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MATHEMATICAL MODEL OF ADJUSTMENT OF CONTROL PARAMETERS FOR DRONE FLIGHT ALONG THE PLANNED FLIGHT PATH

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МАТЕМАТИЧЕСКАЯ МОДЕЛЬ КОРРЕКТИРОВКИ УПРАВЛЯЮЩИХ ПАРАМЕТРОВ ДЛЯ ПОЛЕТА ДРОНА ПО НАМЕЧЕННОЙ ТРАЕКТОРИИ

Summary. In the paper, the modeling method has been offered and investigated for an adjusting the movement of an unmanned aerial vehicle (drone) based on navigation data. The constructed mathematical model is described in terms of distributed forces and is universal in nature. It allows determining the distributed control force, which within a short time offsets the deviation from the planned path. The proposed model is applied to solution of the problem of adjusting control parameters for quadcopter type drones. It is assumed that the design of a quadcopter is absolutely rigid, its propulsion systems (four identical motors that rotate propellers) are symmetrically located and rigidly fixed relative to its central part. The variation of the propeller rotation speed needed to control the quadcopter is calculated on the basis of data from navigation devices (gyroscopes and an accelerometer) that specify the Krylov angles. The numerical experiments allowed to estimate the values of suitable matching factors between the components of the angular velocity vector of the propellers and the rate of variation of pitch and roll angles.

Аннотация. В работе исследуется метод моделирования корректировки движения летательного аппарата (дрона) на основании навигационных данных. Построенная математическая модель описывается в терминах распределенных сил и носит универсальный характер. Она позволяет определить управляющее распределенное усилие, которое в пределах короткого времени компенсирует отклонение от намеченной траектории. Предложенная модель применена к задаче корректировки параметров управления для дронов типа квадрокоптера. Считается, что конструкция квадрокоптера абсолютно жесткая, его силовые установки (четыре идентичные моторы, вращающие пропеллеры) являются симметрично расположенными и жестко укреплены относительно его центральной части. Необходимое для управления квадрокоптером изменение частот вращения пропеллеров вычисляются на основе данных навигационных приборов (гироскопов и акселерометра), задающих углы ориентации Крылова. Проведенные численные эксперименты позволили оценить значения подходящих коэффициентов согласования между компонентами вектора угловой скорости пропеллеров и скоростью изменения углов тангажа и крена.

Key words: mathematical model, coordinate system, Krylov angles, flight path, control, drone
Ключевые слова: контрольная область, рейтинговая оценка, формирование шкалы оценки.

Introduction

The widespread use of drones has led to numerous publications devoted to various aspects of controlling individual drones or a group of drones. The starting point of all these models is obviously the classical laws of mechanics, and one or another approach is used, depending on the design, control principles and the task, see e.g. [1-4].

The fulfillment of tasks by a drone naturally involves flying along a certain trajectory, which can be drawn by an operator or an automatic planning system relative to the earth.

A simplified model of drone movement results in its deviation from the planned trajectory under the influence of random external factors (wind, poor balance of the drone, etc.). It becomes necessary to adjust the flight movement to minimize the deviation along the entire flight path. Similar problems were considered, for instance, in [5–8]. In these studies, the orientation of the drone is set by Euler angles, and they are convenient to use in the computer simulation of a drone flight. However, currently widely used navigation devices installed on board drones calculate Krylov angles.

In this paper, the universal modeling method has been developed and investigated for drone movement adjustment based on processed sensor data, orientation and propeller speed of the propulsion systems. The coordinates of the location and current speed of the drone are determined on the basis of data from the gyroscopes and the accelerometer.

Problem statement

Suppose that a drone flies in such limited boundaries that in calculating its flight path, the curvature of the Earth can be neglected and a Cartesian coordinate system can be used to describe its position in space. Let us introduce the "earth-fixed" right-handed coordinate system $O_g x_g y_g z_g$, placing its origin at some point on the earth's surface, directing the axes $O_g x_g$ and $O_g y_g$, respectively, say, to the north and the west, and the axis $O_g z_g$ upward vertically (perpendicular to the plane $O_g x_g y_g$). It is known that at each time instant t considered, the position of a solid in space can be determined by six parameters: the spatial coordinates of the center of gravity $x_g(t)$, $y_g(t)$, $z_g(t)$ and the angles that specify its orientation relative to the Earth's fixed coordinate system $O_g x_g y_g z_g$.

