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VIRTUAL FIELD FORMATION FOR A DISCRETE JOYSTICK THROUGH SEGMENT AREA BALANCING

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Abstract. *Problem statement.* Ensuring precise and convenient control of mobile platforms through a discrete joystick is a current challenge in modern automation systems. One of the primary issues is the uneven sensitivity of the joystick in different directions due to the heterogeneous distribution of the areas of its virtual field segments. *Purpose.* The aim is to develop and optimize a methodology for balancing the areas of virtual field segments of the discrete joystick in rectangular, diagonal, and polar coordinate systems to ensure uniform control sensitivity. *Methodology.* The study is based on the use of analytical methods for determining the areas of virtual field segments for three coordinate systems. A geometric transformation method was applied to derive area formulas. The analysis took into account the conditions for equalizing the areas of the central, axial, and diagonal groups of segments. Graphs of the dependence of segment areas on the parameter determining the size of the central segment were obtained. *Findings.* Analytical formulas for determining the areas of virtual field segments in three coordinate systems are proposed. Conditions for balancing the areas of segments for different groups are established, enabling uniform sensitivity or adaptation for specific control tasks. The optimal parameter values for achieving balance in each coordinate system are identified. *Originality.* This work presents, for the first time, a methodology for analytically balancing the areas of joystick virtual field segments in various coordinate systems. A mathematical model accounting for the geometry of the segments in rectangular, diagonal, and polar coordinate systems is developed. *Practical value.* The results of this study allow for adjusting joystick parameters based on mobile platform control tasks. This contributes to improved precision, reduced control errors, and adaptation of the joystick to operator needs in various operational conditions. *Scopes of further investigations.* Further research may focus on the development of adaptive algorithms for real-time joystick parameter adjustments. Another promising direction is to incorporate the dynamic characteristics of mobile platforms and test the proposed models in practical conditions.

Keywords: mobile platform, discrete joystick, virtual field, area balancing, coordinate system, rectangular system, diagonal system, polar system.

Introduction

The joystick is one of the most widely used control devices, enabling the operator to interact with a mobile platform or other systems in real time. Its operation is based on the conversion of mechanical movement of the joystick handle into electrical signals through potentiometers, which determine the position of the handle along the X and Y axes. A key concept in this process is the virtual field, an imaginary plane where the coordinates of the handle are recorded, allowing the computational system to accurately interpret its position and movements. At the same time, the effectiveness of operator interaction with the joystick heavily depends on the uniformity of sensitivity within the virtual field. Uneven areas of this field, especially within different coordinate systems (rectangular, diagonal, polar), can lead to reduced control accuracy, increased errors, and difficulty in task execution. This is particularly critical in applications such as robotics, aviation, space exploration, and gaming systems, where high precision and adaptability from the joystick are required.

Research aimed at optimizing the geometry of virtual field segments is highly relevant, as it ensures uniform joystick sensitivity, improves the quality of mobile platform control, and enhances operator comfort. The development of methods for balancing the areas of segments in three coordinate systems will contribute to the creation of more intuitive and efficient control systems, which has significant practical implications for modern technologies.

Problem Statement

Ensuring precise and convenient control of mobile platforms using a discrete joystick is a critical task in modern automation systems. One of the main challenges is the uneven sensitivity of the joystick in different directions due to the non-uniform distribution of the areas of its virtual field segments.

Review of Modern Information Sources on the Subject of the Paper

The analysis of previous research in the field of joystick use for controlling various systems reveals a wide range of applications and scientific approaches to optimizing the functionality of these devices. Paper [1] focuses on adapting the joystick interface for people with severe physical disabilities. The study proposes the adjustment of parameters such as dead zones and axis shifts, enabling individualized control. The use of fuzzy logic rules allowed for compensation of hand tremors, which is important for improving the accuracy and ease of use. Paper [2] explores joystick control of robotic systems. The presented system, which includes control of both a vehicle and a manipulator, stands out for its simplicity and low cost. The implementation of such solutions in industry contributes to increased labor productivity and a reduction in the number of accidents. Paper [3] examines control schemes for redundant manipulators. Two methods are proposed: cosine-based mapping and a joystick motion planning scheme in real-time (JCMP), based on the minimum velocity norm. Testing on a six-DOF manipulator confirmed the effectiveness of the approach. Paper [4] focuses on the fundamentals of joystick use, specifically signal processing and output to an LCD. This study is foundational for understanding the principles of joystick operation. Paper [5] focuses on monitoring joystick operation in electric wheelchairs. The developed PWhML system relies on IMU usage to assess joystick tilt angles. The advantages of this approach are confirmed by high measurement accuracy and reliability in various terrain conditions. Paper [6] is dedicated to developing an intelligent control algorithm to ensure the safety of wheelchair users. The integration of a fuzzy controller with a vector histogram field algorithm achieved smooth control and obstacle avoidance.

