Evaluation of open-loop linear drive accuracy achieved by calibration and linear thermal expansion compensation

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The study is a part of the current work on the design and creation of a precision mechanism with parallel kinematics such as a space hexapod. The positioning accuracy and repeatability of the movable platform of the machine relative to its fixed base in the structure under consideration depends on the accuracy of the actuating elements of the hexapod — linear drives. The aim of the work is to assess the achievable accuracy of the linear drive, taking into account the main factors affecting the accuracy of its rod movement. The article describes the studies of the accuracy of the open-loop linear drive, which has no common feedback on the output coordinate. The main factors affecting the accuracy of movement are highlighted. The experimentally obtained estimates of the linear drive rod displacement errors are given. A technique is proposed for improving the linear drive accuracy by programmatically calibrating its ball screw drive and compensating for linear thermal expansion (LTE) when the drive is operating in a wide temperature range. An estimate of the calibrated linear drive rod movement accuracy with LTE compensation has been obtained.

Keywords: Gough–Stewart platform, hexapod, linear actuator, calibration, compensation, thermal expansion

Introduction

At present, parallel-structure mechanisms (PSMs) are widely used to solve problems of guiding and orienting objects for various purposes. The use of mechanisms with a parallel structure in space technology is of particular relevance. Thus, the papers [1, 2] consider the possibility of creating a manipulator based on PSM to provide navigation tasks of the Millimetron astrophysical observatory.

The use of PMSs in the tasks of guidance and orientation of precision onboard instruments of spacecraft (SC), as well as their stabilization and vibration isolation, is promising [3]. This paper considers the mechanism of high-precision guidance of the Gough–Stewart platform [4], which is also called hexapod.

The hexapod allows moving an object located on its movable platform in six degrees of freedom (three translational and three rotational), which is achieved due to the presence of six independent control linear actuators, connecting the fixed base and the movable platform using hinges [5]. The linear actuator (LA) consists of two half-bars, one of which can move linearly relative to the other. The movable part of the LA is called rod.

One of the options for controlling the position and orientation of an object is to solve the inverse kinematics problem (IKP) of the hexapod, when six linear coordinates of the actuators are calculated by the six given spatial coordinates of the movable platform, which are independently performed by each of the LAs [5].

The accuracy of movement of an object with an independent control by the LA depends on both the PSM manufacturing errors and on the correct accounting of all kinematic parameters entered into the mechanism control system for solving the IKP. First of all, the accuracy of movement of the output link, which is the movable platform with an object, is affected by the accuracy of the linear actuators. The set of requirements for the accuracy of the translational and rotational movement...
of the platform in tens of micrometers and tens of angular seconds, respectively, leads to the need to move the rods of linear actuators with accuracy in units of micrometers with a displacement range up to 200 mm [6].

To achieve the highest accuracy of the actuator control system, it is necessary to close the control loop of the LA with feedback on the output coordinate, which is the linear position of its rod. The use of the existing linear position sensors allows achieving high accuracy of the load movement. However, the extreme environmental conditions in which the spacecraft equipment functions impose a number of restrictions on the component base used. First of all, stringent operational requirements for resistance to ionizing radiation, vacuum, a wide range of temperatures, as well as reliability, are imposed on sensors. In addition, the spacecraft and its payload must have a minimum mass in order to reduce the cost of launching the payload by the launch vehicle. Thus, sensors with various operating principles can be used as linear position sensors. Variable potentiometer transducers provide simple information retrieval by the LA control system (normally, the analog-to-digital conversion is used) but they also have a significant drawback – low accuracy and reliability. Inductive and capacitive sensors along with high reliability, as well as resistance to external factors, have low accuracy. Interferometric sensors allow measuring the position with accuracy in fractions of micrometers, but they have a complex structure with expensive components and a specialized electro-optical information processing system.

These features impose a number of restrictions on construction of the linear actuator. The purpose of this paper is to estimate the accuracy of movement of the linear actuator rod without feedback on the output coordinate and to determine the main principles of the method for increasing its accuracy.

**Linear actuator structure**

The executive part of the LA includes an electric motor (EM) of linear or angular displacement, a gearbox, as well as mechanical transmission. The electric motor of angular displacement is currently the most common; there is a wide range of engines of the space version. In LAs with EMs with an angular displacement rotor, a linear gear is used: screw-nut, roller-screw, ball-screw (BS), an elastic displacement system, etc. [7–9]. At the same time, a sufficiently developed and reliable technical solution for positional LAs is the use of a bundle of a stepping EM – gearbox – BS.

The considered LA uses an indirect position measurement sensor (the angular position sensor of the EM shaft of rotating transformer type), which allows constructing an inexpensive and reliable system capable of operating in space conditions. Fig. 1 shows the structure of a linear actuator.

The mechanical part of the LA includes an executive motor, gearbox, ball screw, and also a rod fixed on a moving element of BS. The LA control system includes a microprocessor control module, power amplifier, LA temperature sensors, angular position sensor (APS) of the motor shaft, and rod end position sensors.

The LA control system operates according to the commands of the upper-level control system, which solves the IKP and specifies the necessary linear positions for all six LAs. The LA control module forms a pulse-width modulated control signals in accordance with the sensor signals and a predetermined position, and then sends the signals to the motor windings through the power amplifier.