Typically, operators set the planned flight path, which can be implemented in different ways, within the technical capabilities of the drone [9]. Depending on the flight mission, such a line can be parameterized in time in various ways. In this paper, we will assume that the flight path is plausibly parameterized and represented by the known functions $x_p(t), y_p(t), z_p(t)$ set in the coordinate system $O_g x_g y_g z_g$.

When modeling the process of controlling the flight path adjustment, the following conditions are accepted:

The elements of the drone have a negligibly small impact on its flight qualities, and the design of the drone is considered absolutely rigid;

At each instant t_0, the current coordinates $x(t_0), y(t_0), z(t_0)$ and the flight speed $x'(t_0), y'(t_0), z'(t_0)$ can be determined based on sensor data;

Within a limited time, the impact of external factors is systematic, and the drone mass m remains unchanged.

Problem: Given the planned flight path $\mathcal{L}_p = \{x_p(t), y_p(t), z_p(t)\}$, the mass of the drone m, the current location $\{x(t_0), y(t_0), z(t_0)\}$ and the flight speed $\{x'(t_0), y'(t_0), z'(t_0)\}$ at moment t_0. Find the distributed control force $\Delta\boldsymbol{F}$, which within a short time Δt compensates for the cumulative deviation from the planned path.

A quadcopter of symmetrical shape will be considered as a specific type of drone. Since the air flow created by the propulsion systems is directed downward and the lifting force is directed perpendicularly upward, when implementing the compensation $\Delta\boldsymbol{F}$, it is necessary to tilt the drone during the maneuver, adjusting the angular rotation velocities of the propellers.

When solving the problem of adjusting the drone's flight, it will be necessary to know the drone's orientation in space. The yaw angle $\varphi(t)$, the pitch angle $\vartheta(t)$, and the roll angle $\gamma(t)$ are taken as the angles of current orientation [10]. The setting of these six functions completely determines the trajectory and orientation of the aerial vehicle.

Analysis of the impact of the forces acting on the drone

Let us introduce the drone-fixed coordinate system $Oxyz$. The origin is located at some arbitrary point, usually the center of gravity of the drone. The axes Ox, Oy and Oz are directed so that at the starting moment of flight they are parallel to the axes $O_g x_g$, $O_g y_g$ and $O_g z_g$.

Suppose $\{\boldsymbol{F}_1, \boldsymbol{F}_2, \dots\}$ denotes the set of all forces that act on the drone. These include the drone's gravity, the lift generated by the drone's propulsion systems, aerodynamic drag, gyroscopic forces, Coriolis force [8], etc. As is known [11, P.234], all forces acting on a solid can be reduced to one resultant force $\boldsymbol{F}$ and the resulting moment $\boldsymbol{M}$ applied to its center of gravity.

Each force $\boldsymbol{F}_k$ creates torque relative to the drone's center of gravity. The moment of force will change depending on the drone specific design features (for instance, tricopter drones with a propulsion system rotating around an axis located at an angle to the direction of thrust), on the orientation of the drone in space during flight (the gravity of the drone is always directed along the earth vertical axis).

Suppose $\left\{\alpha_k^{(1)}, \alpha_k^{(2)}, \dots\right\}$ denotes the parameters determining the arm of force $\boldsymbol{F}_k$ relative to the center O. For instance, the coordinates of the points of force application and the Krylov angles [10, P.9] of its orientation in space can act as these parameters. Obviously, the formula for calculating the arm of force, depending on its nature, can be described analytically. Let us denote this arm by $R_k(\alpha_k^{(1)}, \alpha_k^{(2)}, \dots)$. Then the resulting force and torque created by the forces $\boldsymbol{F_1}, \boldsymbol{F_2}, \dots$ are calculated, respectively, from the formulas:

$$\boldsymbol{F} = \sum_{\boldsymbol{k \geq 1}} \boldsymbol{F}_k,$$

$$\boldsymbol{M} = \sum_{\boldsymbol{k \geq 1}} \boldsymbol{F}_k R_k(\alpha_k^{(1)}, \alpha_k^{(2)}, \dots), \qquad (1)$$

It should be noted that when the resulting force is different, due to the specific design features of the drones, the resulting moment $\boldsymbol{M}$, in the general case, can depend nonlinearly on $\boldsymbol{F}_1, \boldsymbol{F}_2, \dots$. Since the problem of adjusting deviations occurring over a short period of time in the following paragraphs has been considered, the nonlinearity of dependence (1) can be neglected and it can be assumed that during this period the values of $R_k(\alpha_k^{(1)}, \alpha_k^{(2)}, \dots)$ remain constant.