Thus, the literature review demonstrates significant progress in the use of joysticks for control, while also indicating the need for further optimization. Particular attention should be paid to the uniformity of sensitivity and the accuracy of data transmission to the virtual field, which is a key aspect of contemporary research.

Objectives and Problems of Research

The research aims to develop a methodology for analyzing and optimizing the virtual field of a discrete joystick by balancing the areas of its segments in rectangular, diagonal, and polar coordinate systems to enhance the effectiveness and accuracy of controlling mobile platforms.

To achieve this goal, the following objectives must be addressed:

1. To analyze the features of the discretization of the joystick's virtual field in three coordinate systems and determine the geometric characteristics of the segments.

2. To develop analytical expressions for calculating the areas of segments in rectangular, diagonal, and polar coordinate systems.

3. To propose methods for balancing the areas of segments to ensure uniform sensitivity of the joystick in different directions.

4. To conduct a comparative analysis of the area balancing in three coordinate systems, identifying their advantages and disadvantages for various operational conditions.

Main Material Presentation

To model the virtual field of the discrete joystick, rectangular, diagonal, and polar coordinate systems are used (Fig. 1).

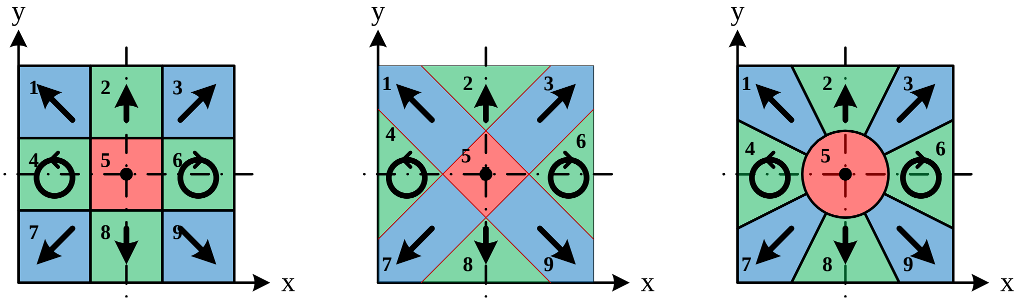

Fig. 1. The virtual field of the discrete joystick: a – rectangular coordinate system; b – diagonal coordinate system; c – polar coordinate system

The rectangular coordinate system (Fig. 1, *a*) is based on the classical division of the plane using vertical and horizontal axes. The diagonal coordinate system (Fig. 1, *b*) describes the field based on the placement of diagonals as key axes. The polar coordinate system focuses on the radial distribution of data relative to the center of the field. Discretization of the virtual field is an important step in simplifying control. The field is divided into nine segments, each corresponding to a specific type of movement (translational, rotational, stop), direction (forward, backward, left, right, clockwise, or counterclockwise), and speed of movement of the mobile platform: Specifically, the first segment is a left turn when moving forward; the second segment is moving forward; the third segment is a right turn when moving forward; the fourth segment is counterclockwise rotation; the fifth segment is stop (stationary state); the sixth segment is clockwise rotation; the seventh segment is a right turn when moving backward; the eighth segment is moving backward; the ninth segment is a left turn when moving backward. Discretization simplifies control algorithms, especially in cases where precision is not critical.

In turn, the segments of the virtual field are divided into diagonal, axial, and central groups. The axial group, which includes the second, fourth, sixth, and eighth segments, comprises straight-line and rotational movements. The diagonal group, which includes the first, third, seventh, and ninth segments, describes the platform's turns. The central group, responsible for the stationary state of the platform, contains only the fifth segment. Grouping simplifies mathematical analysis and allows for the determination of general patterns for each group. The same formulas are used to calculate areas for segments within the same group.

