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¹Mykola Voitekh,²Vitaly NechyporukFORMULATION OF A NAVIGATION PATH FOR AN UNMANNED AERIAL VEHICLE
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Abstract—This paper considers the formation of a navigation path for an unmanned aerial vehicle operating in a dynamic environment. The relevance of the study is determined by the need to ensure stable autonomous flight under external disturbances, navigation measurement uncertainty, and temporal delays in control processes. The aim of the work is to develop a mathematical framework for a navigation control loop that maintains the predefined flight path and compensates for dynamic deviations. A navigation control loop architecture combining spatial state estimation, trajectory tracking, motion stabilisation, and corrective control synthesis is proposed. The developed mathematical framework formalises trajectory deviation estimation, control generation, disturbance compensation, and stability assessment. Simulation modelling in Mission Planner demonstrated that the proposed approach reduces spatial trajectory deviations and improves route tracking stability under dynamic disturbances. The developed approach can be applied in autonomous flight, navigation, and trajectory stabilisation systems of unmanned aerial vehicles.

Keywords—Unmanned aerial vehicle, autonomous flight, flight path stabilisation, dynamic disturbances, spatial positioning, adaptive control.

I. INTRODUCTION

Modern autonomous aerial complexes are increasingly used in monitoring, surveillance, mapping, logistics, and spatial analysis tasks operating under conditions of dynamic environmental changes and limited stability of navigation measurements.

The efficiency of autonomous flight directly depends on the ability of the onboard navigation system to ensure stable trajectory formation, timely compensation of external disturbances, and coordinated operation of computational and executive subsystems in real time.

During autonomous movement, the aerial complex is continuously affected by external aerodynamic disturbances, instability of spatial positioning parameters, temporal delays in information transmission, and uncertainty of navigation measurements. Under such operating conditions, even minor deviations of motion parameters may lead to significant trajectory disturbances, instability of flight modes, and reduction of navigation accuracy.

Therefore, ensuring stable operation of the navigation contour under conditions of dynamic

environmental influence is one of the key problems of modern autonomous flight systems.

An important feature of autonomous aerial navigation is the use of heterogeneous sensor subsystems that differ in operating principles, data update frequency, and measurement accuracy.

The interaction between inertial navigation modules, satellite positioning systems, visual sensors, laser rangefinders, and onboard computational components forms a complex multilevel navigation environment in which the consistency of information processing directly affects the stability of trajectory formation and motion correction efficiency.

Existing approaches to autonomous flight control mainly focus on separate navigation, stabilisation, or trajectory planning tasks. However, many existing methods insufficiently consider the influence of dynamic disturbances, instability of navigation parameters, temporal inconsistency of information flows, and adaptive correction of motion deviations within a unified navigation contour. In addition, under conditions of rapidly changing external factors, conventional control approaches may not provide the required level of trajectory stability and disturbance compensation.

In this regard, the problem of forming a stable navigation contour capable of adaptive correction of flight parameters and compensation of dynamic trajectory deviations becomes particularly relevant. Such an approach should ensure coordinated interaction between navigation, computational, and executive subsystems while maintaining stable autonomous flight under uncertainty conditions.

The aim of this work is to develop a mathematical framework for the formation of the navigation contour of an autonomous aerial complex in a dynamic environment. The proposed approach is focused on trajectory stabilisation, compensation of external disturbances, adaptive synthesis of control actions, and improvement of autonomous flight stability under dynamically changing operating conditions.

The practical significance of the obtained results lies in the possibility of applying the proposed approach in autonomous flight systems, trajectory stabilisation subsystems, spatial positioning technologies, and adaptive flight control systems of autonomous aerial complexes operating under conditions of uncertainty and external dynamic disturbances.

