

## Review

# A Review of Research on Travel Error in Planetary Roller Screw Mechanisms

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## Abstract

Planetary roller screw mechanisms (PRSMs) are critical transmission components in high-end equipment and precision electromechanical systems, and their travel error directly affects motion accuracy and operational stability. This review systematically examines the main sources and research progress of PRSM travel error, including manufacturing and geometric errors, installation errors, load and thermal deformation errors, and service and environmental factors. It further reviews the current state of research on travel error models, with emphasis on travel error modeling and dominant error identification. Existing measurement methods are classified into static measurement, dynamic measurement based on linear encoders or laser interferometers, machine vision measurement, and auxiliary methods for specific operating conditions, and are compared in terms of accuracy, applicable test objects, and engineering limitations. The review shows that current studies have established an important basis for travel error prediction, compensation, and test system development, but limitations remain in experimental validation, dedicated test rigs, component-level measurement of roller external raceways and nut internal raceways, and unified evaluation standards. Future research should develop specialized measurement systems that consider multi-contact characteristics, representative loading conditions, backlash elimination, error separation, and data compensation to support high-precision PRSM applications.

**Keywords:** planetary roller screw mechanisms; travel error; error generation mechanism; detection technology

## 1. Introduction

With the accelerating global technological revolution and industrial transformation, fields such as humanoid robotics [1], high-end aerospace equipment [2], and the automotive industry [3] are experiencing breakthrough developments. These fields impose more stringent performance demands on transmission systems: high reliability, high precision retention, and high stability under certain extreme environments [4,5]. Against this background, PRSMs, as an advanced linear transmission technology, offers significant advantages over conventional ball screw mechanisms in terms of load-carrying capacity, stiffness, operating speed, and service life. Owing to these performance advantages, as shown in Figure 1, PRSMs have been increasingly applied in aerospace electromechanical actuators, high-load precision linear actuators, and other electromechanical systems requiring high load-carrying capacity and motion accuracy, while also showing considerable application potential in emerging fields such as joint actuators for humanoid robots [6–8].



Academic Editors: Marco Ceccarelli and Ciro Santus

Received: 28 July 2026

Revised: 26 August 2026

Accepted: 9 September 2026

Published: 11 September 2026

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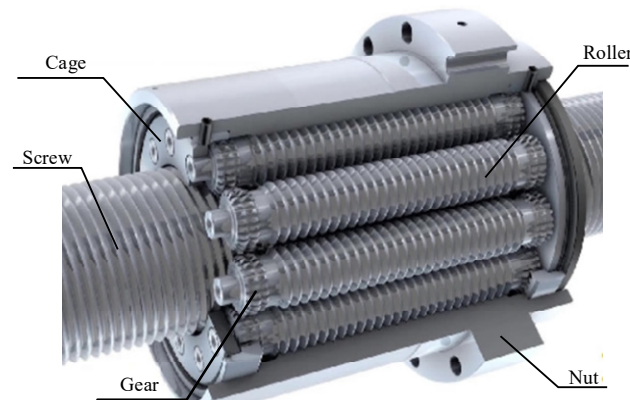


**Figure 1.** Typical Applications of PRSM. (a) PRSM applications in high-load industrial applications; (b) PRSM applications in the aerospace field; (c) PRSM applications in precision robotic control [9].

A PRSM is a transmission mechanism that enables the conversion between rotary and linear motion and mainly consists of a screw, a nut, multiple threaded rollers uniformly distributed around the circumference, and retainers [10]. During transmission, multiple rollers simultaneously form threaded contact with the lead screw and nut. While rotating around their own axes, the rollers also revolve around the lead screw axis, driving the lead screw or nut to achieve axial linear motion and transmitting motion and load through contact. The two most common configurations are the standard PRSM [11] and the inverted PRSM [12]. Figure 2 shows the structure of a typical standard PRSM. As a critical functional component of transmission, the accuracy of the PRSM directly determines the positioning accuracy, motion stability, and reliability of the entire machine. Because multiple rollers and multiple threaded contact interfaces simultaneously participate in motion and load transmission, the transmission accuracy of a PRSM is jointly affected by multiple factors, including geometric errors of individual components, assembly errors, applied loads, contact deformation, frictional heat generation, and dynamic response during operation. Travel error is defined as the deviation between the actual axial displacement value and the theoretical axial position value corresponding to the circumferential angular position during screw rotation [13]. Travel error serves as a key evaluation indicator for characterizing its precision grade [14], reflecting the comprehensive precision level of the screw within its travel range. Therefore, research on travel error analysis and measurement methods for the PRSM constitutes the foundation for ensuring the precision retention and operational reliability of high-end equipment.

Currently, the measurement of travel error for PRSM still relies on equipment designed for ball screws, and specialized measurement systems tailored to the specific characteristics of PRSM have not yet been established. Compared with ball screws, the travel error of PRSM is no longer dominated by the lead error of a single helical pair; instead, it forms an equivalent travel error through the collective effects of multi-contact pair errors. This structural characteristic changes both the error formation mechanism and the measurement target. Consequently, when conventional measurement equipment is applied

to PRSM, problems such as inaccurate measurement and poor dimensional adaptability frequently arise.



**Figure 2.** Structure of a standard PRSM.

To address the aforementioned issues, researchers both domestically and abroad have carried out relevant studies focused on the error formation mechanism, theoretical modeling, and measurement methods of PRSM. Consequently, certain progress has been achieved in fields such as geometric error analysis, installation error modeling, load-thermal deformation coupling, environmental and lubrication effects, comprehensive travel error prediction, and dynamic measurement platform design. However, existing studies still heavily draw on the theoretical models and measurement methods of ball screws. Insufficient discussion has been dedicated to the error propagation relationships among multiple components, including the screw, rollers, nut, and synchronized gears in the PRSM, as well as the issue of component-level travel error measurement. Consequently, it remains difficult to comprehensively support the demands for high-precision design, manufacturing, and testing of the PRSM. Therefore, this paper presents a comprehensive review of the research on the travel error of the PRSM. First, the influence mechanisms of manufacturing and geometric errors, installation errors, load-induced and thermal deformation errors, and their coupling effects on the travel error are analyzed. Second, the theoretical research progress in travel error modeling, sensitivity analysis, and dominant error identification is summarized. Subsequently, the development status of static measurement, dynamic measurement, machine vision measurement, and auxiliary measurement methods under specific operating conditions is reviewed. Finally, the deficiencies of existing studies are summarized, and the prospects for specialized measurement systems and evaluation methods tailored to the structural characteristics of the PRSM are discussed, aiming to provide a valuable reference for travel error analysis, measurement equipment design, and precision improvement.

## 2. Influencing Factors and Generation Mechanisms of Travel Error

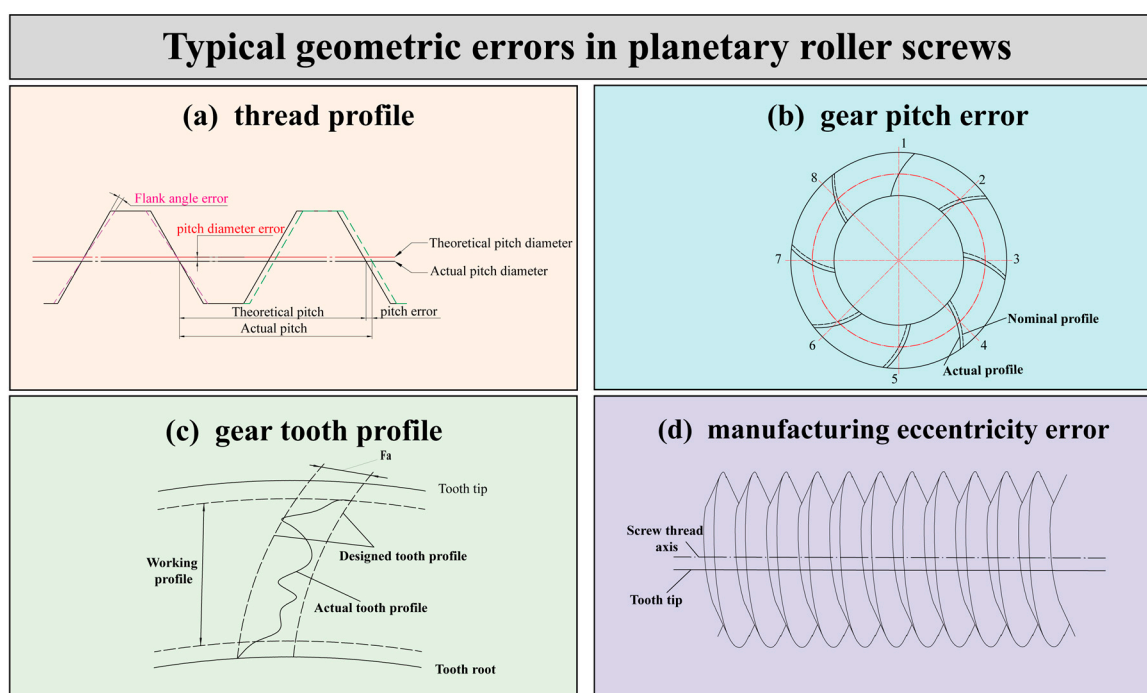
### 2.1. Manufacturing and Geometric Errors

Early scholars mainly focused on the impact of screw manufacturing precision on the travel error, establishing quantitative relationships between helical geometric errors and lead errors. Lead error is defined as the deviation between the actual axial travel of the nut relative to the screw over one revolution and the nominal or specified lead. A research team, represented by the Hanjiang Machine Tool Works, carried out a systematic analysis of the manufacturing processes for precision ball screws in the late 1980s, pointing out that the thread lead error was one of the primary sources leading to the travel error, and proposed a correction method for the lead error from the perspective of processing

technology. This work represented the first study to treat the travel error as a critical factor affecting screw transmission accuracy, laying the foundation for subsequent investigations into travel error mechanisms and compensation technologies [15]. The geometric errors of the PRSM include thread profile errors, gear profile errors, and manufacturing eccentricity errors. Among them, thread profile errors consist of thread pitch errors, thread flank angle errors, and thread pitch diameter errors. Gear profile errors include gear pitch errors and gear profile deviations [16–18].

### 2.1.1. Thread Profile Errors

The deviation between the actual pitch and the theoretical pitch can be expressed as the pitch error, which is the major factor affecting transmission accuracy and simultaneously influences the thread meshing. In Figure 3a, the solid line represents the theoretical thread profile, while the dashed line indicates the actual thread profile. The angular deviation generated between them constitutes the flank angle error, which affects the load distribution of the thread teeth, thereby accelerating thread wear and deteriorating transmission accuracy. The thread pitch diameter error refers to the deviation between the actual pitch diameter and the theoretical pitch diameter of the thread. This error alters the meshing clearance and contact positions among the screw, nut, and roller, thereby affecting the positioning accuracy of the transmission.



**Figure 3.** Typical geometric errors of the PRSM. (a) Schematic of the thread profile; (b) schematic of the gear pitch error; (c) schematic of the gear tooth profile; (d) schematic of the manufacturing eccentricity error.

### 2.1.2. Gear Profile Errors

Currently, gear meshing exists between the roller and the nut in most designs of the PRSM. Therefore, the geometric error of the gear is also an indispensable part when studying transmission accuracy. The gear pitch error refers to the deviation between the actual pitch and the theoretical pitch of the gear. Since each gear tooth exhibits varying degrees of pitch deviation, the research on gear pitch errors generally considers the total cumulative pitch error of the entire gear. The pitch error leads to fluctuations in the

gear rotation angle, thereby reducing the synchronized motion accuracy of the roller, and ultimately manifesting as an increase in the travel error.

