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AUTOMATION, CONTROL AND MONITORING OF THE ROTATION OSCILLATION PLANE WITHIN FOUCAULT PENDULUM

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Abstract: *The present paper reprezent the implementation of the functional concept of the Foucault Pendulum developed by the academician Ion BOSTAN in 2004-2006, that represents the constructive-functional core of a genuine research platform of the influence of Lunar and Solar eclipses on the Earth's gravitational field. It aims to automate the operation of the Foucault Pendulum. Remote control and monitoring of the rotation of the oscillating plane was achieved.*

Key words: *Focault pendulum, plane of oscillation, electromagnet, optical decoupling, laser, phototransistor, addressable asynchronous bus, USB transceiver.*

1. INTRODUCTION

The given work describes the Foucault Pendulum developed by UTM collaborators and built in the premises of Bl. 1 st. Stefan cel Mare 168 using the technical possibilities of several companies from the Republic of Moldova. Within the given project, the automation of the operation, control and monitoring of the rotation of the Foucault Pendulum oscillation plane was realized, which represents a sufficiently complicated technical task.

Academician Ion BOSTAN developed the concept of the Foucault Pendulum with interactive kinematics described in this work, an indispensable component of a genuine research platform of the influence of lunar and solar eclipses on the gravitational field of the planet Earth.

The Foucault pendulum oscillates in a vertical plane that changes its coordinates with the rotation of the Earth. At the suspension point of the pendulum, a normal goes up to the surface of the ground. At this point a circle with the diameter of the maximum amplitude of the pendulum is built.

In realizing the Foucault Pendulum concept with interactive kinematics, see figure 2, 3 the following collaborators participated:

Students
Vitalie Secrieru, Maxim Vaculenco, Anatol Sochireanu, Oleg Ciobanu, Radu Ciobanu, Dumitru Vengher, Nicolae Trifan, Ion Dicusară, Valeriu Odainai, Eugen Munteanu, Stefan Balica.

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Spiridon Rusu, Valeriu Podborschi, Veaceslav Nastasenco, Viorel Bostan, Mihai Traci, Iurie Liunenco.

Manufactured at industrial enterprises in the Republic of Moldova
"Etalon - U.T.M.", "Topaz", "Reupies", "Moldovahidromas", "Acvila Group", "Hidrotehnica", "Incomas", "Azurit", "Restauratorul", "Arta pentru Viata".

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2. METHODOLOGY FOR RECORDING AND DISPLAYING THE PLANE OF OSCILLATION OF THE FOUCAULT PENDULUM

The basic task of the given installation is to provide as much information as possible about the state of the Foucault pendulum, both in visual and digital form. The information base are the coordinates of the oscillation plane of the Foucault pendulum. The visual way of indicating the oscillation plane of the pendulum is realized with the help of some light points located on a disk with numbers, and the digital form is obtained by transmitting the information to the computer through a processing unit.

The structure of the peripherals of the Foucault pendulum elaborated and implemented by us is presented in figure 1. The system uses a single bus for all the Focault pendulum peripherals. The interconnection between the modules was realized by means of an addressable asynchronous bus. Its use allowed to minimize the number of cables, their length and finally to greatly simplify the physical connection between the system modules. On the physical level, this interconnection is realized by means of TTL-RS485 converters.

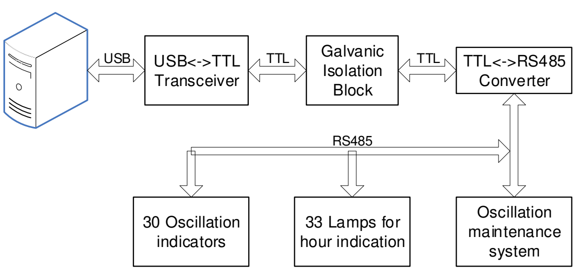

Fig.1. The structure of the Focault pendulum peripherals.

The RS485 type bus provides high data transmission reliability by using the signal inversion transmission method with galvanic decoupling by means of current mirrors see references [1, 2]. This method increases the reliability of data transmission because it does not allow noise to pass through the power lines.

For a more convenient computer management of the pendulum systems, the use of USB ports for connecting peripherals was proposed. A USB<->RS485 transceiver was used to receive and transmit data via USB to an addressable asynchronous bus. The FT232RL circuits from FTDI chip were used because of their ease of use and advanced software support, see references [3-5]. These circuits have an asynchronous port and special pins that can be used to implement an RS485 bus.