Determining the resulting control vector

In accordance with the statement of the problem, it is need to determine a distributed control force $\Delta\boldsymbol{F}$ such that the deviation from the flight path is compensated for over a sufficiently small Δt time period. Since Δt is a fairly short time, the adjusting force can be realized as a vector $\Delta\boldsymbol{F} = \left(\Delta F_x, \Delta F_y, \Delta F_z\right)$

with constant components ΔF_x, ΔF_y, ΔF_z. Denote $\Delta x = x(t) - x_p(t)$, $\Delta y = y(t) - y_p(t)$, $\Delta z = z(t) - z_p(t)$. Then the system of equations for the compensating term of the flight path is written in the form:

$$\begin{cases} m\Delta x''(t) = \Delta F_x, \\ m\Delta y''(t) = \Delta F_y, \\ m\Delta z''(t) = \Delta F_z. \end{cases} \quad (2)$$

Here, initial condition (3) will represent the detected deviation at t_0, and condition (4) – the fact of compensation for this deviation over time $t_0 + \Delta t$:

$$\begin{cases} \Delta x(t_0) = x_p(t_0) - x(t_0), \\ \Delta y(t_0) = y_p(t_0) - y(t_0), \\ \Delta z(t_0) = z_p(t_0) - z(t_0), \end{cases} \quad (3)$$

$$\begin{cases} \Delta x(t_0 + \Delta t) = 0, \\ \Delta y(t_0 + \Delta t) = 0, \\ \Delta z(t_0 + \Delta t) = 0. \end{cases} \quad (4)$$

System (2) - (4) can be supplemented with the condition that the deviation compensation rate be equal to zero:

$$\begin{cases} \Delta x'(t_0 + \Delta t) = 0, \\ \Delta y'(t_0 + \Delta t) = 0, \\ \Delta z'(t_0 + \Delta t) = 0. \end{cases} \quad (5)$$

Solving problem (2)-(5), the values of the components of the control vector $\Delta \boldsymbol{F}$ has been obtained:

$$\begin{cases} \Delta F_x = \frac{2m}{\Delta t^2}\left(x_p(t_0) - x(t_0)\right), \\ \Delta F_y = \frac{2m}{\Delta t^2}\left(y_p(t_0) - y(t_0)\right), \\ \Delta F_z = \frac{2m}{\Delta t^2}\left(z_p(t_0) - z(t_0)\right). \end{cases} \quad (6)$$

As mentioned above, the propulsion systems of the drone are located in different points of the drone, depending on the technological solution and specific design features. Therefore, if, on the one hand, a change in the forces of the propulsion systems creates excess torque (e.g. drones with fixed propulsion systems), then, on the other hand, a change in the torque and redistribution of the components of the resulting force relative to the earth can be the result of a rotation of the axes of the propulsion systems (e.g. tricopter type drones [1]). It will be reflected in the variation of the corresponding angles $\left\{\alpha_k^{(1)}, \alpha_k^{(2)}, \dots\right\}$. Thus, for the drone to offset its deviation along the planned trajectory, it is necessary that the propulsion systems of the drone, within the limits of their capabilities, change the generated forces $\boldsymbol{F}_k^*$ so that the following condition is satisfied:

$$\sum_{k\geq 1}(\boldsymbol{F}_k^* - \boldsymbol{F}_k) = (\Delta F_x, \Delta F_y, \Delta F_z).$$

Ensuring a quadcopter's stable flight mode

The description and mathematical model of the movement of a typical quadcopter have been studied in various sources [2, 3, 12, 13]. The propulsion systems of quadcopters are four identical propeller-rotating motors symmetrically and rigidly fixed relative to the central hardware component of the drone. For clarity, we number them from 1 to 4 in the counterclockwise direction around the center of the drone (Figure 1).