II. LITERATURE ANALYSIS

The rapid development of autonomous aerial complexes and intelligent flight control systems has significantly increased the relevance of research related to trajectory stabilisation, navigation contour formation, and adaptive compensation of dynamic disturbances during autonomous flight. Modern aerial platforms operate under conditions of uncertainty, instability of navigation measurements, external aerodynamic influences, and temporal delays in information transmission, which requires the development of new approaches to autonomous navigation and flight control.

The theoretical foundations of information support and mathematical modelling of complex decision-making systems are presented in [1]. The approaches described in this work provide a basis for constructing mathematical frameworks for autonomous navigation systems functioning under conditions of uncertainty and dynamic environmental changes.

Methods of optimisation and intelligent search for control solutions are considered in [2] and [5]. In these works, bio-inspired and population optimisation algorithms are proposed for solving multidimensional optimisation problems.

Such approaches can be applied for adaptive synthesis of navigation trajectories and formation of control actions in autonomous flight systems.

In article [3], a methodological approach for assessing the condition of complex organisational and technical systems is proposed.

The presented approaches focus on analysing the stability and behaviour of systems under destabilising influences and may be used for evaluating the stability of autonomous aerial complexes operating in dynamic environments.

The scientific-method apparatus for improving the efficiency of information processing using artificial intelligence methods is presented in [4]. The proposed approaches to adaptive information analysis and intelligent data processing can be used during the formation of navigation contours and the synthesis of autonomous flight control mechanisms.

Research related to anomaly detection and adaptive processing of multidimensional information structures is presented in [6], [9], and [10]. These studies demonstrate the relevance of intelligent methods for processing complex information flows under uncertainty conditions and support the necessity of adaptive mechanisms for analysing navigation parameters and compensating dynamic deviations.

In articles [7] and [8], approaches to monitoring, event correlation, and adaptive management of critical infrastructure systems are investigated.

The presented methods emphasise the importance of stability, reliability, and coordinated interaction between distributed computational and control subsystems under conditions of dynamic external influence.

The problem of processing multidimensional time series in information systems is considered in [11]. The proposed approaches are relevant for autonomous aerial navigation systems because the trajectory formation process may be represented as a multidimensional temporal sequence describing spatial motion parameters and dynamic changes in the state of the aerial platform.

In article [12], the influence of unmanned aerial vehicle imaging parameters on terrain recognition accuracy is analysed.

The obtained results confirm the importance of stable navigation and coordinated operation of sensor subsystems during autonomous flight and spatial positioning tasks.

The optimisation of route formation in unmanned aerial vehicle data exchange systems is investigated in [13]. The proposed approach demonstrates the effectiveness of adaptive optimisation methods for trajectory formation and coordinated interaction between navigation and communication subsystems of aerial complexes.

At the same time, analysis of the existing studies shows that many approaches focus mainly on separate optimisation, positioning, monitoring, or information processing tasks without sufficient consideration of integrated formation of the navigation contour under dynamic environmental conditions. In addition, the influence of external disturbances, instability of flight parameters, adaptive trajectory correction, and coordinated interaction of navigation and executive subsystems remains insufficiently investigated.

Therefore, the problem of developing a mathematical framework for navigation contour formation of an autonomous aerial complex capable of adaptive compensation of trajectory deviations and ensuring stable autonomous flight under dynamic external influences remains relevant and requires further research [15].

In addition, the influence of temporal inconsistencies, uncertainty propagation, and adaptive correction of trajectory estimation remains insufficiently investigated.

III. PROBLEM STATEMENT

Autonomous aerial complexes operating in dynamic environments require stable navigation support capable of ensuring accurate trajectory formation, adaptive correction of motion parameters, and compensation of external disturbances during flight. The efficiency of autonomous motion directly depends on the consistency of interaction between navigation, computational, and executive subsystems, as well as on the stability of the navigation contour under conditions of uncertainty and dynamically changing environmental parameters.

During autonomous flight, the aerial complex is affected by external aerodynamic disturbances, instability of navigation measurements, temporal delays in information transmission, and local deviations of motion parameters. Under such conditions, even minor disturbances may lead to accumulation of trajectory errors, destabilisation of flight modes, deterioration of spatial positioning accuracy, and reduction of the efficiency of autonomous navigation.

