitor long-distance flexible elements in real time and predict their service life degradation, thereby achieving early warning and proactive maintenance, which significantly enhances system operational safety [14]. In addition to overcoming the common physical bottlenecks mentioned above, timing belts and chain drives—due to their distinct materials and structures—have each given rise to specific defects that urgently need to be addressed.

5. The necessity of multi-drive combination designs and typical solutions

Based on the preceding analysis of the strengths and weaknesses of various mainstream drive methods and the discussion of their improvement schemes, it is evident that to maximize the overall operational efficiency of automated production lines, hybrid drive configurations must be adopted at different stages of actual production.Main production lines usually focus on heavy load capability and long distance transmission, whereas branch production lines place emphasis on high precision positioning; furthermore, all processes are required to follow the design principles that promote energy conservation and cost reduction. Therefore, "servo motor, planetary gearbox, synchronous belt/rack-and-pinion" became the mainstream, cost-effective choice for medium-to-long stroke applications: The planetary gearbox amplifies the torque from servo motor. Combined with a synchronous belt or rack-and-pinion, it can achieve high-speed transmission over long distances without suffering problems related to insufficient power and limited speed inherent to single-drive belt systems. Flexible parts like belts need to be maintained or replaced frequently to avoid

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misalignment or wear but they remain very popular due to their low costs and high cost-effectiveness within the industrial sector.

For example, such combination solutions have been widely adopted in the automotive manufacturing and smart warehousing sectors. The automotive manufacturing industry employs rack-and-pinion-driven gantry robots to facilitate the high-speed transfer of components between workstations; simultaneously, high-speed synchronous belt combinations are extensively used in the sorting lines of warehousing systems to achieve efficient logistics. Unlike the aforementioned combination solutions, which emphasize long-distance efficiency, short-distance precision control in high-tech manufacturing requires a completely different rigid precision transmission architecture.

For medium- to short-stroke applications with stringent positioning accuracy requirements, the "servo motor, coupling, ball screw , linear guide" configuration is widely recognized in the industry as the optimal solution.Because this configuration directly utilizes a ball screw driven by a servo motor, the entire drive module possesses exceptional precision and high rigidity. In practical applications, a two-stage combination of linear guides and ball screws is often employed for motion control: first, the lower linear guide rapidly moves the actuator to an approximate position for coarse positioning, followed by the ball screw to achieve micron-level precision positioning and motion control.Although this combination is relatively expensive overall and places extremely stringent demands on the flatness of the mounting base and assembly processes, its unmatched precision makes it the undisputed choice for high-precision manufacturing. This solution is widely used in 3C manufacturing and the semiconductor industry; semiconductor giants have also extensively adopted this hybrid solution in wafer handling and lithography alignment equipment to ensure extremely high yield rates and absolute stability during transport.

6. Conclusion

As the manufacturing industry continuously develops toward high speed, high precision, and intelligence, the performance of transmission systems in mechanical equipment directly determines the overall operational efficiency and reliability of the entire system. This paper systematically introduces the characteristics of four common transmission methods, namely gear drives, belt drives, chain drives, and ball screw drives. Based on typical problems in actual production scenarios, it summarizes the advantages, limitations, and application characteristics of different transmission solutions, so as to provide a reference for the selection of transmission systems. The paper also points out that the future upgrading of transmission technology will rely on advances in materials, manufacturing processes, and engineering technologies to improve the comprehensive performance of traditional mechanical transmission systems.

Because of constraints imposed by field research conditions, this paper mainly analyzes related literature and public data without on-site operational data for enterprises or long-term verification with actual working conditions. In-depth research needs to be conducted on some transmission solutions' applications. The future research direction will be focused on using new materials and precision manufacturing to improve the performance of transmissions; we also need to utilize intelligent sensing and data monitoring technology to achieve condition monitoring, fault prediction, and intelligent maintenance of transmission systems so that mechanical transmission moves towards digitalization and intelligent operation.

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