The 33 tricolor lanterns with magnetic transducers and 30 additional lanterns presented in figure 2, are positioned along the perimeter of the swing area. Lanterns are used to indicate the information given by the transducers.

The 33 tricolor lanterns positioned along the perimeter of the pendulum's swing area provide information about the position of the pendulum's swing plane. Each lantern contains a transducer that changes its state upon the pendulum entering the lantern area. There is a controlled multicolor transmitter inside the lantern, which indicates the position of the oscillating plane. An I2C (TWI) synchronous serial bus connects the 33 lanterns. The bus enables the determination of the pendulum's oscillation plane position by communicating with the microcontroller located in each lantern.

The tricolor lanterns are situated on a mobile platform that rotates approximately 50 times per year around its axis. Electric brushes positioned around the edge of the mobile platform make contact between the I2C bus and the power supply of the lanterns.

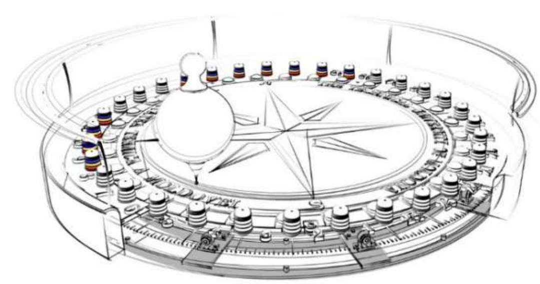

Fig.2. Sketch diagram of the Foucault pendulum

Thirty secondary lanterns with two light emitters each are designed for measuring time. A multicolored emitter is used to light up the emitter lenses. A white emitter is used to light up the inscription "TECHNICAL UNIVERSITY OF MOLDOVA" and the movable gradation. Super luminescent diodes of different colors are incorporated in each emitter. The LEDs are powered by a 17.5V direct current. A transistor controls each LED.

The external image of the Foucault Pendulum located in 168 Stefan cel Mare str., block 1 of the UTM is presented in figure 3.

a. Lateral vision

b) Top view

Fig.3. Foucault's pendulum image

3. MEASURING THE AMPLITUDE OF THE FOUCAULT PENDULUM OSCILLATION

To maintain a constant amplitude of a pendulum, its oscillations must be harmonic in an ideal system without energy losses, see reference [6]. The attenuation of amplitude for harmonic oscillations of a pendulum is primarily caused by the presence of air in its environment. Suppose that: $\Delta E_{pend} = E_{comp}$.

Here ΔE_{pend} represents the energy lost by the pendulum over a period of time and E_{comp} refers to the energy transmitted to the pendulum during the same duration for compensating these losses. Under such circumstances, the pendulum will retain its intended amplitude.

The energy losses and compensation system of the Foucault pendulum under normal conditions depend on various secondary factors, including current amplitude, air density, temperature, humidity, and supply voltage for the compensation system. In conclusion, the relationship among these factors is: $\Delta E_{pend} \neq E_{comp}$;

To keep the amplitude relatively constant it is necessary that: $\Delta E_{pend} < E_{comp}$;

Whenever A is greater than Amax (where A is the amplitude), the compensation system should be disconnected - $E_{comp}=0$.

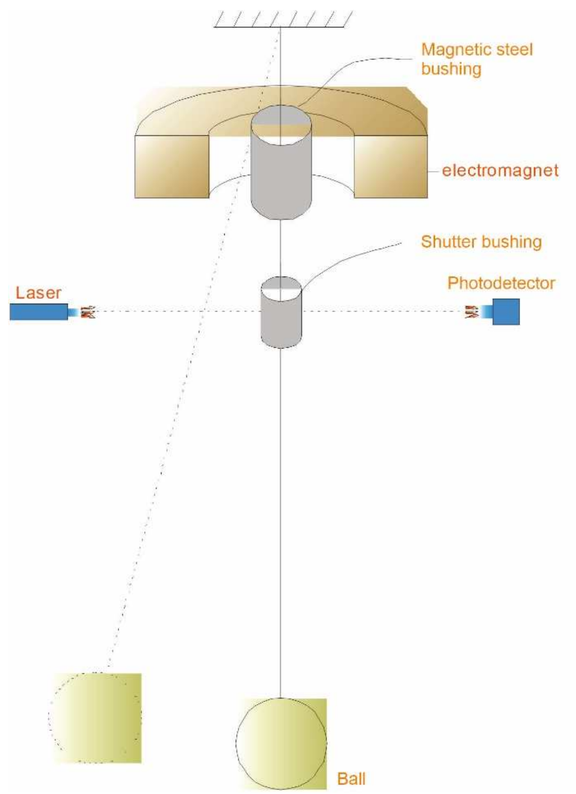

Fig.4. Amplitude measurement method

To measure the amplitude of the pendulum, we established the following methodology.