An important feature of autonomous [14] flight systems is the simultaneous operation of heterogeneous navigation and sensor modules characterised by different update frequencies, measurement principles, and reliability levels. The inconsistency of information flows and instability of sensor measurements complicate the process of coordinated trajectory formation and adaptive synthesis of control actions.

In this study, the navigation contour is understood as a closed-loop structure that combines estimation of the current spatial state of the aerial vehicle,

comparison with the reference trajectory, generation of corrective control actions, and feedback-based compensation of trajectory deviations.

The navigation process of an autonomous aerial vehicle in a dynamic environment can be considered as a trajectory tracking problem under external disturbances, measurement uncertainty, and temporal inconsistency of sensor data. Let the current spatial state of the aerial vehicle be represented by:

$$q(t) = [x(t) \ y(t) \ z(t) \ \varphi(t) \ \theta(t) \ \psi(t)]^T,$$

where $x(t)$, $y(t)$, and $z(t)$ determine the spatial position of the aerial vehicle, while $\varphi(t)$, $\theta(t)$, and $\psi(t)$ define its angular orientation.

The predefined flight route is described by the reference state $q^r(t)$. The deviation of the current state from the reference trajectory is determined as:

$$\Delta q(t) = q(t) - q^r(t).$$

The motion of the aerial vehicle under the influence of control actions and external disturbances is represented in the general form:

$$\dot{q}(t) = F(q(t), u(t), d(t)),$$

where $u(t)$ is the control action and $d(t)$ represents external disturbances affecting the flight trajectory.

Navigation information is obtained from heterogeneous sensor sources and may contain measurement errors and temporal delays. For the i -th information source, the measurement model is represented as:

$$y_i(t) = H_i(q(t - \tau_i)) + v_i(t), \quad i = 1, \dots, m,$$

where H_i is the measurement function, τ_i is the corresponding time delay, v_i is the measurement error, and m is the number of navigation information sources.

Thus, the problem is to determine the control action $u^*(t)$ that provides minimum deviation from the predefined trajectory while limiting excessive control actions. The corresponding optimisation criterion is:

$$u^*(t) = \arg \min_{u(t)} \int_0^T [\Delta q^T(t) Q \Delta q(t) + u^T(t) R u(t)] dt.$$

The solution must ensure bounded trajectory deviation under admissible external disturbances:

$$\limsup_{t \rightarrow T} \|\Delta q(t)\| \leq \varepsilon,$$

where ε is the admissible trajectory tracking error.

Therefore, the research task consists in developing a navigation contour that estimates the deviation of the current aerial vehicle state from the predefined trajectory and generates corrective control actions that minimise the trajectory tracking error under external disturbances, sensor measurement uncertainty, and temporal delays. The mathematical implementation of the formulated problem and the synthesis of the corresponding control actions are presented in the next section.

In this study, the navigation problem is formulated as maintaining the aerial vehicle motion along a predefined route by estimating trajectory deviations and generating corrective control actions under external disturbances.

IV. ELEMENTS OF THE METHODOLOGICAL FRAMEWORK

The formation of a stable navigation contour of an autonomous aerial complex in a dynamic environment is one of the key tasks of modern autonomous flight control systems. The efficiency of trajectory generation and flight parameter stabilisation directly depends on the accuracy of spatial position estimation, the consistency of sensor information flows, and the ability of the control system to compensate external disturbances in real time.

During autonomous flight, the aerial complex continuously interacts with a dynamically changing environment affected by external aerodynamic disturbances, sensor measurement noise, temporal delays in information transmission, and instability of navigation parameters.

Under such conditions, the navigation contour should ensure not only the determination of the current spatial position of the aerial complex, but also continuous correction of trajectory parameters according to changes in the external environment and the internal dynamic state of the platform.