The area of the segments for the rectangular, diagonal, and polar coordinate systems will be determined based on the geometric properties of the central segment. The use of geometric transformations allows for the derivation of analytical expressions that will serve as the foundation for further balancing of the segments.

The central segment in the rectangular coordinate system is square-shaped, and its side length is equal to the vertical side of the axial segment rectangles. Let half the side length of the central segment's square be denoted as h.

The area of the central segment:

$$S_5(h) = 4h^2. \tag{1}$$

The area of the axial group segments:

$$S_2(h) = S_4(h) = S_6(h) = S_8(h) = -2h^2 + h. \tag{2}$$

The area of the diagonal group segments:

$$S_1(h) = S_3(h) = S_7(h) = S_9(h) = h^2 - h + \tfrac{1}{4}. \quad (3)$$

The central segment in the diagonal coordinate system is rhombus-shaped, with diagonals equal to h. The side of the rhombus coincides with the side of the trapezoids in the diagonal segments.

The area of the central segment:

$$S_5(h) = 4h^2. \quad (4)$$

The area of the axial group segments:

$$S_2(h) = S_4(h) = S_6(h) = S_8(h) = 2h^2 - \sqrt{2}h + \tfrac{1}{4}. \quad (5)$$

The area of the diagonal group segments:

$$S_1(h) = S_3(h) = S_7(h) = S_9(h) = -3h^2 + \sqrt{2}h. \quad (6)$$

The central segment in the polar coordinate system is a circle with a radius of h. The other segments are ring sectors, divided by equal angles.

The area of the central segment:

$$S_5(h) = \pi h^2. \quad (7)$$

The area of the axial group segments:

$$S_2(h) = S_4(h) = S_6(h) = S_8(h) = \tfrac{1}{8}\left[-\pi h^2 + 2\tan\left(\tfrac{\pi}{8}\right)\right]. \quad (8)$$

The area of the diagonal group segments:

$$S_1(h) = S_3(h) = S_7(h) = S_9(h) = \tfrac{1}{8}\left[-\pi h^2 + 2\left(1 - \tan\left(\tfrac{\pi}{8}\right)\right)\right]. \quad (9)$$

The derived formulas for the areas of the segments in the virtual field across the three coordinate systems enable analytical calculations for segment balancing. These dependencies form the basis for optimizing joystick parameters for specific operator tasks.

Balancing the segments of the joystick's virtual field involves adjusting the areas of the segments to certain ratios to ensure equal sensitivity in all directions or to meet specific tasks. In this work, the method of equalizing the areas of segments within individual groups (central, axial, diagonal) is used. This approach allows the joystick to be adapted to the operator's needs, reduces control errors, and ensures predictable movements.

In the rectangular coordinate system, balancing is achieved by equalizing the areas of all nine segments. This ensures the joystick's sensitivity is the same in any direction. Using the derived formulas for the areas of the segments (1), (2), and (3), the parameter h is determined, which ensures the equality of the areas of segments from all three groups:

$$\begin{gathered} S_1(h) = S_2(h) = S_5(h) \\ h^2 - h + \frac{1}{4} = -2h^2 + h = 4h^2 \\ h = \tfrac{1}{6}. \end{gathered} \quad (10)$$

In the diagonal coordinate system, three balancing conditions can be demonstrated. The first condition involves the equality of the areas of the axial and diagonal segments, which ensures equal sensitivity for linear motion and rotation around its axis. Based on the area formulas (5) and (6):

$$\begin{gathered} S_1(h) = S_2(h) \\ -3h^2 + \sqrt{2}h = 2h^2 - \sqrt{2}h + \frac{1}{4} \\ 5h^2 - 2\sqrt{2}h + \frac{1}{4} = 0 \\ h = \frac{\sqrt{2}}{5} - \frac{\sqrt{3}}{10} = 0.10964 \end{gathered} \quad (11)$$

The second condition involves the equality of the areas of the axial segments and the central segment, ensuring proportionality between the stop state and linear motion. Using the area formulas (4) and (5), it's obtained:

$$\begin{gathered} S_2(h) = S_5(h) \\ 2h^2 - \sqrt{2}h + \frac{1}{4} = 4h^2 \\ 2h^2 + \sqrt{2}h - \frac{1}{4} = 0 \\ h = \frac{1}{2} - \frac{\sqrt{2}}{4} = 0.14645 \end{gathered} \tag{12}$$