As shown in Figure 3c, the gear profile error is denoted as  $F_a$ . The normal distance between the actual profile and the ideal profile constitutes the gear profile error. The generation of profile errors leads to uneven tooth surface contact during gear meshing, thereby reducing the gear transmission accuracy and consequently affecting the precision of the PRSM.

### 2.1.3. Manufacturing Eccentricity Errors

The manufacturing eccentricity error refers to the geometric error formed by the deviation between the actual rotational center axis and the theoretical axis of a component, which includes the screw manufacturing eccentricity error and the roller manufacturing eccentricity error. Both types of eccentricity errors exert a significant impact on the meshing state of the threads, thereby reducing the precision of the PRSM.

### 2.1.4. Theoretical Analysis of Geometric Errors

The mechanisms underlying the travel errors discussed above are qualitatively summarized in Figure 3. For typical manufacturing and geometric errors in PRSMs, the schematic illustrates the principal forms of thread profile errors, gear profile errors, and manufacturing eccentricity errors. Thread profile errors include pitch errors, flank angle errors, and pitch diameter errors, which affect the theoretical travel, contact load, and meshing clearance. Gear tooth profile errors lead to nonuniform tooth surface contact and consequently reduce the meshing accuracy of the rollers. Manufacturing eccentricity causes radial runout and axial displacement deviations.

To investigate the effects of different geometric errors on the travel error of PRSMs, researchers have developed various modeling and analytical methods [19]. In early studies, ball screw mechanisms were used to investigate the effects of geometric errors on travel error. Zhao et al. [20] analyzed the influence of thread-raceway parameter errors on the incremental lead deviation and established the relationship between thread-raceway parameter errors and lead error. This study was based solely on derivations from static relationships and represented an early theoretical development of travel error. Subsequently, Huang et al. [21] proposed a new algorithm for evaluating lead accuracy indices. This method replaced the conventional manual line-drawing procedure for determining accuracy indices with mathematical fitting and computational analysis, thereby laying the foundation for the algorithm design and computational implementation of precision measurement instruments, but early studies predominantly used ball screw mechanisms as test specimens for both theoretical and experimental investigations. As research progressed, studies on geometric errors gradually shifted from conventional error identification and accuracy evaluation toward quantitative modeling and simulation analysis of the mechanisms underlying transmission errors in screw drives. Mamaev et al. [22] experimentally investigated the effects of the motion errors of individual components on the displacement of a PRSM. They found that the travel accuracy was primarily affected by geometric errors in the synchronizing gears and threaded surfaces introduced during manufacturing. Zhang et al. [23] established a thread load-distribution model for PRSMs that accounted for lead deviations and analyzed the effects of machining errors in the lead, thread angle, and pitch diameter. The results showed that pitch deviations caused fluctuations in the load distribution along the threads. Model validation further revealed that the variation in pitch deviation was consistent with that in thread wear depth. However, the relationship between such machining errors and dynamic travel error was not further modeled or experimentally investigated. Hu et al. [24] developed a semi-analytical model of thread

contact in PRSMs based on spatial coordinate transformations and differential geometry. They further employed machine learning to identify the sensitivity of contact characteristics to geometric parameters, thereby providing a new analytical approach for modeling and optimizing the mechanisms associated with geometric errors. However, the machining errors were substantially simplified in this study, and the analysis was mainly conducted under idealized conditions, with direct experimental validation under actual operating conditions still lacking. Xing et al. [25] established a contact kinematics model for PRSMs. By combining conjugate surface contact conditions with coordinate transformations, they analyzed and elucidated the effects of geometric errors on the direction of contact sliding and the distribution of sliding velocity, thereby clarifying the mechanisms through which pitch-circle mismatch and structural parameters influence transmission performance. However, this study neglected the influence of the states of individual rollers on travel error and also lacked direct experimental validation under actual operating conditions.

In summary, geometric errors constitute the most fundamental source of travel error in PRSMs. The studies reviewed above indicate that, although the mechanisms underlying these errors are relatively well understood, geometric errors cannot be completely eliminated during precision manufacturing and remain one of the key factors limiting high-precision transmission performance. Therefore, future research should further incorporate the measured geometric errors of individual components and establish the relationship between actual machining errors and travel error, providing a basis for tolerance design of critical geometric parameters, machining accuracy control, and travel accuracy improvement.

## 2.2. Installation Errors

Installation errors refer to geometric deviations introduced during the assembly of components such as the screw, rollers, and nut owing to inaccurate positioning, alignment, support, or clamping [26]. Assembly errors in PRSMs mainly arise from positional deviations of the nut, screw, and supporting structures during assembly [27]. These deviations can cause shifts in the roller meshing centers, non-uniform tooth surface contact, and bending deformation of the component axes [28], thereby inducing additional lead errors and periodic displacement deviations during transmission [29].

### 2.2.1. Positional Errors

Positional errors refer to deviations arising during the assembly of a screw mechanism when clearances between the components allow the rollers and nut to shift under gravity, causing their actual positions to deviate from their nominal axes. Under the influence of gravity, the rollers and nut may deviate from their nominal axes, resulting in internal positional misalignment. Ideally, the rotational axis of the screw should coincide with the geometric central axis of the nut, corresponding to an error-free configuration. In actual assemblies, however, the nut or rollers may be displaced under the combined effects of clearances and external forces, causing the roller meshing centers to deviate from their nominal positions and altering the contact locations and load distribution. Such deviations not only induce localized contact stress concentrations but also generate travel errors during the operation of the screw mechanism.

### 2.2.2. Installation Errors in Testing

The test installation error refers to the additional error introduced by the mounting method of the PRSM on the test bench during the travel error measurement. PRSMs are commonly measured using a between-centers mounting configuration. This arrangement gives rise to two typical installation errors in testing: screw inclination error and support lifting error. Screw inclination error primarily arises from imperfect alignment of the

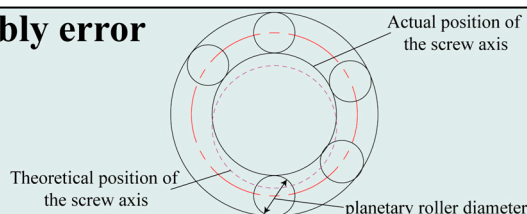
two centers in a between-centers mounting configuration, causing the rotational axis of the screw to be inclined relative to its nominal axis. This inclination alters the meshing angles and contact conditions between the rollers and the nut, resulting in localized load concentration and additional travel error. Support lifting error occurs when the support units hold both ends of the screw during testing, which causes radial deformation of the screw and consequently introduces an additional travel error to the mechanism. These two types of errors are typically superimposed on the inherent manufacturing and geometric errors of the screw, thereby amplifying the travel error of the PRSM.

### 2.2.3. Theoretical Analysis of Installation Errors

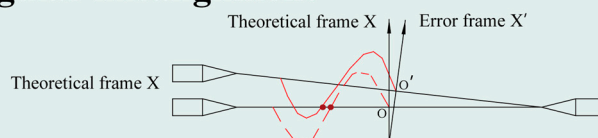
The mechanisms underlying the travel errors discussed above are qualitatively summarized in Figure 4. For the typical installation errors of the PRSM, the schematic illustrates the principal forms of screw positional error, screw inclination error during testing, and screw support lifting error.

## Typical Installation errors in planetary roller screws

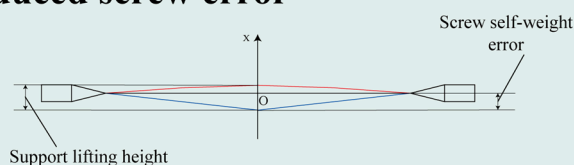
### (a) Screw assembly error



### (b) Screw angular misalignment



### (c) Support lifting-induced screw error



**Figure 4.** Typical installation errors of the PRSM. (a) Schematic of the screw assembly error; (b) schematic of the screw angular misalignment; (c) schematic of the support lifting-induced screw error.

Installation errors alter the relative positional relationships among the screw, rollers, nut, and gear pairs, thereby affecting the meshing conditions, load-carrying capacities at different contact points, and travel accuracy. Accordingly, existing studies have mainly focused on the effects of assembly accuracy, the modeling of gear meshing errors, and the analysis of meshing states involving multiple contact pairs. Guo [30] investigated the effect of screw assembly accuracy on lead error and found that assembly parallelism errors caused the screw axis to become inclined, thereby increasing the susceptibility of the screw to bending deformation and degrading its lead accuracy. However, this study mainly focused on ball screws used in vertical lathes and did not further establish a quantitative relationship between actual installation errors and travel error over the

full travel range. Due to the characteristics of gear meshing in PRSMs, Lin et al. [31] developed a mathematical tooth-contact model considering center-distance installation error, axis installation error, and combined installation error. The results showed that the gear transmission was particularly sensitive to axis installation error, which could lead to edge contact and periodic transmission errors. However, this study mainly analyzed the effects of installation errors on contact trajectories and transmission errors based on gear contact theory, while the modeling of travel error involving multiple threaded contact interfaces should also be considered. Dong et al. [32] developed a new design method by considering the combined threaded and toothed features of the rollers as well as their design requirements. Through virtual modeling and assembly, they identified a more accurate assembly method, providing useful guidance for the modeling of assembly errors. However, this study did not consider the effects of actual manufacturing and assembly deviations on the spatial positions and meshing states of the rollers. Liu et al. [33] proposed an analytical model for a standard PRSM incorporating errors. Their computational analysis showed that installation accuracy errors altered the meshing points within the PRSM, thereby affecting its transmission accuracy. Qiao et al. [34] analyzed the structural characteristics of PRSMs and developed cross-sectional design methods for the rollers, screw, and nut. The results showed that adjusting the clearances between the two inclined flanks and between the circular arc and the inclined flank could improve the meshing accuracy of both the screw–roller and roller–nut thread pairs. However, direct experimental validation under actual assembly conditions is still lacking.

In summary, installation errors are an important factor affecting the travel error of PRSMs. They essentially arise from deviations between the actual and nominal positions of the components during assembly or test mounting. Existing studies have shown that installation errors not only reduce the travel accuracy of PRSMs but also cause problems such as non-uniform load distribution. However, the evaluation indices used in existing studies are mainly focused on contact positions, load distribution, and rolling–sliding characteristics, while the relationship between installation errors in the actual assembled state and travel error over the full travel range has not been investigated in sufficient depth. Therefore, future research should further combine actual measurements of installation errors and travel errors to establish a mathematical model describing the relationship between actual installation errors and travel error over the full travel range, while considering an appropriate range of installation accuracy, so as to provide a basis for improving the accuracy level and travel accuracy of PRSMs.

### 2.3. Load and Thermal Deformation Errors

Load and thermal deformation are important dynamic factors affecting the travel error of PRSMs. They mainly arise from the axial elongation and structural thermal deformation of the screw caused by rolling-contact stress and frictional heat during operation. Figure 5 schematically illustrates the mechanisms through which load and thermal deformation affect travel error.