An important feature of autonomous navigation is the simultaneous use of heterogeneous sensor sources characterised by different measurement principles, data update frequencies, and levels of uncertainty.

The coordinated interaction of such sensor modules makes it possible to improve the reliability of spatial positioning and ensure stable trajectory formation under conditions of partial degradation of individual information channels.

The navigation contour of the autonomous aerial complex is formed as a multilevel structure combining the processes of sensor data acquisition, spatial state estimation, trajectory generation, angular parameter stabilisation, and synthesis of control actions.

At the same time, the efficiency of autonomous motion directly depends on the consistency of interaction between navigation, computational, and executive subsystems.

The integration of heterogeneous sensor sources makes it possible to improve the stability of spatial position estimation and reduce the influence of local measurement errors caused by dynamic disturbances and changes in environmental parameters.

During the operation of the aerial complex, sensor information flows are transmitted to the navigation processing subsystem, where synchronisation, filtering, and coordinated estimation of motion parameters are performed. Based on the obtained results, the current trajectory parameters and spatial orientation of the platform are determined.

The structural scheme of navigation contour formation of the autonomous aerial complex is shown in Fig. 1.

The presented architecture reflects the interaction between trajectory generation subsystems, motion parameter stabilisation modules, feedback channels, and executive control mechanisms.

The presented navigation contour includes the trajectory generation subsystem, angular stabilisation modules, dynamic correction blocks, feedback channels, and executive control mechanisms responsible for flight parameter regulation.

The interaction of these components ensures continuous correction of the aerial complex motion parameters according to changes in external disturbances and current navigation conditions.

The proposed architecture makes it possible to improve the stability of autonomous flight, reduce trajectory deviations, and provide adaptive compensation of destabilising influences during the operation of the aerial complex in a dynamic environment.

To formalise the processes of navigation contour formation and trajectory stabilisation, it is necessary to move from the structural representation of the aerial complex to a mathematical description of spatial motion dynamics, synthesis of control actions, and coordinated analysis of navigation information flows.

The schemes presented in Fig. 1 define the general logic of interaction between sensor, computational, and executive subsystems; however, further analysis requires formalisation of these processes using a mathematical framework describing the dynamics of autonomous flight and adaptive trajectory correction.