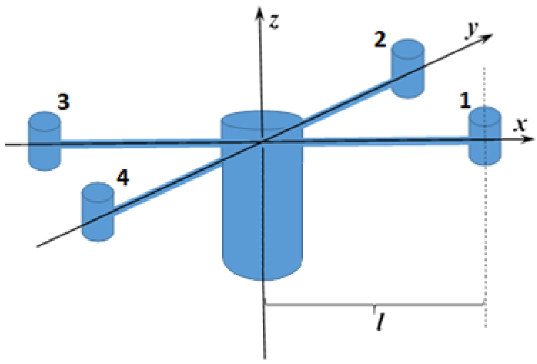

Figure 1. Quadcopter schematic

Let us introduce the bound right-handed Cartesian coordinate system $Oxyz$ with the origin in the center of the quadcopter. Suppose the propulsion systems are located in the points

$$(l, 0,0), (0, l, 0), (-l, 0,0), (0, -l, 0). \quad (7)$$

Let us number them in the order indicated in (7) and assume that propellers 1 and 3 create a moment in the clockwise direction, and 2 and 4 in the opposite direction. If it is assumed that the mass of the quadcopter is concentrated only on the segments connecting the center of the drone and the point (7), then its inertia matrix will be diagonal, with elements J_{xx}, J_{yy}, J_{zz} [14, P.18].

Suppose $\omega_i(t)$ denotes the rotation speed of the i-th propeller at the instant t. The task of controlling the flight of the drone along the planned path involves determining new values of $\omega_i^*(t)$, which contribute to the variation of the components of the generated force by values (6). The input information for solving this problem is at the time t_0 the rotation velocities of all propellers $\omega_i(t_0)$, $(i = 1,2,3,4)$, the current yaw angle $\varphi(t_0)$, the pitch angle $\vartheta(t_0)$ and the roll angle $\gamma(t_0)$ and the components of force (6). Let the pitch and roll angles vary within the interval $(-\pi/2, +\pi/2)$.

Due to the smallness of the angular acceleration of the drone during maneuvering and the smallness of gyroscopic forces and Coriolis force arising during rotation, they can be neglected. According, for instance, to [13, P.3], the i-th propeller creates thrust and torque relative to its rotation axis

$$f_i = k\omega_i^2, \Im_i = b\omega_i^2,$$

where k and b are the known coefficients determined experimentally for a particular type of propulsion system. Total force F and torques M_{Ox}, M_{Oy}, M_{Oz} generated by the propellers relative to the axes Ox, Oy and Oz, respectively, will be [11, P.138, §11]:

$$F = \sum_{i=1}^{4} f_i = k\sum_{i=1}^{4} \omega_i^2, \quad (8)$$

$$M_{Ox} = f_2 l - f_4 l = kl(\omega_2^2 - \omega_4^2), \quad (9)$$

$$M_{Oy} = f_3 l - f_1 l = kl(\omega_3^2 - \omega_1^2), \quad (10)$$

$$M_{Oz} = \Im_1 - \Im_2 + \Im_3 - \Im_4 = b(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2), \quad (11)$$

Transformation matrices corresponding to the rotation by the set $\{\varphi, \vartheta, \gamma\}$ are the matrices [10, P.42]

$$A(\gamma) \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_\gamma & -S_\gamma \\ 0 & S_\gamma & C_\gamma \end{pmatrix}, A(\vartheta) \equiv \begin{pmatrix} C_\vartheta & 0 & -S_\vartheta \\ 0 & 1 & 0 \\ S_\vartheta & 0 & C_\vartheta \end{pmatrix},$$

$$A(\varphi) \equiv \begin{pmatrix} C_\varphi & -S_\varphi & 0 \\ S_\varphi & C_\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

where $C_\xi \equiv Cos\xi$, $S_\xi \equiv Sin\xi$ are denoted for brevity. Since force $\boldsymbol{F}$ generated by the propellers is always directed along the axis Oz, then the following representation can be written for it in the coordinate system $O_g x_g y_g z_g$: $\boldsymbol{F} = F(-S_\vartheta, -S_\gamma C_\vartheta, C_\gamma C_\vartheta)$. Let us denote

$$\boldsymbol{\mathcal{F}} = (\Delta F_x - S_\vartheta F, \Delta F_y - S_\gamma C_\vartheta F, \Delta F_z + C_\gamma C_\vartheta F). \quad (12)$$

In order for the quadcopter to offset its deviation from the planned trajectory, the propulsion systems must change the rotation speed of the propellers by some values $\omega_i^*(t)$, $(i = 1,2,3,4)$ to:

(A) create a force equal in modulus to $|\boldsymbol{\mathcal{F}}|$, on the one hand, and

(B) tilt it in the direction of the vector $\boldsymbol{\mathcal{F}}$ relative to the coordinate system $O_g x_g y_g z_g$.