#### 2.3.1. Thermal Deformation Errors

Thermal deformation error refers to the error arising when non-uniform internal temperature distribution is caused by factors such as rolling–sliding friction and the external thermal environment during the actual operation or testing of a planetary roller screw mechanism. The resulting temperature rise induces deformation of the screw mechanism and further affects travel error [35]. Figure 6a presents a thermal image of a PRSM after 30 min of continuous testing, showing a maximum temperature of 120 °C. This temperature reflects the local thermal state under specific operating conditions, and under such

conditions, the elevated temperature may adversely affect the reliability and service life of the planetary roller screw mechanism. Based on the mechanism by which temperature rise induces axial deformation of the screw, the resulting axial and radial thermal deformations can be derived as follows:

$$\begin{cases} \delta y_z = \rho \Delta T L \\ \delta y_r = \rho \Delta T d_s \end{cases} \quad (1)$$

where  $\delta y_z$  and  $\delta y_r$  denote the axial and radial deformations, respectively;  $\rho$  is the coefficient of thermal expansion of the material;  $\Delta T$  is the temperature rise; and  $L$  and  $d_s$  are the nominal length and diameter of the screw, respectively [36]. The above equation represents a simplified solution developed by previous researchers, in which key locations of the components are selected as temperature measurement points. During actual operation, PRSMs involve multiple heat-flow paths, and the temperature field and thermal deformation field at different spatial locations vary continuously throughout the operating cycle. Therefore, modeling is generally required for quantitative analysis.

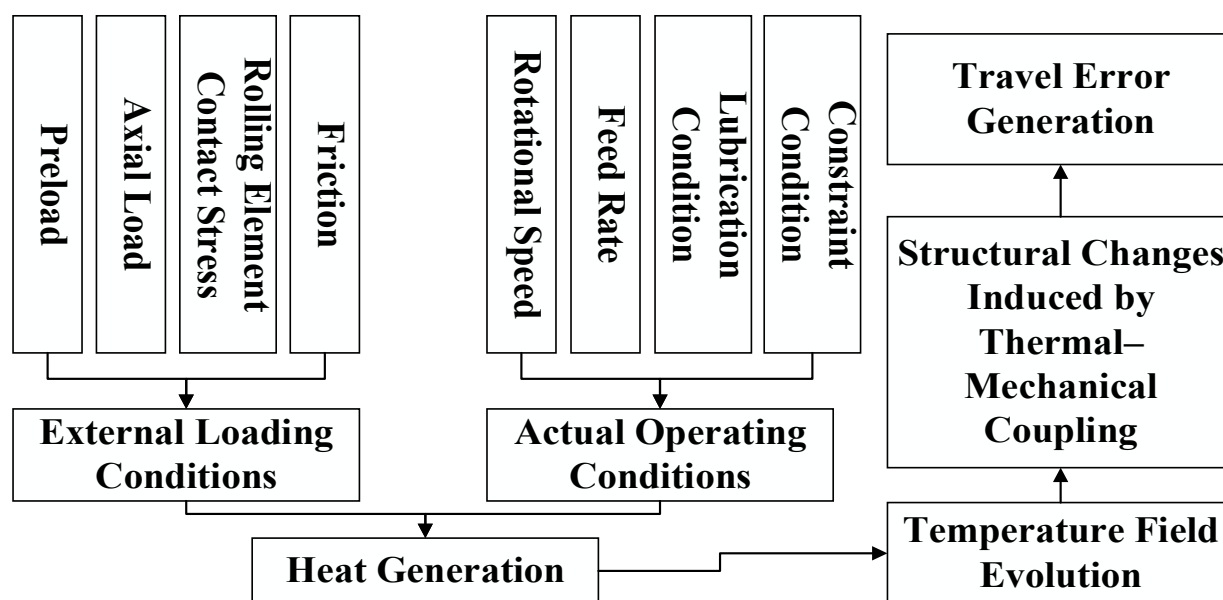
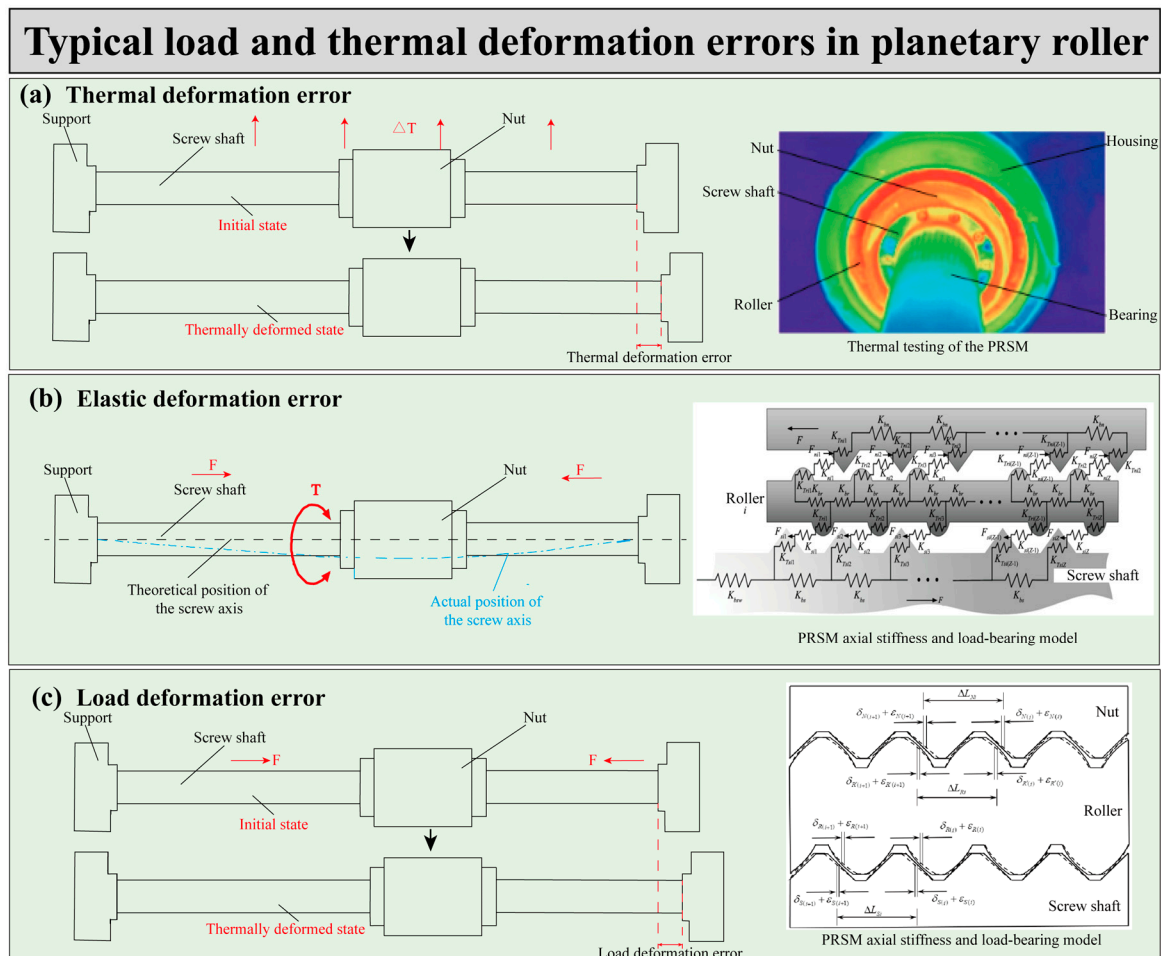


Figure 5. Schematic of the influence pathways of load and thermal deformation.

### 2.3.2. Elastic Deformation Errors

Elastic deformation errors refer to errors arising when a PRSM undergoes elastic deformation under axial force or torque during operation. Such deformation alters the actual contact positions and contact characteristics of the threads and gears, thereby affecting the travel error of the PRSM. Stiffness is an important parameter characterizing the resistance of a PRSM to deformation. The axial stiffness of the PRSM, the stiffness of the fixed-end bearing assembly, and the gear meshing stiffness should all be considered important factors affecting elastic deformation errors [37,38]. Under stable loading conditions, this type of error mainly manifests as a quasi-static displacement deviation related to the load level. When the axial load or driving torque varies with time, the elastic deformation of each component also exhibits time-varying characteristics, causing corresponding fluctuations in the actual axial displacement. As a typical form of time-varying loading, periodic loading also causes periodic variations in elastic deformation and axial displacement, which in turn affect travel accuracy under different operating conditions.



**Figure 6.** Typical load and thermal deformation errors [36,40,41]. (a) Schematic of the thermal deformation error; (b) schematic of elastic deformation error; (c) schematic of the load deformation error.

### 2.3.3. Load Deformation Errors

Load deformation errors refer to errors arising when a PRSM is subjected to an axial load. Under such loading, the threaded sections of the screw, nut, and rollers carry axial forces, while each roller undergoes contact deformation at both the screw–roller and roller–nut interfaces. A contact-deformation value is generated between each pair of mating thread teeth. The axial deformation at the loaded end is then obtained by summing the differences among these individual deformation values, thereby affecting the travel error of the PRSM [39]. During actual operation, time-varying axial loads often occur, causing the loads and contact deformations at individual contact points to vary with time, which in turn leads to changes in the contact positions and axial relative displacement. Related studies have focused on accuracy modeling by analyzing the stiffness of different elements and the slide-to-roll ratio, in order to evaluate the influence of load-induced deformation errors caused by axial loads on the travel error of the screw mechanism.

### 2.3.4. Theoretical Analysis of Load and Thermal Deformation Errors

The mechanisms underlying the travel errors discussed above are qualitatively summarized in Figure 6. For the typical load and thermal deformation errors in PRSMs, the schematic illustrates their principal forms.

In early studies on the thermo-mechanical coupling modeling of PRSMs, researchers employed finite element analysis and thermoelastic theory to elucidate the coupled relationships among load distribution, frictional power, and temperature field evolution.

They also proposed thermal error prediction methods based on infrared thermography and multipoint temperature acquisition, enabling accurate modeling of the axial thermal elongation of the screw [42]. Yue [43] investigated the effects of feed rate, preload, machining conditions, and mounting configuration on thermal deformation. A thermal error model of the screw was then developed based on multibody system theory and neural networks. Experimental results showed that thermal error compensation significantly improved the accuracy of the screw, but this study lacks validation using a sufficiently large experimental dataset. Zhou et al. [44] established a theoretical model relating the preload elongation of the screw mechanism to its thermal deformation, providing a reliable theoretical and experimental basis for thermal deformation compensation and accuracy correction in travel error testing. Yao et al. [45] established a load distribution model considering pitch errors and mounting configurations and proposed an improved multi-objective optimization algorithm. The results showed that the improved algorithm could effectively adjust the axial load, thereby improving the travel accuracy of the screw mechanism, but this study still lacks thermal error experiments under dynamic operating conditions. Chen [46] conducted an in-depth investigation into the mechanisms underlying screw thermal errors under operating conditions, as well as thermal error modeling and stability compensation methods for different mounting configurations. This study provided a feasible approach for temperature correction and error separation of travel error test results and offers an important reference for improving the accuracy and reliability of travel error measurements in screw mechanisms. Chen et al. [47] developed a comprehensive performance test platform for PRSMs. Load testing and accuracy testing showed that, as the load-carrying performance entered the degradation stage, the deterioration of transmission accuracy accelerated. Moreover, the degradation rate of transmission accuracy was higher than that of load-carrying performance.

In summary, existing studies [48–50] have systematically elucidated the coupled mechanisms among load distribution, frictional heat generation, axial elongation, and accuracy degradation in PRSMs during operation using methods such as finite element analysis, multibody system theory, and neural networks. These studies have confirmed that thermal deformation and load conditions are important dynamic sources of travel error. However, existing studies still have the following limitations. First, existing accuracy models considering thermo-mechanical coupling are mostly established under room-temperature operating conditions and do not fully account for factors that may arise during actual operation, such as high-temperature environments and time-varying loads. Consequently, they have difficulty in comprehensively reflecting the coupled effects under actual dynamic operating conditions. Second, existing studies mainly focus on theoretical modeling, while actual test platforms still provide insufficient consideration of operating conditions involving load and thermo-mechanical coupling. In particular, experimental conditions for accuracy testing under dynamic loads and high-temperature environments remain lacking, resulting in deviations between theoretical modeling results and those obtained under actual operating conditions. Future research should further investigate test equipment design, operating-condition simulation, and data compensation strategies to improve the accuracy and engineering applicability of travel error analysis.