The third condition involves the equality of the areas of the diagonal segments and the central segment, ensuring proportionality between the stop state and turns. Using the area formulas (4) and (6), it’s obtained:

$$\begin{gathered} S_1(h) = S_5(h) \\ -3h^2 + \sqrt{2}h = 4h^2 \\ 7h^2 - \sqrt{2}h = 0 \\ h = \frac{\sqrt{2}}{7} = 0.20203 \end{gathered} \tag{13}$$

In the polar coordinate system, area balancing is performed taking into account circular symmetry based on two conditions. The first condition involves the equality of the areas of the diagonal and central segments. Using the area formulas (7) and (9), it’s obtained:

$$\begin{gathered} S_2(h) = S_5(h) \\ \frac{1}{8}\left[-\pi h^2 + 2\tan\left(\frac{\pi}{8}\right)\right] = \pi h^2 \\ 9\pi h^2 - 2\tan\left(\frac{\pi}{8}\right) = 0 \\ h = \sqrt{\frac{2\sqrt{2} - 2}{9\pi}} = 0.17117 \end{gathered} \tag{14}$$

The second condition involves the equality of the areas of the axial and central segments. Using the area formulas (7) and (8), it’s obtained:

$$\begin{gathered} S_1(h) = S_5(h) \\ \frac{1}{8}\left[-\pi h^2 + 2\left(1 - \tan\left(\frac{\pi}{8}\right)\right)\right] = \pi h^2 \\ 9\pi h^2 - 2\left(1 - \tan\left(\frac{\pi}{8}\right)\right) = 0 \\ h = \sqrt{\frac{4 - 2\sqrt{2}}{9\pi}} = 0.20356 \end{gathered} \tag{15}$$

The proposed conditions ensure consistency between different groups of segments, which improves control accuracy and reduces the operator’s load. The computational expressions allow for the adaptive adjustment of the joystick to specific tasks.

Results and Discussion

Let’s balance the areas of the segments in the virtual field of the discrete joystick for the rectangular coordinate system. Fig. 2 presents the graphs of the segment areas as a function of the parameter *h*, where the blue line represents the area of the diagonal segments, the green line represents the area of the axial segments, and the red line represents the area of the central segment. The range of *h* is limited from 0.0 to 0.5, which corresponds to the maximum side of the square that can be inscribed in the virtual field. Let’s consider the sections of the virtual field for the extreme values and the balance condition.