It is easy to calculate the necessary angles $\{\varphi^*, \vartheta^*, \gamma^*\}$ providing an inclination of direction of the axis Oz along $\boldsymbol{\mathcal{F}}$. It is clear that the yaw angle φ is not involved in representation (12), therefore, it can be considered unchanged during the adjustment maneuver. Thus, next formulas have been written below:

$$\begin{cases} \operatorname{tg}\gamma^* = -\dfrac{\Delta F_y - S_\gamma C_\vartheta F}{\Delta F_z + C_\gamma C_\vartheta F}, \\ \operatorname{tg}\vartheta^* = \dfrac{\Delta F_x - S_\vartheta F}{(\Delta F_y - S_\gamma C_\vartheta F) C_{\gamma^*}}, \\ \varphi^* = \varphi. \end{cases}$$

These angles, over a short period of time Δt can be implemented by changing angles $\{\varphi, \vartheta, \gamma\}$ at the rate of $\left\{\nu_\varphi = 0, \nu_\vartheta = \kappa_\vartheta \frac{\vartheta^* - \vartheta}{\Delta t}, \nu_\gamma = \kappa_\gamma \frac{\gamma^* - \gamma}{\Delta t}\right\}$, where the coefficients κ_ϑ and κ_γ can be determined experimentally. Then the angular velocity vector $\boldsymbol{\nu}_g$ relative to the coordinate system $O_g x_g y_g z_g$, accordingly [14, P.164], is

$$\boldsymbol{\nu}_g = \begin{pmatrix} \nu_{gX} \\ \nu_{gY} \\ \nu_{gZ} \end{pmatrix} = \begin{pmatrix} \nu_\gamma C_\varphi C_\vartheta + \nu_\vartheta S_\varphi \\ \nu_\gamma S_\varphi C_\vartheta - \nu_\vartheta C_\varphi \\ \nu_\gamma S_\vartheta \end{pmatrix} \quad (13)$$

Successively applying the transformations $A(\varphi)$, $A(\vartheta)$ and $A(\gamma)$ to (13), the representation for the angular velocity vector in the coordinates of the bound coordinate system $Oxyz$ has been obtained below:

$$\begin{pmatrix} \nu_X \\ \nu_Y \\ \nu_Z \end{pmatrix} = A(\gamma)A(\vartheta)A(\varphi) \begin{pmatrix} \nu_{gX} \\ \nu_{gY} \\ \nu_{gZ} \end{pmatrix}.$$

Further, taking into account the above assumptions and following [14, P.167], next formulas for calculating the torques have been obtained

$$\begin{cases} M_{Ox} = J_{xx}\nu_X, \\ M_{Oy} = J_{yy}\nu_Y, \\ M_{Oz} = J_{zz}\nu_Z. \end{cases}$$

Now, based on (8) - (11), conditions (A) and (B) will be rewritten as follows:

$$\begin{cases} (\omega_1^*)^2 + (\omega_2^*)^2 + (\omega_3^*)^2 + (\omega_4^*)^2 = \frac{1}{k}|\boldsymbol{\mathcal{F}}| \,, \\ (\omega_2^*)^2 - (\omega_4^*)^2 = \frac{J_{xx}}{kl}\nu_X \,, \\ (\omega_3^*)^2 - (\omega_1^*)^2 = \frac{J_{yy}}{kl}\nu_Y \,, \\ (\omega_1^*)^2 - (\omega_2^*)^2 + (\omega_3^*)^2 - (\omega_4^*)^2 = \frac{J_{zz}}{b}\nu_Z \,. \end{cases} \quad (14)$$

The main determinant of the system (14) $\Delta = 8$, therefore all $\omega_i^*(t)$, $(i = 1,2,3,4)$ are determined uniquely.