#### *2.4. Service and Environmental Effects*

In addition to geometric errors of individual components, installation errors, and load deformation and thermal deformation errors, planetary roller screw mechanisms are also affected during actual service by factors such as the external environment, lubrication conditions, and surface degradation that develops with prolonged operation. Such factors generally exert indirect or time-varying effects on travel accuracy by altering the

contact conditions of the thread pairs, friction and lubrication characteristics, and surface integrity. Among these factors, external vibration and impact can be transmitted to the screw mechanism through the supporting structure, causing additional dynamic displacement; humidity, dust, particulate contamination, and corrosive media may aggravate the degradation of contact interfaces by affecting surface conditions and lubrication conditions. The lubrication condition is directly related to friction, temperature rise, and wear in the threaded contact regions, while long-term friction and wear gradually alter the thread profile, meshing clearance, and actual contact positions, causing travel accuracy to exhibit degradation characteristics that evolve with service time. Therefore, it is necessary to further analyze the relationships between travel error and these factors from two aspects: the external environment and lubrication conditions together with friction and wear.

#### 2.4.1. Environmental and External Disturbance Factors

Under actual operating conditions, PRSMs are exposed to environmental disturbances that differ from those encountered in laboratory environments, and their travel accuracy may therefore also be affected by the external environment. Mechanical disturbances, such as external vibration and impact, can be transmitted to the screw mechanism through the supporting structure and housing, causing dynamic responses of the individual components. Resonance may then alter the threaded contact conditions within the PRSM and consequently induce travel error.

Environmental factors, such as dust, humidity, contamination, and corrosive environments, mainly affect the accuracy retention of screw mechanisms indirectly by altering the contact surfaces and lubrication conditions, with travel error gradually developing after long-term operation. When dust or hard particles enter the threaded contact regions, they may disrupt the lubricant film and cause surface scratching, indentation, and abrasive wear. The ingress of humidity and moisture may alter lubricant performance and promote oxidation, corrosion, and other tribochemical reactions on the contact surfaces. Corrosive environments may directly damage the surfaces of the screw mechanism, further aggravating travel error. Current research on the effects of such factors mainly focuses on vibration response and condition monitoring, as well as performance degradation under complex service conditions.

#### 2.4.2. Lubrication, Friction, and Wear

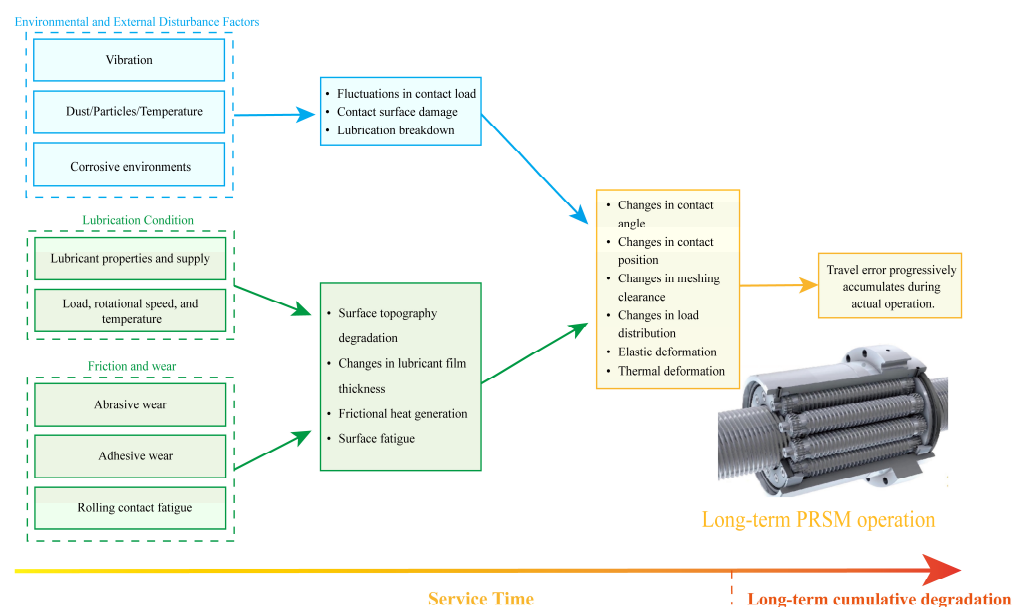
Rolling and relative sliding coexist in the motion between the components of a PRSM, and the lubrication condition directly affects the frictional characteristics of the contact surfaces. The lubrication condition mainly depends on lubricant properties, lubricant supply, load, rotational speed, temperature, surface roughness, and other factors, and may exhibit different lubrication regimes, including boundary lubrication, mixed lubrication, and elastohydrodynamic lubrication. When the lubrication conditions change, the lubricant film thickness, asperity contact ratio, and lubricant shear state in the contact region change accordingly, resulting in variations in the friction coefficient, friction torque, and frictional heat generation.

During long-term operation, loads and relative sliding cause material removal and surface damage on the thread surfaces, resulting in wear. Insufficient lubrication or deterioration of the lubrication condition generally increases direct asperity contact and may aggravate surface damage such as abrasive wear and adhesive wear. Meanwhile, the degree of wear is also affected by multiple factors, including contact load, sliding distance, material and surface properties, and temperature. As wear gradually accumulates, the thread profiles, surface topography, and meshing clearances of the screw, rollers, and nut may change, causing the actual contact positions and load distribution to deviate from

their initial states and consequently altering the actual axial displacement relationship of the mechanism. Therefore, lubrication and friction mainly induce travel error indirectly by affecting the operating conditions of the contact surfaces and the elastic deformation of the screw mechanism, whereas the geometric errors and changes in contact conditions caused by accumulated wear are important reasons for the long-term increase in travel error and the degradation of accuracy retention. Future research should further consider the time-varying coupling relationships among lubrication, friction, temperature rise, and wear, and establish quantitative models of PRSM travel error and long-term accuracy degradation propagation that account for lubrication factors.

#### 2.4.3. Theoretical Analysis of Service and Environmental Effects

The relationships between the service and environmental factors discussed above and travel error can be qualitatively summarized in Figure 7. The schematic illustrates the pathways through which the external environment and mechanical disturbances, lubrication conditions, and friction and wear contribute to travel error during long-term actual operation of a PRSM.



**Figure 7.** Influence pathways of service and environmental factors on travel error.

Existing studies on the service and environmental factors of PRSMs have mainly focused on lubrication, friction, and wear, whereas direct investigations of environmental factors remain relatively limited. In terms of mechanical disturbances, related studies [51–53] have mainly established dynamic models of PRSMs to analyze time-varying loads, meshing excitations, and vibration responses, and have revealed the effects of vibration states on contact forces, dynamic displacements, and operational stability. However, most existing studies have focused on internal excitations of the mechanism, while investigations into the transmission of environmental disturbances, such as external base vibration and impact, to travel error remain limited. For dust, contamination, humidity, and corrosive media, their effects have been more extensively investigated in rolling bearings, gears, and other rolling-sliding contact pairs, where they mainly manifest as lubricant-film breakdown, abrasive wear, corrosion, and surface-condition degradation. However, quantitative relationships between these environmental factors and PRSM travel error have not yet been sufficiently investigated. In contrast, relatively systematic theoretical and experimental studies have been conducted on lubrication, friction, and wear in PRSMs. Aurégan et al. [54] simulated the

threaded contact conditions of PRSMs through rolling–sliding contact tests and investigated friction and surface damage under different lubrication conditions. The results showed that dry friction and poor lubrication significantly aggravated adhesive wear, whereas adequate lubrication maintained a relatively low friction level, providing experimental evidence for understanding how lubrication conditions affect the long-term accuracy retention of PRSMs through wear evolution. SHI [55] analyzed the sources of rolling friction in PRSMs and considered the effects of lubricants on friction torque and heat dissipation performance. Combined with thermal characteristic analysis and dust-generation tests, the lubrication condition and its degradation during service were investigated. This study preliminarily revealed, from the perspectives of friction and thermal effects, the pathways through which lubrication conditions affect the operational performance of PRSMs. However, the study mainly focused on friction, thermal characteristics, and lubrication degradation, and the quantitative relationships between these factors and PRSM travel error were not investigated in depth. Miao et al. [56] established a thermo-elastohydrodynamic lubrication–wear model for PRSMs considering surface roughness and temperature rise and comparatively analyzed the accuracy loss rates under dry-contact and lubricated conditions, thereby preliminarily establishing a relationship among lubrication conditions, wear evolution, and the accuracy retention of PRSMs. Zhu [57], based on high-temperature unlubricated conditions, established a method for calculating the friction coefficient of PRSMs under lubricated and mixed-contact conditions and compared the friction characteristics under unlubricated and lubricated conditions, providing a theoretical basis for revealing how lubrication conditions affect travel error through frictional behavior.

In summary, existing studies have mainly focused on the mechanisms by which service-related factors affect the performance degradation of PRSMs, with research objectives still largely centered on wear amount, performance degradation limits, and life prediction. Comparatively less attention has been paid to the travel error caused by various factors under operating conditions and its time-varying evolution. In particular, changes in lubrication conditions, friction fluctuations, temperature rise, external vibration, and accumulated wear are often investigated separately, and a unified transmission relationship that takes travel error as the final evaluation index is still lacking. Therefore, future research should further investigate the effects of environmental factors and lubrication-induced friction and wear on travel error, as well as cumulative travel error. Combined with dynamic travel error testing under long-term operating conditions, such studies should reveal the evolution of PRSMs from initial accuracy fluctuations to long-term accuracy degradation.

### 3. Theoretical Analysis of Travel Error

Analysis of an individual error can reveal its mode of action and resulting effects. However, in practical engineering applications, travel error does not arise from the linear superposition of individual errors. Therefore, a coupled model of multiple error sources should be established to comprehensively analyze the interactions among different types of errors. From the perspective of error transmission paths, geometric errors primarily alter the initial meshing positions, whereas installation errors change the relative spatial positions of the components. Applied loads induce contact deformation and load redistribution, while thermal deformation causes axial elongation and changes in meshing clearance. These factors interact through meshing point migration, variations in contact stiffness, uneven load distribution, and thermal drift, ultimately manifesting as the travel error of the screw mechanism.

### 3.1. Research on Multisource Travel Error Coupling Modeling

In studies of travel errors in PRSMs, the experimentally measured travel error curve does not reflect a single isolated error source. Instead, it represents the combined effects of multiple factors, including manufacturing and geometric errors, installation errors, and load and thermal deformation errors. With the continuous improvement of testing methods and the growing demands of engineering applications, research has increasingly shifted toward the modeling and analysis of multi-source coupled transmission errors [58]. The core of travel error analysis is to incorporate the various influencing factors into a unified theoretical framework and reveal how different error sources are transmitted, superimposed, and coupled along the transmission chain.