At each oscillation of the pendulum, a bushing is placed on the suspension wire (see figure 4), covering the phototransistor (photodetector) and measuring the duration of time during which the phototransistor is closed. This time measurement is proportional to the speed of the bushing, enabling us to measure the amplitude of the pendulum. Furthermore, it is possible to measure the oscillation period of the pendulum, which remains constant regardless of the speed of the ball.

The expression for determining the speed of the bushing is presented in formula 1:

$$V = A\omega \cos(\omega t); \quad (1)$$

A denotes the amplitude, while ω represents the angular velocity. As per the measurement methodology, the time of passage through the normal suspension point will be determined. This point is localized where the ball has the highest speed, and at this point, the component cos(ωt) = 1. Therefore, it follows speed from formula 2:

$$V = A\omega = A * 2\Pi/T; \quad (2)$$

The speed of the bushing when passing through the normal suspension point V_{opt} will be done with formula 3:

$$V_{opt} = d/t; \quad (3)$$

Where: d – the diameter of the bushing, t – the time the bushing passes through the laser beam. For the measurement system the ratio is true as in formula 4:

$$\frac{V}{V_{opt}} = \frac{l}{L} \quad (4)$$

where: l – the distance between the suspension point and the light beam; L – the length of the suspension wire for the pendulum. If one replaces (3) in (4), we will get the expression from formula 5:

$$V = \frac{d*l}{t*L} \quad (5)$$

The amplitude calculation (formula 6), can be obtained by replacing (5) in (2):

$$A = \frac{d*L*T}{2\pi*l*t} \quad (6)$$

For harmonic oscillations, the period T can be calculated as follows in formula 7:

$$T = 2\pi\sqrt{\frac{L}{g}} \quad (7)$$

Due to the rotation of the Earth around its axis, the plane of oscillation of the Foucault pendulum changes. At the poles, the oscillation plane of the Foucault pendulum changes by 360°, while it remains unchanged at the equator, see reference [7]. However, at the latitude where the pendulum is located, in the premises of the first building of the TUM, it changes by approximately 261 degrees.

The straight line containing the Laser-Photodetector pair must be rotated in a plane perpendicular to the pendulum's oscillation for an accurate measuring of the amplitude. This approach is challenging to be practically implemented, as it necessitates a sophisticated and finely-tuned mechanical device that can enable calibration of the Laser-Photodetector pair, while rotating the plane of oscillation of the Foucault pendulum.

Our approach involves the placement of a set of Laser-Photodetector pairs. By measuring the shortest T, we can calculate the amplitude with minimal error.

According to the technical task, it is crucial to maintain the amplitude value at 1.2 meters, with an error margin of 3 cm. It's evident that a higher number of sensors reduces the margin of error. Our project requires that the relative amplitude error stays within 2.5%.

Whenever the laser beam deviates from the normal to the plane of oscillation of the pendulum, the true amplitude of the pendulum will be calculated using the following expressions:

$$A_{real} = K * A_{calculated} \quad (8)$$

or :

$$A_{real} = A_{calculated}/cos\varphi \quad (9)$$

There, K is an error coefficient.

In figure 5, the sketch of the location of the transmitter/photoreceptor pairs is shown, which de facto represents an optocouple designed by a red laser and a phototransistor with the highest sensitivity in the visible spectrum. The red color of the laser allows to visually follow the interaction of the optical shutter with the laser beam and the photoreceptor.