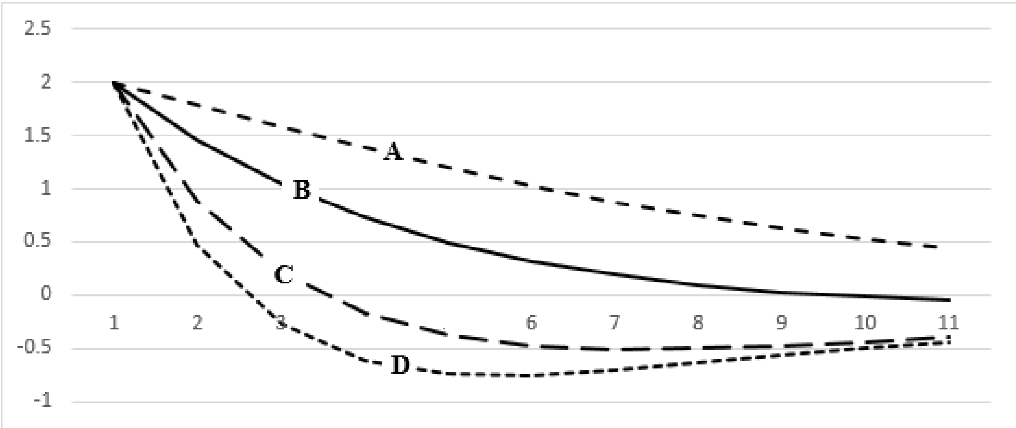

Figure 2. Diagram of deviation compensation at $\kappa_\gamma = 6.2$ for different values of κ_ϑ : (A) $\kappa_\vartheta = 3.0$; (B) $\kappa_\vartheta = 6.0$; (C) $\kappa_\vartheta = 9.0$; (D) $\kappa_\vartheta = 10.0$.

A software module has been developed for estimating the coefficients κ_ϑ and κ_γ. Our experiments conducted for the case $k = 1.5 \times 10^{-5}$ and $b = 0.5 \times 10^{-6}$ have demonstrated that the coefficients κ_ϑ and κ_γ can be taken within the interval $(5, 7)$. Fig. 2 shows the plots of deviation compensation for different values of κ_ϑ, at $\kappa_\gamma = 6.2$. The horizontal axis shows time, in 100 milliseconds, the vertical – deviation from the flight path, in meters. Similar plots are obtained for different values of κ_γ at $\kappa_\vartheta \in (5, 7)$.

Results

A mathematical model has been developed and proposed for determining the distributed control force, which compensates for the deviation from the planned flight path within a short time. The proposed model is applied to the problem of adjusting control parameters for quadcopter type drones, which are calculated based on feedback from sensors that specify orientation angles in Krylov angles. Numerical experiments have been carried out, and the values of the suitable matching factors between the components of the angular velocity vector and the rate of variation of pitch and roll angles have been estimated.

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ОРГАНІЗАЦІЯ І ТЕХНОЛОГІЯ АВТОМАТИЗАЦІЇ ВИРОБНИЦТВА АСФАЛЬТОБЕТОНУ,ТЕНДЕНЦІЇ ТА ПЕРСПЕКТИВИ РОЗВИТКУ

Аннотация. В стаττі відзначено, що для будівництва доріг і благоустрою території у всьому світі застосовують асфальтобетон, що дає якісне і довговічне покриття. Асфальтобетон є надзвичайно популярним матеріалом який використовується в сучасній будівельній галузі. Відзначно, що може бути отриманий додатковий ефект від отримання нових знань про процес виробництва асфальтобетонної суміші. Так, якщо присутні і деякі показники компонентів асфальтобетонної суміші, і показники якості готової продукції, то за допомогою розробленої математичної моделі є можливість досліджувати статистичні технологічні залежності виду $\omega_m - \varphi(\upsilon_i)$ і отримати моделі технологічного процесу виробництва асфальтобетонної суміші, які можуть бути використані в тому числі і для підвищення ефективності управління виробництвом.

В статті реалізовано та запропоновано підхід на самому верхньому рівні пропонованої системи управління. В даний час закінчується розробка автоматизованої системи управління виробництвом асфальтобетону, в якій реалізується викладений в даній статті підхід, заснований на розширенні поняття об'єкта управління за межі АБЗ і включенні в контур управління транспорт, укладання і навіть експлуатацію готового асфальтобетонного покриття.

Ключові слова: автоматизація, асфальтобетон, управління транспорту, покриття, управління виробництвом, підвищення управління.

Для будівництва доріг і благоустрою території у всьому світі застосовують асфальтобетон, що дає якісне і довговічне покриття. Асфальтобетон є надзвичайно популярним матеріалом який використовується в сучасній будівельній галузі. Його відносна недорога вартість матеріалу поряд з оптимальними характеристиками дозволяють використовувати асфальтобетон як верхнє дорожне покриття. Асфальтобетон досить міцний і надійний матеріал,тому виготовлення асфальту, будівництво заводів з виробництва асфальтних сумішей - один з перспективних напрямків бізнесу. Виробництво асфальту в Україні ще довго буде залишатися одним з найприбутковіших видів бізнесу. Сьогодні