Khan et al. [59] proposed a systematic error propagation framework based on homogeneous transformation matrices, enabling the unified representation of multiple types of geometric errors and revealing, for the first time, their coupling behavior during error transmission and accumulation. Li et al. [60] investigated three categories of error sources in PRSMs: intrinsic mechanism errors, intermediate device errors, and environmental errors. They quantified the influence of different error sources on travel error and subsequently established a transmission error model. However, machining errors of the screw were not considered comprehensively. Ma et al. [61] established a load distribution model for PRSMs that accounts for errors, wear, and temperature variations based on deformation compatibility relationships. The model was validated through analytical calculations and finite element analysis, providing a new approach to multi-factor coupling modeling of travel errors in PRSMs. Zheng et al. [62] investigated the travel error of PRSMs by analyzing the effects of machining errors, installation errors, and deformation errors. They established a screw travel error model and validated it experimentally. However, their model did not account for the travel errors of the nut and rollers. Yang et al. [37] developed a transmission accuracy model for PRSMs that simultaneously considers installation errors and elastic deformation. They systematically analyzed the effects of gear and screw installation errors and elastic deformation on the overall transmission accuracy and experimentally verified the effectiveness of the model. Liu et al. [63] developed a thread contact prediction model that accounts for gravity-induced roller displacement and multiple machining errors. Rolling and sliding were also incorporated into the calculation of transmission error, further improving the accuracy of transmission accuracy prediction.

In summary, existing research has gradually expanded from early analyses of geometric error propagation to comprehensive investigations of the combined effects of machining errors, installation errors, elastic deformation, temperature variations, and wear degradation. The corresponding models have revealed how multiple error sources are transmitted, accumulated, and coupled along the transmission chain of PRSMs, thereby providing a theoretical basis for travel error prediction, error source identification, and accuracy optimization. However, current travel error models still have several limitations. First, most existing models focus on the travel error of the screw or the overall travel error of the screw mechanism. The mapping relationships through which errors in individual components, such as the external roller raceway, internal nut raceway, and synchronizing gears, are transmitted separately and jointly contribute to travel error remain insufficiently understood. Second, some theoretical models are still based on idealized boundary conditions or static operating conditions and lack experimental validation under realistic loads, temperature rise, long-term wear, and dynamic operating conditions.

### 3.2. Sensitivity Analysis and Dominant Error Identification

Under multi-source error coupling, the travel error of a PRSM is jointly affected by multiple error sources. However, the contribution of each error source to the final

travel error varies under different operating conditions. Therefore, sensitivity analysis and dominant error identification are necessary on the basis of travel error modeling.

Zhang [64] designed a two-stage PRSM and constructed matrices for the individual error sources. The corresponding error coefficient matrix was then obtained through calculation. The results showed that, under conventional operating conditions, lead error and flank angle error had substantially greater effects on travel accuracy than the other error sources. This study provided a method for identifying dominant errors, although its applicability remains limited under multiple operating conditions. Liu [65] established an accuracy degradation model for PRSMs based on fractal geometry theory and analyzed the effects of different operating conditions on accuracy degradation. The results showed that factors such as axial load, fractal dimension, and operating time all increase travel error. Among them, fractal dimension, as a quantitative indicator of surface roughness, has a significant influence on accuracy degradation. This finding indicates that controlling surface topography during design and manufacturing can help slow the growth of travel error. Wu et al. [66] established a numerical analytical model of PRSM travel accuracy under multiple roller engagement conditions. A random forest algorithm was used to evaluate the importance of individual machining error parameters in the travel accuracy model, identify the sources of travel error, and derive a rapid prediction formula for travel accuracy. Liu et al. [67] developed a physics-based transmission accuracy model incorporating 16 error terms. A generative adversarial network was then used to augment the small sample dataset and predict travel deviation. The results showed that consistency in the nominal roller diameter is an important factor affecting travel variation. This method provides a new approach to dominant error identification and tolerance allocation. However, it mainly focuses on machining errors, and the coupled effects of installation errors, loads, and thermal deformation require further investigation.

Existing studies have employed error coefficient matrices, fractal geometry models, random forest algorithms, and hybrid physics–data approaches to analyze the effects of different error sources on travel accuracy from the perspectives of geometric and machining errors, surface topography, operating conditions, and consistency among multiple rollers [68]. Studies have shown that the dominant factors affecting travel error vary with operating conditions, error types, and evaluation indices. Identifying the dominant error sources not only clarifies the origins of travel error but also provides a basis for tolerance allocation, assembly accuracy control, surface quality optimization, and error compensation. However, existing studies still have several limitations. First, some sensitivity analyses have been conducted only under specific operating conditions or using a single evaluation index, with insufficient consideration of changes in dominant error relationships under multiple operating conditions, such as variable loads, temperature rise, and long-term operation. Second, previous studies have mainly focused on machining errors and surface topography parameters, whereas comprehensive sensitivity analyses involving installation errors, testing installation errors, thermal deformation, and wear degradation remain inadequate.

Overall, the travel error of a PRSM is not caused by a single factor but results from the combined effects of manufacturing, assembly, loading, and thermal factors. Manufacturing and geometric errors affect the initial meshing relationships, installation errors cause spatial misalignment among the components, and load-induced and thermal deformation alter the contact conditions and actual axial displacement. When multiple error sources coexist, their coupled interactions further complicate the formation mechanism of travel error. Existing theoretical studies have provided a foundation for error source analysis, accuracy prediction, and error compensation. However, the travel error must ultimately be validated through experimental measurement, because theoretical models alone cannot

fully represent the actual transmission accuracy of the screw mechanism. Therefore, this paper systematically reviews the available travel error measurement methods and discusses their characteristics and application fields.

## 4. Research on Travel Error Testing Methods

Travel error results from the combined effects of multiple error sources. Therefore, quantitatively analyzing the contribution of each error is of great significance for calculating travel error and improving the accuracy of PRSMs. With the development of precision measurement technology and computer numerical control testing equipment, researchers have extensively investigated travel error measurement methods, test platform configurations, and error compensation algorithms for PRSMs. These methods can be broadly classified into two categories: static measurement methods and dynamic measurement methods.

### 4.1. Travel Error Testing Procedure and Basic Principles

The core of travel error testing is to obtain the actual axial displacement of the PRSM during operation and compare it with the nominal axial displacement, thereby determining the displacement deviation generated during the actual transmission process. The differences among these testing methods mainly lie in how the nominal displacement is calculated and how the actual displacement is measured. However, their ultimate objective is to obtain a travel error curve that reflects transmission accuracy. The nominal axial displacement is typically obtained using a calculation model based on the ideal transmission relationship of the PRSM. During screw testing, the screw rotation angle is typically obtained from an encoder, an indexing device, or feedback signals from the servo system. The nominal axial displacement is then calculated based on the nominal lead of the screw. If the nominal lead of the screw is  $P$  and the input rotation angle is  $\theta$ , the nominal axial displacement can be expressed as follows:

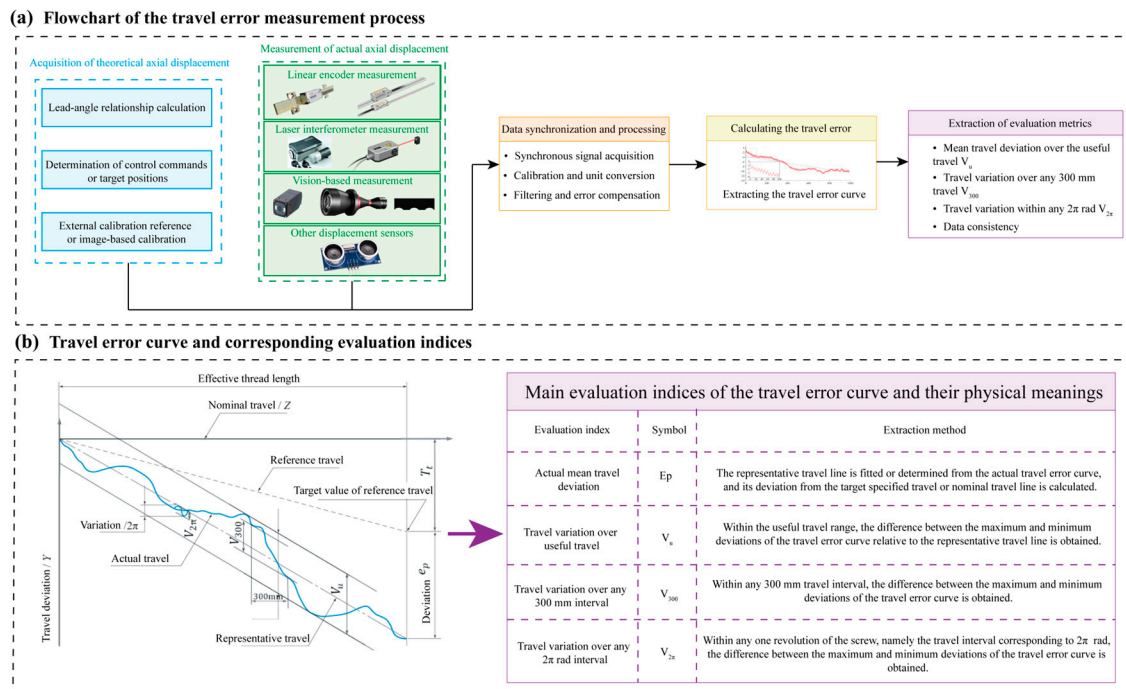
$$x_t = \frac{P\theta}{2\pi} \quad (2)$$

where  $x_t$  denotes the nominal axial displacement. For testing devices equipped with servo control systems, the nominal displacement can also be determined from motion control commands or a standard displacement reference. For non-contact testing methods such as machine vision, a nominal displacement reference can be established through image calibration, feature point displacement conversion, or an external calibration reference.

The actual axial displacement is the directly measured quantity, and its measurement accuracy determines the reliability of the travel error curve. Depending on the measurement reference, the actual axial displacement can be measured using a linear encoder, laser interferometer, machine vision system, or displacement sensor. These measurement methods differ in measurement accuracy, dynamic response, environmental adaptability, and system integration complexity. Therefore, an appropriate method should be selected according to the test object, travel range, accuracy requirements, and test conditions.

The test results are generally presented not as a single displacement value but as an actual travel curve that reflects travel accuracy. Since no dedicated standard for travel error testing of PRSMs is currently available, the relevant test items can refer to the provisions on travel deviation of ball screw assemblies specified in GB/T 17587.3-2017 [69], Ball Screws—Part 3: Acceptance Conditions and Acceptance Tests, and ISO 3408-3:2006. The measurement procedure and evaluation indicators of travel error are shown in Figure 8. Common evaluation indices include the actual mean travel deviation, the travel variation over the useful interval, the travel variation over any 300 mm interval, and travel

variation over any  $2\pi$  rad interval. The current requirements for travel error of ball screw assemblies specified in GB/T 17587.3-2017 [70] are shown in Table 1.



**Figure 8.** Travel error measurement procedure and evaluation indices [71]. (a) Flowchart of the travel error measurement process; (b) travel error curve and corresponding evaluation indices.

**Table 1.** Travel error requirements for ball screw assemblies specified in GB/T 17587.3-2017 (example for a useful travel of 0–315 mm).

| Accuracy Grade                                                       | P0  | P1 | P2 | P3 | P4 | P5 |
|----------------------------------------------------------------------|-----|----|----|----|----|----|
| Travel variation over any 300 mm interval<br>$V_{300}/\mu\text{m}$   | 3.5 | 6  | 8  | 12 | 16 | 23 |
| Travel variation over any $2\pi$ rad interval $V_{2\pi}/\mu\text{m}$ | 3   | 4  | 5  | 6  | 7  | 8  |
| Travel variation over useful travel $V_u/\mu\text{m}$                | 4   | 6  | 8  | 12 | 16 | 23 |
| Actual mean travel deviation $E_p/\mu\text{m}$                       | 3.5 | 6  | 8  | 12 | 16 | 23 |

The key to travel error testing lies in establishing a reliable nominal displacement reference and accurately obtaining the actual axial displacement, thereby generating a travel error curve for subsequent analysis. On this basis, indices such as travel variation can be used to evaluate the transmission accuracy of the PRSM over travel ranges of different scales.