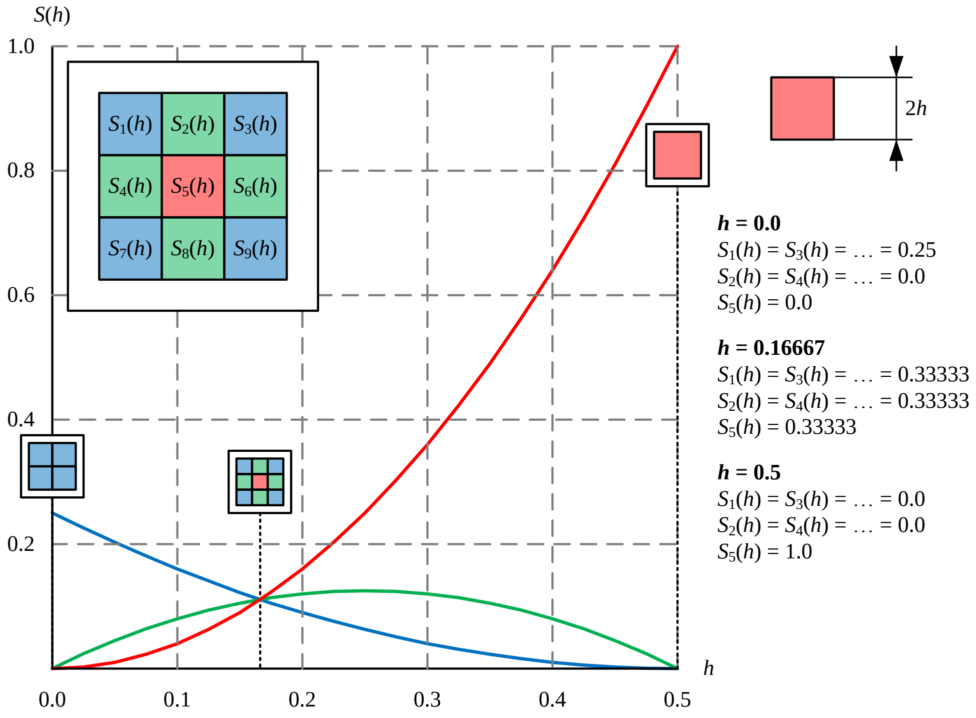

Fig. 2. Dependency between the areas of the segments in the virtual field of the discrete joystick and the parameter h in the rectangular coordinate system

For the section h = 0.0, the central segment and the axial segments do not exist. The virtual field consists of four equal diagonal segments, each in the shape of a square. The area of each segment is maximal, and the influence of the central segment on the control does not exist. For the section h = 0.5, the central segment occupies the entire virtual field, displacing the axial and diagonal segments. The joystick's movement is limited to only the central segment, which corresponds to the stationary state of the platform. For the section h = 0.16667, the areas of all segments are equal. The virtual field consists of nine equal squares, ensuring optimal sensitivity and symmetry in control.

Now, let's balance the areas of the segments in the virtual field of the discrete joystick for the diagonal coordinate system. Fig. 3 presents the graphs of the segment areas as a function of the parameter h, where the blue line represents the area of the diagonal segments, the green line represents the area of the axial segments, and the red line represents the area of the central segment. The range of the parameter h is limited from 0.0 to 0.35355, which corresponds to the maximum size of the rhombus inscribed in the virtual field. Let's consider the sections of the virtual field for the extreme values and the balance conditions. For the section h = 0, the central and diagonal segments do not exist. The virtual field consists of four equal axial segments, each in the shape of a triangle. The area of each segment is maximal, and the influence of the central and diagonal segments does not exist. For the section h = 0.35355, the central rhombic segment occupies half of the virtual field, while the other half consists of diagonal segments with equal areas. The axial segments do not exist. For the section h = 0.10964, which corresponds to the balance condition between the areas of the diagonal and axial segments, the area of the central segment is approximately half of the area of the other segments, with the areas of the diagonal and axial segments being equal. For the section h = 0.14645, which corresponds to the balance condition between the areas of the axial segments and the central segment, the area of the diagonal segments is approximately one and a half times larger than the area of the other segments, including the axial and central segments. For the section h = 0.20203, which corresponds to the balance condition between the areas of the diagonal segments and the central segment, the area of the axial segments is only one-quarter of the area of the other segments, with the areas of the diagonal and central segments being almost equal.