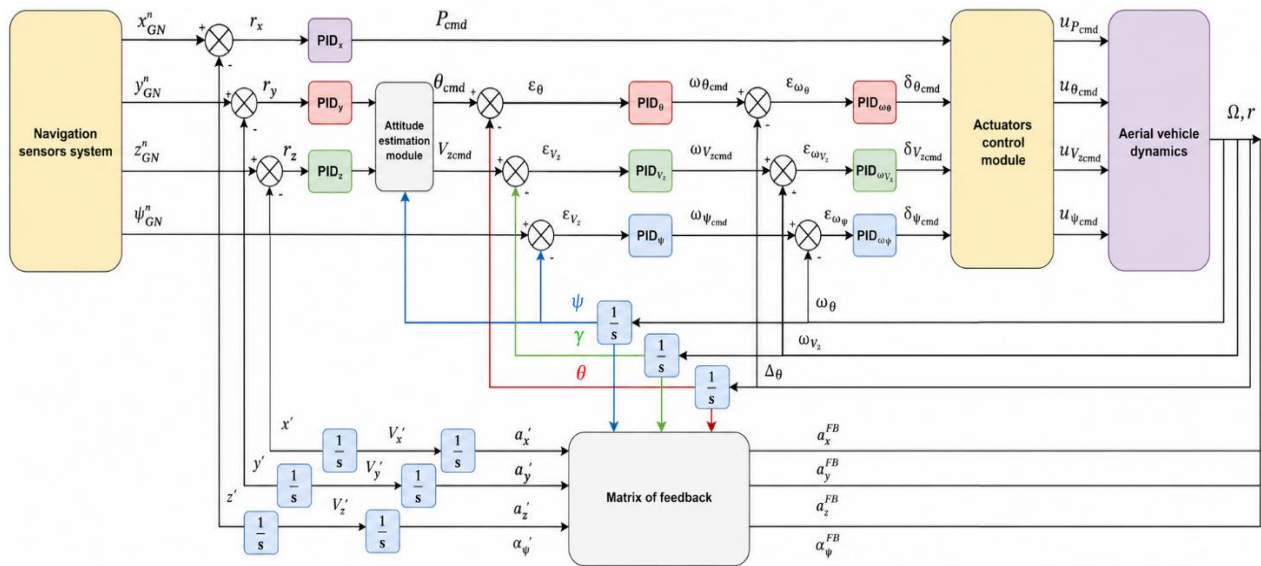


Fig. 1. Block diagram of the navigation loop formation for an unmanned aerial vehicle

The mathematical framework for navigation contour formation of the autonomous aerial complex should take into account the spatio-temporal dynamics of motion, platform orientation parameters, the influence of external disturbances, and the operational features of sensor subsystems in real time. In this case, the autonomous flight process should be considered as a multidimensional dynamic system with variable state parameters and uncertainties caused by measurement noise, temporal delays in data transmission, and instability of navigation information.

The formation of the navigation contour is based on the coordinated interaction between spatial position estimation subsystems, trajectory prediction mechanisms, and synthesis of control actions. Within such an approach, it is necessary to formalise the processes of spatial positioning, motion parameter estimation, angular stabilisation, and compensation of dynamic disturbances affecting the stability of autonomous flight.

A distinctive feature of the proposed approach is the combination of aerial complex motion dynamics models with mechanisms of integrated navigation information analysis and adaptive trajectory parameter correction.

This makes it possible to ensure continuous updating of the spatial state of the system and improve the accuracy of navigation contour formation under conditions of dynamically changing environmental parameters.

In the process of mathematical description of autonomous flight, it is necessary to consider the relationship between spatial position parameters, motion velocities, angular characteristics, and

control actions generated by the motion stabilisation subsystem. In addition, it is important to take into account the influence of random external disturbances and uncertainties of sensor measurements that lead to trajectory deviations from the predefined route.

Considering the above features, the following mathematical framework should be represented as a sequence of formalised stages describing the formation of the aerial complex state vector, the dynamics of spatial motion, integration of navigation information, synthesis of control actions, and the trajectory stabilisation criterion of autonomous flight.

Step 1. Description of deviation from the predefined route:

$$\Delta q(t) = \begin{bmatrix} x(t) - x^{ref}(t) \\ y(t) - y^{ref}(t) \\ z(t) - z^{ref}(t) \\ \phi(t) - \phi^{ref}(t) \\ \theta(t) - \theta^{ref}(t) \\ \psi(t) - \psi^{ref}(t) \end{bmatrix}.$$

Step 2. Dynamic model of disturbed motion:

$$\frac{d}{dt} \begin{bmatrix} \Delta q(t) \\ \dot{\Delta q}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -M^{-1}(t)K_s(t) & -M^{-1}(t)K_d(t) \end{bmatrix} \begin{bmatrix} \Delta q(t) \\ \dot{\Delta q}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1}(t) \end{bmatrix} (u(t) + d(t)).$$

Step 3. Law of control action generation of the navigation contour:

$$u(t) = -K_p(t)\Delta q(t) - K_v(t)\Delta \dot{q}(t) - K_\xi(t) \int_0^t \Omega(t, \tau) \Delta q(\tau) d\tau + u^{ref}(t).$$

Step 4. Compensation of external disturbances in the flight contour:

$$\hat{d}(t) = U(t) \left[\Delta q(t) + C(t) \Delta \dot{q}(t) + K_r(t) \Delta q(t) \right] - B(t)u(t).$$

Step 5. Stability criterion of the navigation contour:

$$J = \int_0^T \left[\Delta q^T(t) Q_1 \Delta q(t) + \Delta \dot{q}^T(t) Q_2 \Delta \dot{q}(t) + u^T(t) R(t) + d^T(t) Q_d d(t) \right] dt \rightarrow \min.$$

The obtained mathematical framework makes it possible to formalise the process of navigation contour formation of an autonomous aerial complex, describe the dynamics of spatial motion, mechanisms of external disturbance compensation, and synthesis of control actions during flight trajectory stabilisation.