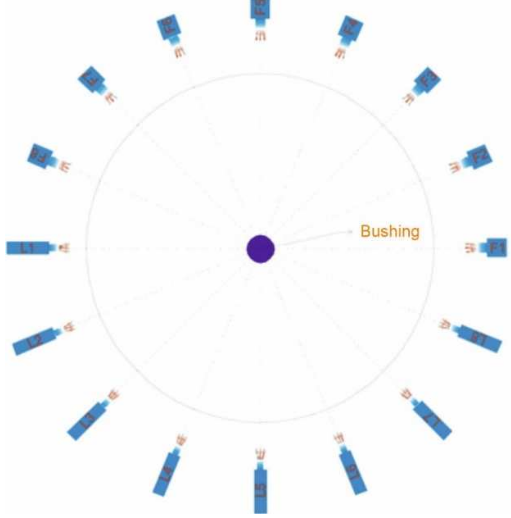

Fig.5. Sketch of the location of the Laser-Photodetector pairs

where: φ – is the angle of deviation from the normal of the oscillation plane. Usage of 8 Laser-Photodetector pairs produces an angle of 22.5° between two sensors, leading to a deviation of φ_{max} of 11.25° from the normal of the closest light beam.

Schemes with 2 and 4 transducer/receiver pairs were analyzed. Finally, the scheme with 8 pairs of transducer/receiver was implemented to reduce the relative error to an acceptable value.

Figure 6 shows the plot of the error coefficient K for each emitter/photoreceptor pair in spots. In optimal centering conditions K takes values of approximately 1.02. The given scheme allows to reduce the relative error of measuring the amplitude of Foucault Pendulum oscillations up to 2%, see reference [8].

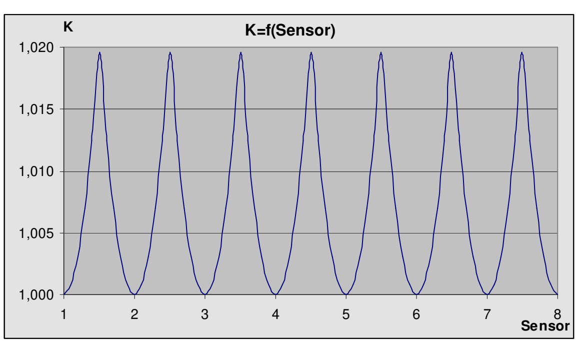

Fig.6 Change of the error coefficient K

Error coefficient K for each pair emitor/senzor from diagram is calculated.

The measurement and control block presented in figure 7, consisting of integrated circuits, helps in adjusting the measurement system for measuring the shutter transit time via the light beam intersection.

Connecting the lasers at the precise moment when the shutter passes through the beams is vital. Their lifespan can be extended by disconnection when the pendulum is deviated from its normal suspended position. The disconnection of lasers is handled by sensors with analogous coverage. The correct measurement and increase of the lifespan of these lasers are functions simultaneously performed by the block.

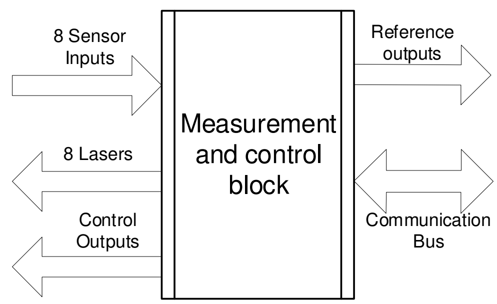

Fig.7. Block diagram of the measurement system

The reference output represents the measurement of the shutter passing time through the laser beam as closely as possible to the normal to the plane oscillation of the Foucault pendulum. This result will be then used to approximately calculate the amplitude.

A communication bus is implemented to provide additional functions required by the system. The primary function is to enhance the precision of amplitude measurement. This is achieved by utilizing $A_{calculated}$, which estimates area through calculations.

4. OSCILLATION COMPENSATION

The article specified in reference [9] was used as a point of reference. The energy losses of the Foucault pendulum are usually determined by the frictional force of the air and the gravity force of the Earth. An effective compensation system requires energy for compensation, according to the formula 10:

$$W_{em} > W_{fr} \quad (10)$$

where: W_{em} – the energy passed by the electromagnet to the pendulum in one half period; W_{fr} – energy loss during this time by the pendulum.

According to the assumption made in reference [10], the electromagnet will be switched for a brief period, leaving the distance between the electromagnet and the magnetic bushing unaltered. Hence, the magnet force of attraction will remain constant.