#### 4.2. Static Measurement Methods

Static measurement is an intermittent measurement method. It measures one or more generatrices of the screw and takes the helical line error along the entire generatrix as the measurement result [72]. The measurement procedure is relatively simple; instruments such as universal tool microscopes, universal length measuring machines, and static profilometers are commonly used for measurement [73]. The principal static measurement methods include the optical imaging method, axial section method, and interferometric method. Typical static measurement devices and their measurement principles are illustrated in Figure 9. Wu [74] was the first to design an auxiliary stop mechanism that allowed the screw to rotate and the nut to translate when the indexing head was turned.

An optical sensitive lever positioned against the nut end face and a longitudinal reading device were then used to obtain the thread reading corresponding to each rotation angle. By comparing the measured reading with the nominal value, the lead error at a specific point was determined.

**(a) Common instruments for static measurement**



**(b) Comparison of pitch measurement methods**

| Method                        | Principle                                                                                                                                                                                                                                                                                                                         | Advantages                                          | Disadvantages                                                                                        |
|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------|------------------------------------------------------------------------------------------------------|
| <b>Imaging method</b>         | The reticle of the microscope is aligned with one flank of the thread profile and the reading is recorded. The microscope is then translated to align the reticle with the corresponding flank of the adjacent thread profile, and a second reading is taken. The pitch is determined by the difference between the two readings. | Intuitive operation; simple procedure               | Limited measurement accuracy                                                                         |
| <b>Knife-edge method</b>      | A precision knife-edge is brought into contact with one flank of the thread profile. The measurement is performed by aligning the fiducial mark on the knife-edge with the reticle of the universal tool microscope. The same procedure is repeated on the corresponding flank of the adjacent profile.                           | Higher accuracy compared to the vision-based method | Non-continuous measurement; results are influenced by the selection of representative cross-sections |
| <b>Interferometric method</b> | Pitch errors are evaluated by observing variations in interference fringe patterns. Using a universal tool microscope, the direction and magnitude of fringe shifts are recorded, from which the lead error of the screw thread can be calculated.                                                                                | High resolution                                     | Sensitive to environmental disturbances; time-consuming procedure                                    |

**Figure 9.** Static measurement device [75]. (a) Common instruments for static measurement; (b) comparison of pitch measurement methods.

The main advantages of static measurement methods are their simple structure, low cost, and modest environmental requirements. These measurement results can reflect the geometric accuracy of individual screw components and provide a basis for evaluating PRSM travel accuracy, but they cannot be directly regarded as equivalent to the overall travel error of an assembled PRSM. Owing to the limited number of measurement points, this method cannot continuously characterize the error distribution along the full thread length. In addition, manual reading and fixturing errors may limit measurement accuracy and repeatability, making it difficult to meet the requirements for error evaluation of high-precision, long-travel screw mechanisms under dynamic operating conditions.

#### 4.3. Dynamic Measurement Methods

Dynamic measurement methods refer to methods that continuously monitor and analyze the travel error of a PRSM during operation [76]. Dynamic measurement methods are currently widely used for travel error measurement of screw mechanisms. Compared with static measurement, which considers only geometric characteristics, dynamic measurement can capture transient deviations, periodic fluctuations, and errors induced by temperature and load during transmission. A typical dynamic measurement system generally consists of a drive unit, a transmission actuator, a displacement reference system, and a synchronous

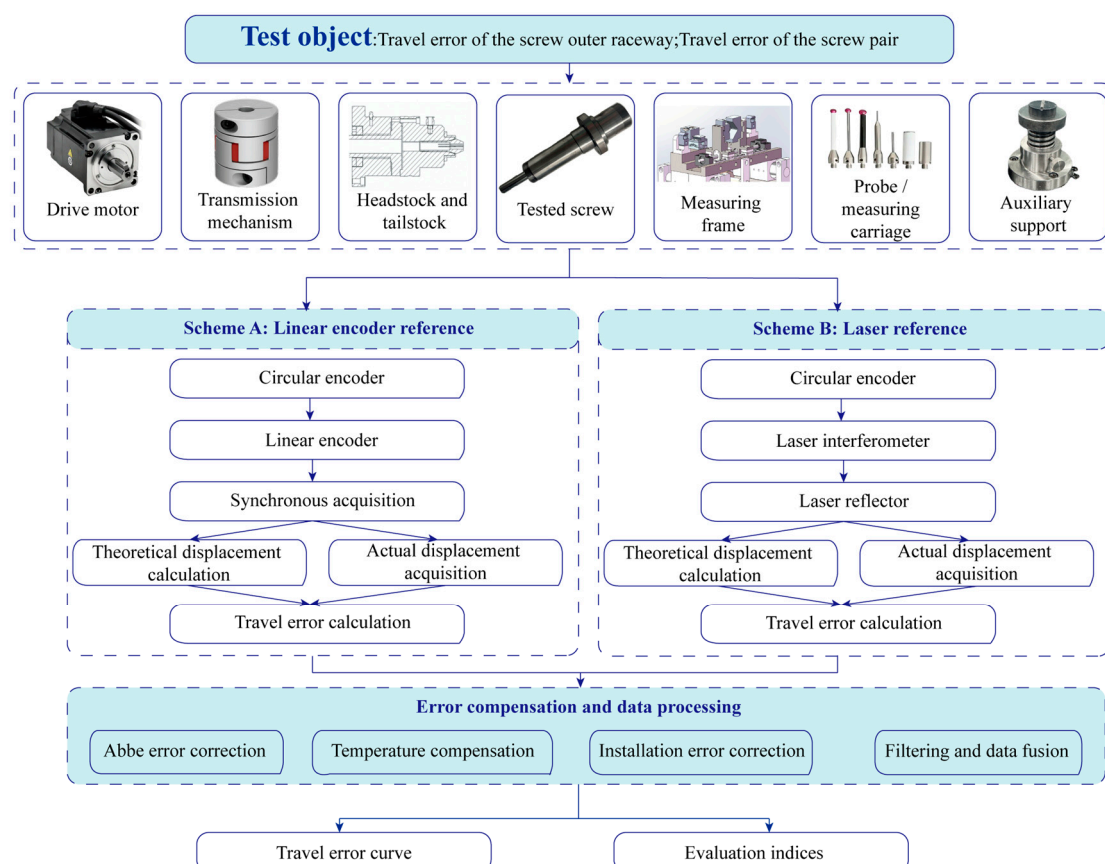
data acquisition module. The displacement reference system is the core of the measurement chain. Current mainstream approaches to travel error measurement commonly use a laser interferometer or a linear encoder as the length reference to ensure adequate measurement resolution and accuracy.

#### 4.3.1. Research Progress on Travel Error Measurement Equipment Based on Optical Displacement References

Measurement systems based on optical displacement references are the mainstream approach for travel error measurement of screw mechanisms. Figure 10 presents a schematic flowchart of the travel error measurement technology based on an optical displacement reference. Figure 11 illustrates a simplified schematic of the fundamental measurement principle of travel error measurement instruments based on an optical displacement reference. Such test benches typically use a linear encoder or a laser displacement sensor as the high-precision displacement reference. For measurement of the travel error of an external screw raceway, a contact probe is brought into contact with the raceway to acquire the displacement error in real time. For measurement of the travel error of a screw mechanism, the measuring carriage is connected to the nut so that its axial displacement can be acquired continuously. Compared with conventional measurement methods, these test benches offer high resolution and strong resistance to interference. They can achieve micrometer-level measurement accuracy and can be readily integrated with a host computer control system for error compensation and dynamic data analysis. Therefore, they are widely used in both scientific research and industrial inspection. However, the nominal accuracy of a high-precision displacement sensor does not directly represent the measurement capability of the entire travel error measurement system. The actual measurement results are also affected by factors such as calibration of the length reference, traceability of the measurement chain, sensor resolution and repeatability, Abbe error, cosine error caused by non-parallelism between the measurement axis and the motion axis, alignment error, environmental temperature, and structural thermal drift. Therefore, for high-precision PRSM travel error measurement, measurement uncertainty should be evaluated by considering the individual error sources, and the measurement capability under specific test conditions should be clearly defined.

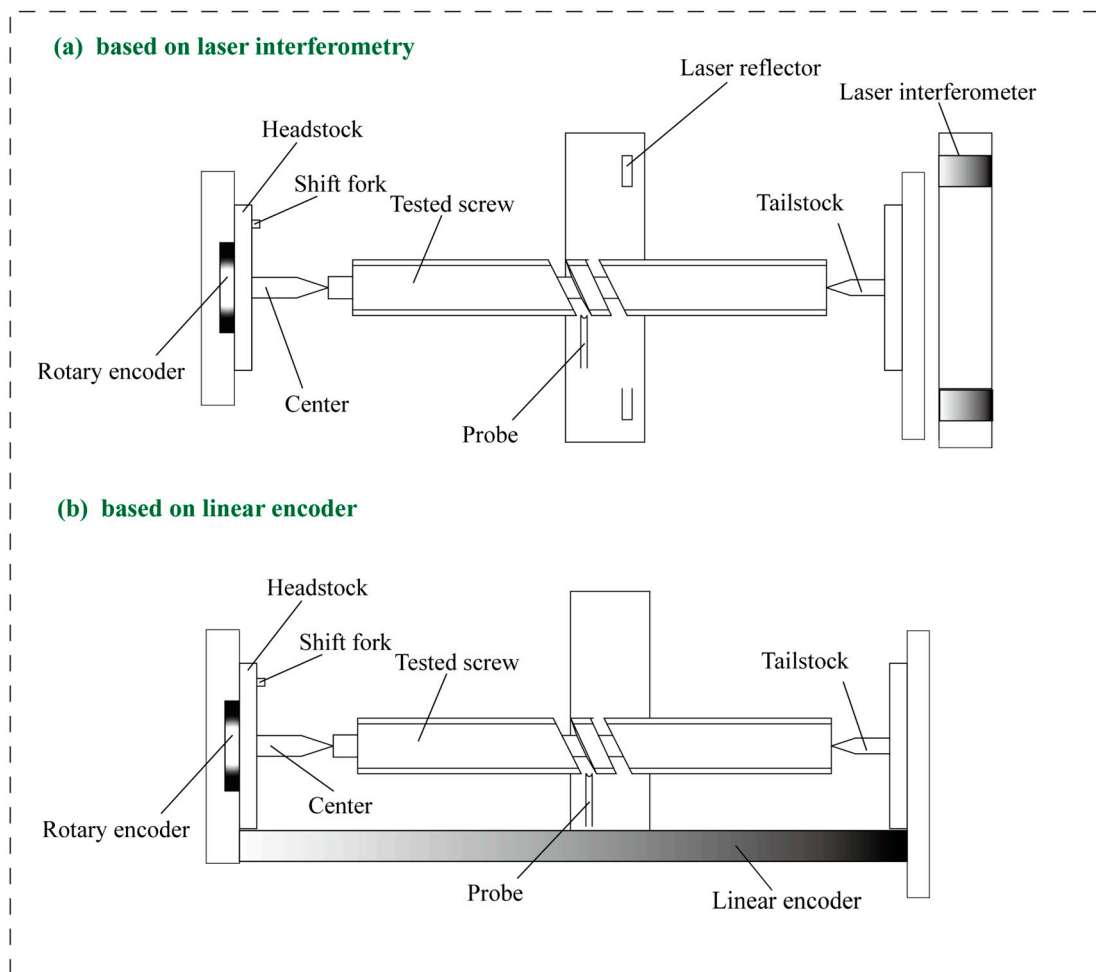
Since screw mechanisms were first manufactured, static measurement methods were initially used to evaluate their travel error. However, these methods cannot characterize the overall linear variation in travel error along the full thread length. In addition, their reliance on manual readings makes it difficult to obtain accurate error values [77]. In the 1970s, NSK of Japan developed the LMS 3 m dynamic laser lead measuring machine. For the first time, the transmission of the measurement system was separated from that of the measuring table, enabling dynamic measurement of lead error [78]. The French company SORO subsequently developed laser lead measuring equipment for screw mechanisms in various specifications, including the CUB3000. This equipment was the first to measure the cumulative lead error of a screw mechanism, with a measurement accuracy of up to 1  $\mu\text{m}$  [79]. The West German company LINDNER developed the GMM-4 screw thread lead measuring machine, which incorporated temperature compensation into dynamic lead error measurement. In the 1990s, Hanjiang Machine Tool Works developed the HJY028 3 m dynamic laser screw measuring instrument [80]. This instrument used a circular encoder as the angular reference and a dual-frequency laser as the length reference. Its dedicated interferometer design effectively corrected Abbe error, providing a wider measurement range and higher accuracy and filling a gap in domestically produced travel error measuring instruments. Universities, represented by Nanjing University of Science and Technology, have conducted extensive research on improving the accuracy of travel error test benches for screw mechanisms. Ding [81] developed a 10 m dynamic thread measuring instrument and