The applied APS provides local feedback, while forming data on the angular position of the shaft within one revolution. The theoretical function of input and output signals connection, i.e., of the angular position of the motor shaft $\gamma$ (rad) and the linear position of the LA rod (mm) is as follows:

$$l(\gamma) = \frac{s(2\pi n + \gamma)}{k},$$

where $s$ is the pitch of the ball screw, mm/rad; $n$ is the number of revolutions of the motor shaft, $k$ is the gear ratio of the gearbox. The number of revolutions of the shaft $n$, as well as the absolute linear position $l$, is determined by the control module after switching on the LA and positioning at the neutral position according to the signals of the end sensors. It should be noted that the use of the stepping motor (SM) as a drive motor allows angular displacement of the shaft $\gamma$ not only with the

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**Figure 1. Block diagram of linear drive**

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SM step discreteness but also with less discreteness by designing a valve drive based on it [10].

**Major factors affecting linear actuator accuracy**

To estimate the linear actuator accuracy (displacement of its rod), studies were conducted on the hexapod linear actuator experimental model designed and manufactured as part of research, development, and engineering works.

The considered linear actuator is based on a ball screw with a step \( s = 4 \) mm of the fifth accuracy class (the maximum error of a typical stroke length is 20 μm). The ball screw has preload and ensures no backlash. The axial rigidity of the LA is 200 N/μm.

Measurements of the linear position of the LA rod, attached to the traveling nut of the ball screw, depending on the specified angular position of the gear screw, were performed. A weight of 1 kg is suspended to the LA rod and used as a load through the unit and an inextensible cord.

In order to control errors of the rod linear position, the LIR-DA7 type absolute photoelectric sensor of the linear position with a measurement resolution of 0.1 μm and an absolute error of up to ± 0.6 μm was used in the studies. The measurement results were recorded in a static mode after the completion of transients in the LA electromechanical system (0.5 s).

According to the papers [7, 11–13], the accuracy of the linear actuator rod displacement at a constant static load is most affected by its own mechanical transmission characteristics (ball screws) associated with the errors in its manufacture.

Fig. 2 shows the graphs of the errors of the rod linear position as a function of its displacement when the rod passes twice in one direction in the range from 0 to 200 mm (solid and dashed lines, respectively) at the same LA temperature \( t = 20 ^\circ C \).

An error in the rod displacement is also made by the change in the temperature of the ball screw and other elements of the mechanical transmission and the associated linear thermal expansion [14–17]. To evaluate the effect of temperature on the LA operation accuracy, studies were carried out under different conditions.

Fig. 3 shows the graphs of the errors of the rod linear position depending on the LA temperature. When the temperature changes by 2 °C, the error in the rod displacement increases by 5 μm, and its absolute value reaches 14 μm at \( t = 22 ^\circ C \).
Thus, in order to ensure high accuracy of the rod displacement, it is necessary to take into account two components: the inherent characteristic of the ball screw and the linear thermal expansion of the LA mechanical transmission. Consider the possibility of increasing the accuracy of an open linear drive using the example of numerical calculations.

**Increasing linear drive accuracy**

The shape of the error curve shown in Fig. 2 is typical for ball screw [18], and it can be seen from the graph that the repeatability of the rod displacement accuracy is provided with a maximum error of 0.4 μm. In this case, it is possible to perform the LA calibration using the following method: the actual linear position of the rod is measured for the entire operating range at a fixed value of the LA temperature with the required resolution, then errors of the rod displacement are calculated and a discrete array of corrections values is formed. The corrections are recorded in the memory of the LA microprocessor control module or the upper-level control system [19, 20] and are subsequently taken into account at linear displacement.

Fig. 4 shows a theoretical graph of the rod linear position error for the inherent characteristics of the ball screws (see Fig. 2, dashed line), taking into account the correction values obtained from the characteristic (see Fig. 2, solid line). Errors are due to the repeatability of the inherent characteristics of ball screws.

To compensate for the linear thermal expansion of the LA (see Fig. 3), after obtaining corrections using the calibration method described above, additional correction values are necessary taking into account the LA temperature measured using an appropriate sensor (see Fig. 1). It is known that the coefficient of linear thermal expansion (CLTE) \( \alpha \) for a body of length \( L \) is described by the formula

\[
\alpha(T) = \frac{\Delta L}{L \Delta T},
\]

where \( \Delta L \) is the elongation of the body; \( \Delta T \) is the temperature change. Then, to calculate the additional correction values for the position (\( \Delta L \) with a minus), it is only necessary to take into account the CLTE of the screw–nut pair material. For steel, it can be averagely taken \( \alpha = 12 \cdot 10^{-6} \text{ K}^{-1} \).

Figure 4. Graph of the rod linear position theoretical error after calibration

Figure 5. Graph of the rod linear position theoretical error after linear temperature expansion compensation calibration
Fig. 5 shows a theoretical graph of the rod linear position error at $t = 22 \, ^\circ\text{C}$ (see Fig. 3), taking into account the correction values obtained for the inherent characteristic of the ball screws (see Fig. 2, solid line), as well as compensation for linear thermal expansion ($\Delta T = 2 \, ^\circ\text{C}$). As can be seen from the graph, the maximum error value does not exceed 1.1 microns.

**Conclusions**

A preliminary estimate of the accuracy of the LA rod linear displacement without feedback on the output coordinate was performed in the course of the study. The study results allow recommending for use the methodology of the LA preliminary calibration and taking into account its temperature in order to improve the accuracy of the LA and the hexapod based on it.

It should be noted that, as part of further development of the study, it is necessary to determine the optimal correction values for the LA calibration, to conduct research at a wider temperature range in order to clarify the CLTE of the LA mechanical transmission, the linearity range of its thermal expansion and the influence of the thermal pattern heterogeneity, as well as the influence of the axial stiffness of ball screws on the accuracy of the LA rod linear displacement depending on the load.

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