In practice, applying a high-energy pulse to the bushing, from which the pendulum hangs, for a short period proved to be an unacceptable solution. A pulse of lower energy but for a longer duration must be applied. The force applied by the electromagnet on the bushing can be described by the following formula:

$$F_{em} = k/X \quad (11)$$

where: k – coefficient that can be calculated based on the regime of the electromagnet and is directly proportional to the current through the winding; X - the distance between the bushing and the electromagnet.

From the formula above, one can notice that the force increases hyperbolically with decreasing distance. Therefore, when $X \to 0$, $F \to \infty$.

Once the pendulum reaches the normal suspension point, the electromagnet is activated by a voltage. The electromagnet is disconnected from the voltage at the maximum point of the amplitude.

Upon examining the above diagram, it can be observed that the electromagnetic bushing is centrally positioned within the toroidal electromagnet, while the suspension wire is flexible. In such cases where the force generated by the electromagnet surpasses a critical value as in formula 12:

$$F_{em} > F_q * 1/L \quad (12)$$

where: Fg represents the force of gravity that acts on the ball, l stands for the distance between the point of suspension and the magnetic bushing, and L denotes the length of the wire that suspends the ball. The wire will bend under the force of the electromagnet, causing the bushing to approach the electromagnet. The Fem force will increase, exceeding the critical force.

The mentioned effect results in the following system deviations: the suspension point of the pendulum is lowered to the height of the electromagnet, and the suspension point deviates from the electromagnet's center. The most concerning issue is that the bush that sticks to the electromagnet can potentially contribute to the Coriolis force in a probabilistic manner [7]. The rotation speed of the oscillation plane for the Foucault pendulum will be affected.

Additionally, the electromagnet is deactivated after being glued. Hence, the point of suspension of the pendulum will return to its initial position, see references [11, 12]. This rapid change causes vibration in the rope which holds the ball. As the optical bush, which calculates the amplitude, is also mounted on the wire, vibrations cause errors in the determination of amplitude.

In such circumstances, the oscillation system must ensure: avoiding the vibration effects of the suspension wire while maintaining the oscillations.

Magnetic remanence is a secondary phenomenon that occurs in all electromagnets. It is necessary to exclude this effect from our system, because of its parasitic nature.

To exclude the influence of magnetic remanence in the forces acting on the bushing, the bushing must be far enough away from the electromagnet at the point of maximum amplitude. When the electromagnet is disconnected, the magnetic force acting on the bushing becomes insignificant.

It is uncertain whether the resultant force of the electromagnet acting on the bushing will be equal to zero, even when the pendulum is in the normal suspension position. However, a slight deviation from this position is enough to deflect the wire suspension with a sufficient force. Consequently, since the optical bushing is also deflected, a reduction in the "dark" time of the shutter will occur. The amplitude calculation result will be inaccurate.

To prevent this situation, it is necessary to apply the voltage to the electromagnet only after calculating the amplitude. Figure 8 shows the shape of the voltage pulse that is applied to the electromagnet at each half-cycle.

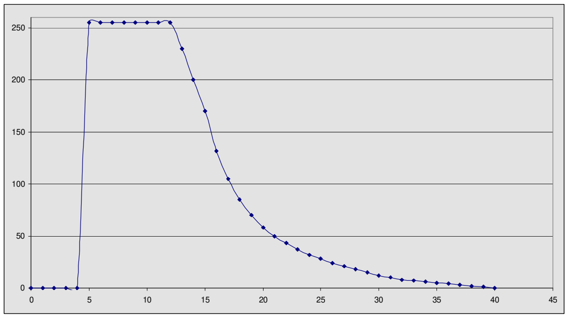

Fig.8. The voltage waveform applied to the electromagnet

Time is represented on the X-axis. The pendulum's normal suspension position is at point 0. Y-axis, voltage applied to the electromagnet.

The waveform in figure 8 is made in the first instance by calculation, then adjusted to the needs of the installation. It was carried out through special software, in which coefficients were introduced, which can change the shape of the curve. Because, the bushing is far from the electromagnet when the voltage is applied, the resulting compensating force will be low.

As closer to the electromagnet, the force reaches its maximum value. This is the point where the pendulum can be provided with maximum energy. However, as it nears the maximum amplitude, it is required to reduce the force applied to the bushing.

To maintain the accuracy of the results, it is crucial to avoid a steep slope in the force decrease, which can cause vibration of the suspension wire at the point of complete relaxation of the force.