performed a systematic analysis of its overall measurement accuracy. The structures of the measuring head and floating measuring frame were also optimized, further improving the accuracy of the travel error test bench. Xia et al. [82] designed a dynamic auxiliary support device that moves synchronously with the nut. The device provides continuous support over the full travel of the screw, thereby reducing vibration, improving coaxiality, and enhancing both transmission accuracy and operational stability. Yao et al. [83] developed a novel clamping mechanism and proposed a transmission accuracy measurement method capable of eliminating axial runout error in real time. This method corrected Abbe error and improved measurement accuracy. Hu et al. [84] optimized the control system of a travel error test bench based on a long linear encoder. By calibrating the encoder with a laser interferometer, the system achieved higher measurement accuracy while reducing cost. Tan [85] combined travel error and friction torque measurements and developed a general test platform for evaluating both parameters in miniature screw mechanisms. This platform filled a gap in performance testing for miniature screw mechanisms. However, it can test only ball screws with diameters of 8–16 mm, and its between-centers configuration cannot accommodate measurement of the external roller raceways of PRSMs with smaller diameters. Lin et al. [86] proposed five accuracy retention evaluation indices, including travel error failure, together with a comprehensive evaluation algorithm, thereby improving the accuracy retention evaluation framework for ball screw mechanisms. However, no corresponding analysis was conducted for PRSMs. Li [87] developed a data acquisition system for ball screw performance evaluation parameters and established a corresponding parameter database. Liu [88] experimentally analyzed the degradation trend of screw mechanisms, classified their health states, and formulated an optimal inspection strategy.



**Figure 10.** Travel error measurement techniques based on optical displacement references.

## Configuration of the travel error measurement test rig



**Figure 11.** Simplified diagram of the basic measurement principle. (a) Simplified schematic of dual-beam laser measurement; (b) simplified schematic of linear encoder measurement.

In addition to the overall design and optimization of travel error test benches, numerous studies have also focused on their individual functional units. Pan [89] proposed an error processing algorithm for the probe system and established a pretravel error prediction model. Yao et al. [90] developed an axial displacement measurement device for screws and improved the accuracy of travel error measurement by introducing compensation terms into the algorithm. Ma et al. [29] established a relatively comprehensive travel accuracy model that accounts for manufacturing errors based on the kinematic relationships of a standard PRSM. By experimentally measuring the manufacturing errors and travel accuracy, they further determined the sensitivity of travel accuracy to individual manufacturing errors. Wang et al. [91] conducted a comprehensive error analysis and compensation study for a large travel displacement measurement system based on a dual-frequency laser interferometer, thereby improving the error compensation method for laser displacement measurement. Wang et al. [92] derived an expression describing the influence of Abbe error on laser interferometric displacement measurement, providing a theoretical basis for error compensation. Jiao Shengsong et al. [93] modified the fixed supports, measuring carriage, and overall structure of the test bench, thereby addressing the challenges associated with travel error measurement of heavy-duty screw mechanisms.

Overall, travel error testing technology for screw mechanisms has gradually evolved from single-displacement measurement toward high-accuracy, long-travel, and application-

specific testing. Figure 12 shows the photographs of representative measuring instruments. Early systems mainly employed single-frequency or dual-frequency laser interferometers to establish the displacement reference. Subsequently, technologies such as aerostatic guideways, floating supports, and real-time data acquisition were introduced to improve the motion stability and automation level of the measurement systems. With the continuous expansion of application requirements, dedicated testing solutions have been developed for ultra-long, miniature, and heavy-duty screw mechanisms. The measurable range has increased from several hundred millimeters to more than ten meters, while the diameter range of the tested screws has also been extended to cover different specifications. Although the test benches listed in Table 2 were mainly developed for ball screw mechanisms, their basic measurement principles, which use laser interferometers or linear encoders to obtain axial displacement, can in principle be applied to the measurement of the overall travel error of assembled PRSMs. Although test benches based on laser interferometers and linear encoders have become relatively mature for travel error measurement of ball screw mechanisms, their measurement targets are generally limited to the travel error of the screw and the overall travel error of the screw mechanism. It remains difficult to separately measure the individual travel errors associated with the multiple roller–nut and roller–screw contact pairs in a planetary roller screw mechanism. Therefore, when such test benches are directly applied to PRSMs, limitations still remain in terms of incomplete measurement coverage and difficulty in distinguishing different error sources.



**Figure 12.** Photographs of representative measuring instruments [85,93,94]. (a) A 12 m dynamic travel error measuring system for ball screw pairs. (b) Travel error measuring system for heavy-duty ball screw pairs; (c) universal travel error and friction torque test platform for miniature screw pairs; (d) 10 m dynamic comprehensive travel error measuring system for ball screw pairs.

Table 2. Comparison of similar testing equipment.

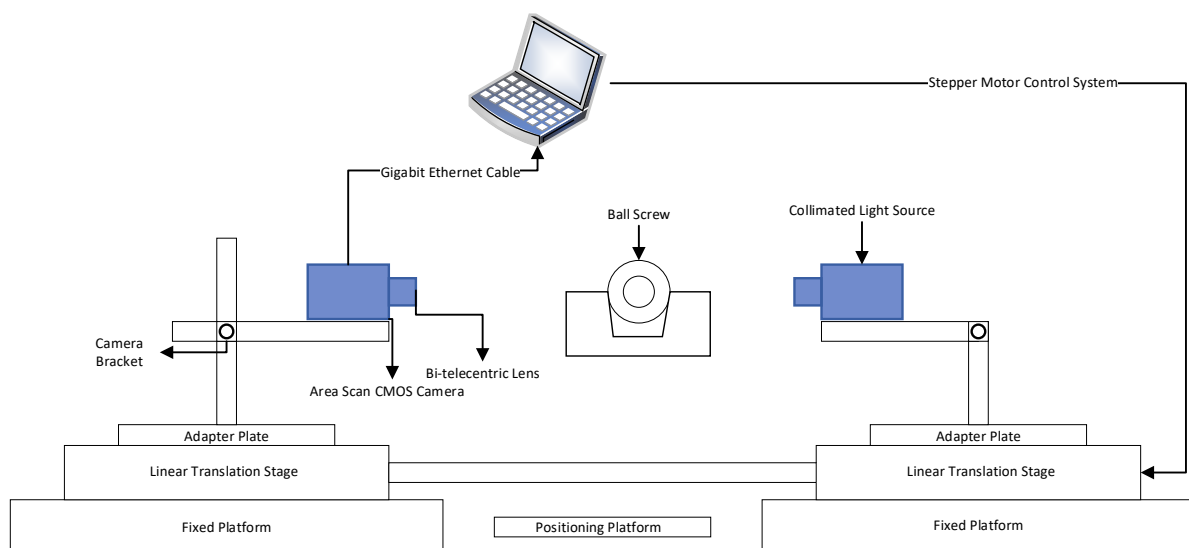
| Test Equipment                                                                             | Year  | Reported Accuracy                   | Primary Displacement Reference                    | Key Technical Features                                                                                        | Measurement Range |                   | Test Object                                                        |
|--------------------------------------------------------------------------------------------|-------|-------------------------------------|---------------------------------------------------|---------------------------------------------------------------------------------------------------------------|-------------------|-------------------|--------------------------------------------------------------------|
|                                                                                            |       |                                     |                                                   |                                                                                                               | Screw Length/mm   | Screw Diameter/mm |                                                                    |
| HJY-05 Measuring Instrument                                                                | 1988  | Not reported                        | Single-frequency laser interferometer             | Single-frequency laser phase comparison measurement                                                           | Max 5000          | Not reported      | 1 m trapezoidal screw                                              |
| HJY-028<br>3 m Dynamic Laser Measuring Instrument                                          | 1990s | Not reported                        | Dual-frequency laser interferometer               | Real-time counting; first use of a dual-frequency laser                                                       | Max 3000          | Not reported      | P3-grade ball screw mechanisms up to 2 m; P5 trapezoidal screws    |
| JCS-040 3 m Laser Travel Error Measuring Instrument for Ball Screw Mechanisms              | 1997  | Not reported                        | HP dual-frequency laser interferometer            | Aerostatic guideway, disc spring support, and real-time output of error curves                                | Max 3000          | Not reported      | P1-grade 1.5 m screws and P3-grade 3 m screws                      |
| 10 m Dynamic Laser Measurement System for Cumulative Travel Error of Ball Screw Mechanisms | 2012  | Maximum measurement error: 6.242 μm | Renishaw laser interferometer                     | Flat-V guideway measuring table and densely packed ball bearing headstock                                     | 5000–10,000       | Not reported      | P2-grade 1–5 m screw mechanisms and P3-grade 10 m screw mechanisms |
| 12 m Dynamic Laser Travel Measuring Instrument for Ball Screw Mechanisms                   | 2013  | Not reported                        | Agilent 5519A dual-frequency laser interferometer | Magnetically balanced aerostatic guideway, optimized headstock and tailstock structures, and floating support | Max 12,500        | 50–220            | P1–P3-grade 12 m large screw mechanisms                            |
| Dynamic Ball Screw Measurement System                                                      | 2017  | Not reported                        | Long linear encoder                               | Integrated measurement and control; laser self-calibration of the linear encoder                              | Max 7000          | Not reported      | P1–P3-grade 7 m ball screw mechanisms                              |

Table 2. Cont.