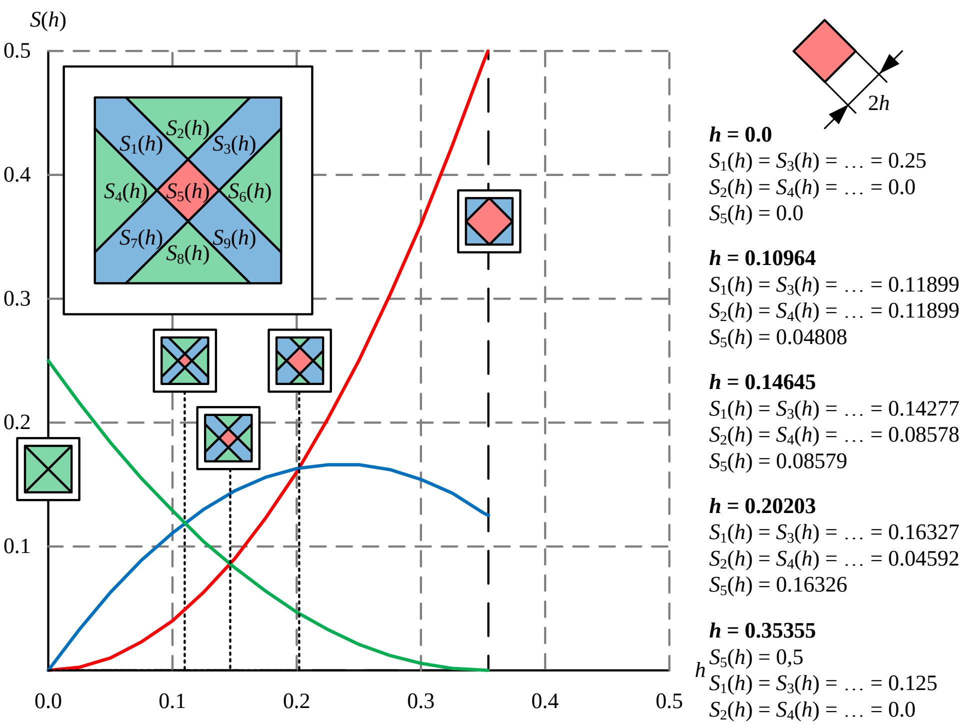

Fig. 3. Dependency between the areas of the segments in the virtual field of the discrete joystick and the parameter *h* in the diagonal coordinate system

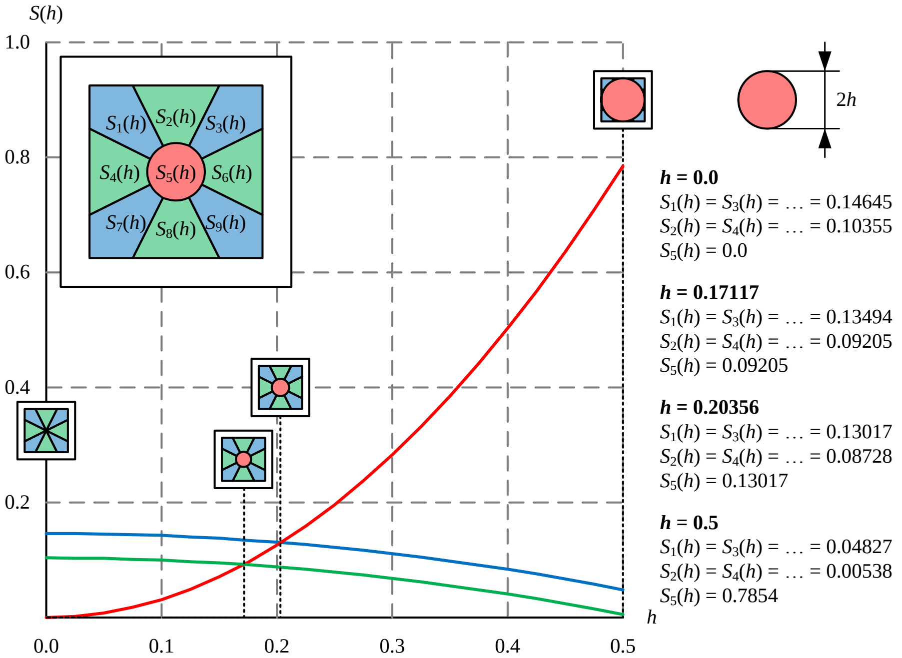

Fig. 4. Dependency between the areas of the segments in the virtual field of the discrete joystick and the parameter h in the polar coordinate system

Let's balance the areas of the segments in the virtual field of the discrete joystick for the polar coordinate system. Fig. 4 presents the graphs of the segment areas as a function of the parameter *h*, where the blue line represents the area of the diagonal segments, the green line represents the area of the axial segments, and the red line represents the area of the central segment. The range of the parameter *h* is limited from 0.0 to 0.5, which corresponds to the maximum radius of the circle that can be inscribed in the virtual field. Let's consider the sections of the virtual field for the extreme values and the balance conditions. For the section h = 0.0, the central segment does not exist, and the virtual field is divided between the axial and diagonal segments. The area of the diagonal segments is slightly larger than the area of the axial segments due to the influence of the angular parts of the virtual field. For the section h = 0.5, the central segment occupies about three-quarters of the virtual field, the axial segments have almost zero area, and the diagonal segments share the remaining area. For the section h = 0.17117, which corresponds to the balance condition between the areas of the axial segments and the central segment, the area of the diagonal segments is approximately one and a half times larger than the area of the axial and central segments. For the section h = 0.20356, which corresponds to the balance condition between the areas of the diagonal segments and the central segment, the area of the axial segments is one and a half times smaller than the area of the diagonal and central segments, contributing to more precise reactions to angular joystick movements.