By modelling the voltage applied to the electromagnet, we obtained a force distribution as shown in Figure 9. The waveform is made in the first instance by calculation. The distribution meets the proposed objectives for the Foucault pendulum loss compensation system:

- The distribution provides sufficient force to increase the amplitude.
- The force pulse has a gradient that does not disrupt the amplitude measurement system.

The compensation system is structured based on the block diagram presented in figure 10. The measurement and control block is a device containing a set of integrated circuits designed to assist the user in setting up the measurement system to perform the function of measuring the time taken for the shutter to pass through the intersection of the light beams.

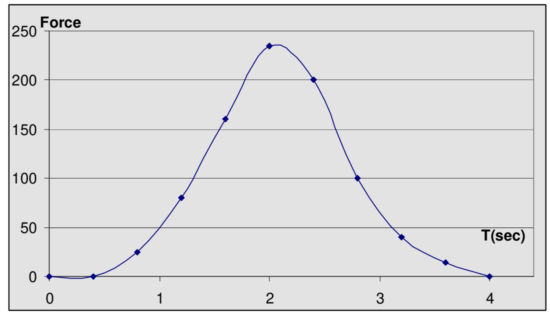

Fig.9. Resultant of the Force applied for compensation

As it is crucial to connect the lasers when the shutter passes through the beams, disconnecting them when the pendulum deviates from its normal suspension prolongs their lifespan.

The reference output is obtained by measuring the transit time of the shutter through the laser beam. This result will then be used to approximately calculate the amplitude.

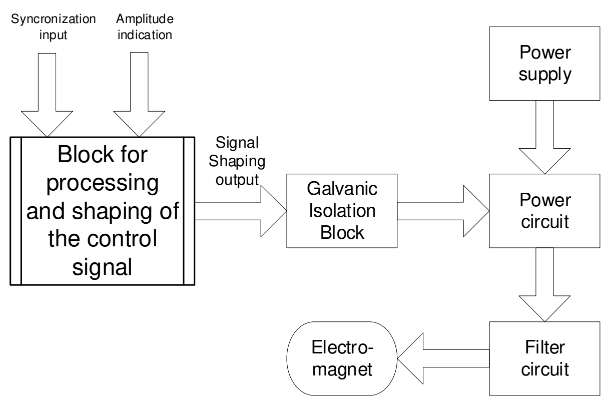

Fig.10. Block diagram of the measurement system

A communication bus is employed to implement additional functions required by the system. The main aim of this is to improve the precision of amplitude measurement. This is achieved based on the usage of $A_{calculated}$ for estimating the area through mathematical calculations.

5. CONCLUSION

In the given work, two main engineering aspects were solved: the monitoring of the rotation of the Foucault Pendulum oscillation plane and the automation of the system.

The most difficult problem: maintaining the amplitude of the pendulum in a narrow range without any impact on its rectilinear movement was solved by implementing a system of precise amplitude maintenance.

For this, a special device has been developed that performs amplitude measurement, which is connected to an electromagnet control device that generates energy to compensate for damping losses.

This system implements modern principles of edge computing devices and provide a reliable solution which is proved by long term operating time.

Also, along the years of running, the system proved to sensible to working regime of electromagnet, especially when it works in extreme mode, thus more attention should be paid to its design and placing of related elements.

The principle of operation (functional block diagram) and the devices developed for the automation, control and monitoring of the rotation of the Foucault Pendulum oscillation plane can be used to build such installations anywhere in the world.

The most sensitive element is the location of the Foucault Pendulum.

It must be placed in a location where the support point cannot be influenced by all kinds of parasitic vibrations, such as: heavy tonnage transport, nearby construction works, vibrations caused by the movement of people or gauge weights, and others.

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Automatizarea, controlul si monitorizarea rotirii planului de oscilație în cazul pendulului Foucault

Lucrarea dată reprezintă implementarea conceptului funcțional al Pendulului Foucault dezvoltat de academicianul Ion BOSTAN în anii 2004-2006, care reprezintă nucleul constructiv-funcțional al unei veritabile platforme de cercetare a influenței eclipselor de Lună și Soare asupra câmpului gravitațional al Pământului. Are scopul de a automatiza funcționarea Pendulului Foucault. A fost realizat controlul de la distanță și monitorizarea rotației planului oscilant.

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