| Test Equipment                                                                           | Year | Reported Accuracy                                                                                                                                                                                                                         | Primary Displacement Reference      | Key Technical Features                                                                              | Measurement Range |                   | Test Object                          |
|------------------------------------------------------------------------------------------|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------|-------------------|-------------------|--------------------------------------|
|                                                                                          |      |                                                                                                                                                                                                                                           |                                     |                                                                                                     | Screw Length/mm   | Screw Diameter/mm |                                      |
| General Test Platform for Travel Error and Friction Torque of Miniature Screw Mechanisms | 2020 | Maximum measurement error: 3.6 $\mu\text{m}$                                                                                                                                                                                              | Long linear encoder                 | Dual-parameter general test platform; suspended headstock structure for miniature screw measurement | 0–500             | 8–25              | P3-grade miniature screw mechanisms  |
| Travel Measuring Instrument for Heavy Duty Screw Mechanisms                              | 2025 | Geometric accuracy validation: rotational error of 2 $\mu\text{m}$ , parallelism $\leq 7 \mu\text{m}/200 \text{ mm}$ , and alignment deviation $\leq 3 \mu\text{m}$ (1–4 m); maximum measurement error of the overall system not reported | Dual-frequency laser interferometer | Flexible support for the gantry carriage and efficient alignment                                    | 200–4000          | 90–305            | P1-grade heavy duty screw mechanisms |

#### 4.3.2. Research Progress on Travel Error Measurement Techniques Based on Machine Vision

Although travel error test benches based on optical principles have become the mainstream solution because of their high measurement accuracy and stable data acquisition, their bulky structures, complex system configurations, and strong dependence on environmental conditions limit their application in certain scenarios. In recent years, researchers worldwide have proposed various improved dynamic measurement methods to meet different testing requirements and accommodate environmental constraints. Among them, machine vision measurement uses captured images as the primary data source and employs image processing techniques to achieve non-contact measurement of lead error [95]. Hunsicker et al. [96] developed a machine vision-based technique for rapid measurement of screw and nut parameters. The method enables measurement of parameters including the major diameter, minor diameter, and lead of the screw. Following the use of a line scan CCD industrial camera by Zuo et al. [97] to acquire thread parameter data, numerous researchers [98–100] investigated the application of line scan CCD vision to thread parameter measurement. These studies ultimately led to the development of a thread parameter measurement system capable of measuring threads of various sizes. Han [101] combined an optical system with an image processing module to develop a screw pitch error measurement device, as shown in Figure 13. By acquiring screw images and processing the data in real time, the device displays the pitch values and corresponding error curves in real time on a LabVIEW platform. Yu [102] developed a machine vision-based screw lead measurement device and proposed a virtual nut-based lead measurement method. The method extracts the coordinates of ball centers from the screw edge pixels, selects the relevant coordinates within the recirculation range of the nut, and fits the axis of a virtual nut. The lead is then accurately calculated from the axial displacement of the virtual nut. However, this method has considerable limitations and is applicable only to specific ball screws.



**Figure 13.** Screw pitch measurement system [101].

The main advantage of machine vision-based travel error measurement methods is that their non-contact nature prevents the probe from introducing additional errors through interaction with the screw surface during measurement, thereby enabling more consistent data acquisition. However, compared with test benches based on laser interferometers or linear encoders, these methods generally provide lower measurement accuracy and stability.

Their direct application to the measurement of comprehensive dynamic travel error in assembled PRSMs remains limited because of the complex internal structure and coupled motion of multiple rollers. Nevertheless, machine vision remains potentially applicable to component-level inspection, such as the measurement of screw thread geometry, roller external threads, surface features, and manufacturing errors [103,104].

#### 4.3.3. Research Progress on Auxiliary Travel Error Measurement Methods for Specific Operating Conditions

Although dynamic testing techniques based on optical displacement references offer extremely high measurement accuracy, their performance can be adversely affected by environmental disturbances or insufficient installation space under specific operating conditions, such as heavy loads, strong vibrations, and spatial constraints. Consequently, accurate measurement may become difficult or even impossible. To address the limitations of mainstream testing approaches in special application scenarios, researchers have investigated auxiliary measurement methods based on ultrasonic sensing, simplified laser systems, and mechanical measurement principles. These methods are generally designed for specific applications, such as short travel measurement, low-cost rapid screening, or operation in extreme environments. Although they still lag behind optical and vision-based methods in system versatility and overall accuracy, their flexible configurations and strong application specificity provide a useful complement for on-site monitoring and rapid engineering evaluation of PRSMs.

Zhang et al. [105] developed an error model for a precision linear stage based on error flow theory and proposed a geometric error sensitivity analysis method. To validate the proposed method, they designed a simplified travel error measurement device based on a single laser beam. The device is compact, structurally simple, and easy to operate. However, it does not compensate for the travel error of the screw and is applicable only to screws with very short travel, resulting in considerable limitations. Fan et al. [106] developed an automated system for measuring the cumulative lead error of a ball screw nut. The system was the first to enable measurement of both cumulative lead error and radial runout of the nut. However, it cannot measure other travel error parameters or comprehensively evaluate the individual travel error components of a screw mechanism during operation. Therefore, its range of application remains limited. Jiang et al. [107] replaced the expensive laser reference with an ultrasonic sensor and achieved real-time feedback of screw displacement through non-contact distance measurement. To address the nonlinear errors and low signal-to-noise ratio of ultrasonic sensors, they developed an accuracy enhancement method based on an adaptive frequency feature extraction network and a deep residual network. Although this approach cannot yet fully replace laser or linear encoder references in terms of absolute accuracy, it demonstrates considerable engineering value in specific applications, including low-cost industrial monitoring, displacement feedback under particular environmental conditions, and coarse accuracy compensation.

#### 4.4. Selection of Travel Error Measurement Methods

The selection of a travel error measurement method should be based on a comprehensive consideration of the measurement objective, accuracy requirements, travel range, structural characteristics of the test object, and test conditions. For high-accuracy laboratory measurement and calibration of the overall travel error of an assembled mechanism, laser interferometers use the laser wavelength as the length reference and offer high accuracy, strong traceability, and a wide measurement range. However, their measurement results are sensitive to environmental temperature, air pressure, humidity, and optical-path stability. Linear encoders can directly measure the actual axial displacement of moving components and offer convenient structural integration and strong capability for con-

tinuous dynamic data acquisition, making them more suitable for integration into test benches and for travel error measurement under continuous operating conditions. Their measurement performance, however, is affected by installation straightness, readhead orientation, thermal deformation, and other factors. Machine vision is mainly suitable for non-contact, component-level measurement of pitch, lead, and thread geometric parameters, and currently has difficulty in directly meeting the requirements for high-accuracy measurement of the overall dynamic travel error of assembled PRSMs. Ultrasonic and other displacement-sensing methods offer flexible configurations and relatively good environmental adaptability and can be used in specific scenarios such as space-constrained environments, complex operating environments, or low-cost measurement. However, in terms of absolute measurement accuracy, calibration stability, and versatility, they generally cannot replace laser interferometers or high-accuracy linear encoders. Therefore, these methods should not be regarded simply as having different levels of measurement accuracy; instead, the appropriate method should be selected according to the specific measurement task and accuracy requirements. Table 3 further compares the different methods in terms of their main measurement targets, advantages and disadvantages, and applicable scenarios.

**Table 3.** Travel error measurement methods.

| Measurement Method                         | Primary Measurand                | Advantages                                                               | Disadvantages                                                                                                               | Typical Application Scenarios                                                  |
|--------------------------------------------|----------------------------------|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Static measurement method                  | Pitch, lead, and helix error     | Simple structure and low cost                                            | Low measurement efficiency; unable to capture dynamic errors; large manual observation errors                               | Component manufacturing accuracy inspection and offline inspection             |
| Linear encoder-based test bench            | Actual axial displacement        | Stable measurement results, high resolution, and good repeatability      | Limited measurable screw length and complex installation and alignment                                                      | Continuous testing and low-cost measurement                                    |
| Laser based test bench                     | Actual axial displacement        | Stable measurement results, wide measurement range, and high accuracy    | High cost and high sensitivity to environmental conditions                                                                  | High-accuracy laboratory calibration and long-travel measurement               |
| Machine vision-based measurement technique | Thread geometry, pitch, and lead | Non-contact measurement avoids errors introduced by contact with a probe | Lower accuracy than optical interferometric measurement; applicable only to screws with clearly defined structural features | Non-contact measurement                                                        |
| Other methods                              | Actual axial displacement        | Highly application specific                                              | Applicable only to specific scenarios and therefore highly limited                                                          | Low-cost measurement, space-constrained applications, and special environments |

## 5. Conclusions

PRSMs are key transmission components in many high-precision instruments and equipment, and their accuracy is critical to transmission reliability. Therefore, the measurement and investigation of travel errors in PRSMs have become an important means of improving equipment operating reliability. This paper first reviews studies on the influenc-

ing factors, generation mechanisms, and modeling of travel error in screw mechanisms, and then summarizes the research progress in travel error measurement technologies. Among these techniques, dynamic test benches based on linear encoders and laser displacement references have been extensively investigated by researchers worldwide and have become relatively mature in practical applications. Machine-vision-based measurement methods have broadened the application scenarios of travel error measurement owing to their non-contact characteristics. In addition, measurement devices developed or improved for specific testing requirements provide valuable references for structural optimization and functional extension. Based on the literature reviewed, future research on travel error in screw mechanisms should focus on the following aspects:

(1) Research on the mechanisms and modeling of travel error in planetary roller screw mechanisms has progressed from the analysis of individual geometric errors to the investigation of multi-source error coupling, providing a theoretical basis for travel error prediction and error compensation. However, because PRSMs involve coupled transmission through multiple contact pairs among the screw, rollers, nut, and synchronizing gears, existing models have not yet clearly described the transmission relationships of travel error among the individual components. In particular, the mapping relationships between the travel errors of the roller external raceways and nut internal raceway, gear meshing errors, and the overall travel error of the PRSM have not been fully established. Meanwhile, some existing models are still based on idealized boundary conditions or simplified operating conditions and lack sufficient experimental validation of error-coupling behavior under realistic loads, temperature rise, clearance, wear, and dynamic operating conditions. Therefore, future research should develop more comprehensive mathematical models for the individual components.

(2) Existing mainstream measurement equipment for screw mechanisms is primarily used as general-purpose testing instrumentation. However, PRSMs differ from ball screw mechanisms in both structural configuration and transmission characteristics. Consequently, existing general-purpose testing equipment is not fully compatible with PRSMs in terms of clamping methods, loading modes, and error compensation, which affects the accuracy and repeatability of the measurement results. Therefore, dedicated test platforms with application-specific structural configurations should be developed to enable high-precision measurement and analysis of transmission errors in PRSMs.

(3) Existing studies have mainly focused on the measurement of travel error of the screw external raceway and the overall travel error of assembled screw mechanisms, whereas comparatively less attention has been paid to the travel errors of the roller external raceway and nut internal raceway. As a result, current measurement results cannot fully characterize the motion accuracy of individual components or clearly reveal how different errors are transmitted and coupled through multiple threaded contact interfaces. Future research should develop dedicated measurement methods for the screw, rollers, and nut, and establish the relationships between component-level errors and the overall travel error of PRSMs, providing an experimental basis for multi-source error identification and error separation.

(4) Further research should explore the application of physics-informed and data-driven methods to dominant error identification, travel error prediction, and error compensation. Existing studies have demonstrated the potential of machine-learning methods for error sensitivity analysis and transmission accuracy prediction, although their reliability remains highly dependent on the quality and representativeness of the available data. Future studies may integrate physics-based models of PRSM travel error generation with experimentally measured data to improve the interpretability and generalization capability

of prediction models, and further apply them to dominant error source identification, prediction of the time-varying evolution of travel error, and related studies.

**Author Contributions:** Conceptualization, X.L. and L.Z.; investigation, X.L.; resources, Y.X., Q.W. and H.C.; writing—original draft preparation, X.L.; writing—review and editing, H.J. and H.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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