Conclusions

To model the virtual field of a discrete joystick, three coordinate systems were used: rectangular, diagonal, and polar. Each coordinate system provided a unique way of discretizing the area of the virtual field, allowing the consideration of platform movements in different directions and modes. The polar coordinate system best accounts for circular symmetry, while the rectangular and diagonal systems account for symmetry relative to the straight axes. The virtual field is divided into nine segments, grouped by functional purpose: the central segment corresponds to the stationary state, the axial segments define translational and rotational movements, and the diagonal segments describe turning movements. This grouping simplifies the mathematical analysis and enables the adaptation of control algorithms to various operator tasks.

For each coordinate system, analytical expressions were developed to describe the areas of the segments as a function of the parameter h, which is crucial for balancing. In the rectangular coordinate system, the central segment is square, in the diagonal system it is a rhombus, and in the polar system, it is circular. Balancing the segments ensured uniform joystick sensitivity in all directions or proportional movement to specific tasks. In the rectangular coordinate system, area equality is achieved for h = 0.16667, ensuring symmetry in control. In the diagonal coordinate system, three balancing conditions were proposed, corresponding to different scenarios: equality of axial and diagonal segments' areas for h = 0.10964, equality of axial segments and the central segment for h = 0.14645, and equality of diagonal segments and the central segment for h = 0.20203. In the polar coordinate system, the main balancing conditions are the equality of axial and central segments' areas for h = 0.17117, and the equality of diagonal and central segments'areas for h = 0.20356.

Balancing the areas of segments allows for joystick adaptation to the operator's tasks, reducing control errors and ensuring predictability of the platform's movements. The computed parameters enable the optimization of the joystick to provide uniform sensitivity, depending on the specific requirements for accuracy or reaction speed.

The proposed mathematical models and dependencies form the basis for further improvement of discrete joysticks. The methodology can be applied to create algorithms for adaptive control of mobile platform movements.

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ФОРМУВАННЯ ВІРТУАЛЬНОГО ПОЛЯ ДЛЯ ДИСКРЕТНОГО ДЖОЙСТИКА НА ОСНОВІ БАЛАНСУВАННЯ ПЛОЩІ СЕГМЕНТІВ

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Анотація. *Постановка проблеми.* Забезпечення точного та зручного управління мобільними платформами за допомогою дискретного джойстика – актуальне завдання сучасних систем автоматизації. Однією з основних проблем є нерівномірність чутливості джойстика у різних напрямках через неоднорідний розподіл площ сегментів його віртуального поля. *Мета* – розроблення та оптимізація методики балансування площ сегментів віртуального поля дискретного джойстика для прямокутної, діагональної, полярної систем координат з метою забезпечення однакової чутливості управління. *Методологія.* Дослідження ґрунтується на використанні аналітичних методів визначення площ сегментів віртуального поля для трьох систем координат. Використано метод геометричних перетворень для отримання формул площ. Аналіз виконано з урахуванням умов рівності площ центральної, осьової та діагональної груп сегментів. Отримано графіки залежності площ сегментів від параметра, який визначає розмір центрального сегмента. *Результати*. Запропоновано аналітичні формули для визначення площ сегментів віртуального поля у трьох системах координат. Встановлено умови балансування площ сегментів для різних груп, що дають змогу забезпечити однакову чутливість або адаптацію під конкретні завдання управління. Визначено оптимальні значення параметра для реалізації балансу в кожній системі координат. *Оригінальність.* У роботі вперше запропоновано методику аналітичного балансування площ сегментів віртуального поля джойстика для різних систем координат. Розроблено математичну модель, яка враховує специфіку геометрії сегментів у прямокутній, діагональній та полярній системах координат. *Практична цінність.* Результати дослідження дають змогу налаштовувати параметри джойстика залежно від завдань управління мобільними платформами. Це сприяє підвищенню точності, зниженню кількості помилок управління та адаптації джойстика до потреб операторів у різних умовах експлуатації. *Перспективи подальших досліджень.* Подальші дослідження можуть бути спрямовані на розроблення адаптивних алгоритмів налаштування параметрів джойстика в реальному часі. Також перспективним є урахування динамічних характеристик мобільних платформ та тестування запропонованих моделей у практичних умовах.

Ключові слова: мобільна платформа, дискретний джойстик, віртуальне поле, балансування площ, система координат, прямокутна система, діагональна система, полярна система.