The presented mathematical relationships provide the possibility of estimating deviations from the predefined route, analysing the stability of the navigation contour, and determining the efficiency of motion parameter correction under conditions of dynamically changing environmental parameters.

To verify the operability of the proposed approach and evaluate the effectiveness of the formed navigation contour, simulation modelling of autonomous flight under conditions of external dynamic disturbances was carried out.

The modelling was performed taking into account the influence of random trajectory deviations, instability of motion parameters, and variable navigation conditions.

During the simulation modelling, changes in the spatial flight trajectory of the aerial complex were analysed for three operating modes: motion along the reference route, motion under the influence of external disturbances without compensation, and motion using the adaptive correction mechanism of the navigation contour.

The main purpose of the modelling is to evaluate the efficiency of trajectory deviation compensation and determine the stability of the formed control contour under dynamic environmental conditions.

Figure 2 shows the results of simulation modelling of the navigation contour formation process of an autonomous aerial complex in a dynamic environment.

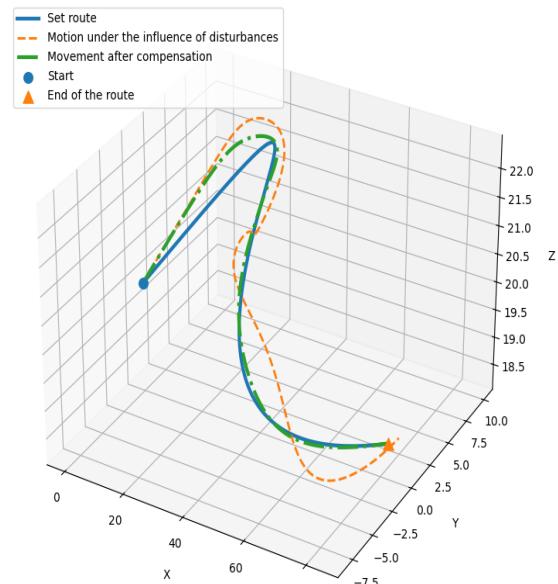


Fig. 2. Stabilisation of the flight path

As shown in Fig. 2, under the influence of disturbances the trajectory deviation reaches approximately 4–5 m, whereas after compensation it is reduced to about 1–2 m, indicating a substantial improvement in trajectory tracking accuracy.

For simulation modelling presented in Fig. 3, an autonomous flight route was generated in the Mission Planner mission format.

The route includes the take-off stage, sequential passing of control points with different flight altitudes, short-term position holding, and return to the initial point. Such a structure makes it possible to evaluate the operation of the navigation contour during changes in spatial coordinates, altitude, and direction of motion.

Within the simulation process, the route defined by the sequence of control points was considered as the reference trajectory.

Deviations of the actual trajectory from the reference route were interpreted as the result of external disturbances, navigation measurement errors, and delays within the control contour.

After applying the disturbance compensation mechanism, the reduction of trajectory errors and convergence of the actual motion to the predefined route were evaluated.

The mission file is used as the basis for generating the reference trajectory, while the simulation results make it possible to compare three operating modes: the predefined route, motion under the influence of disturbances, and motion after correction of the navigation contour.

The obtained results can be used for constructing the flight trajectory stabilisation graph of the

autonomous aerial complex operating in a dynamic environment.

The reference trajectory corresponds to the specified route, whilst the perturbed trajectory demonstrates deviations caused by external dynamic factors.

Following the application of a perturbation compensation mechanism and the adjustment of control inputs, the actual trajectory is observed to converge towards the specified route.

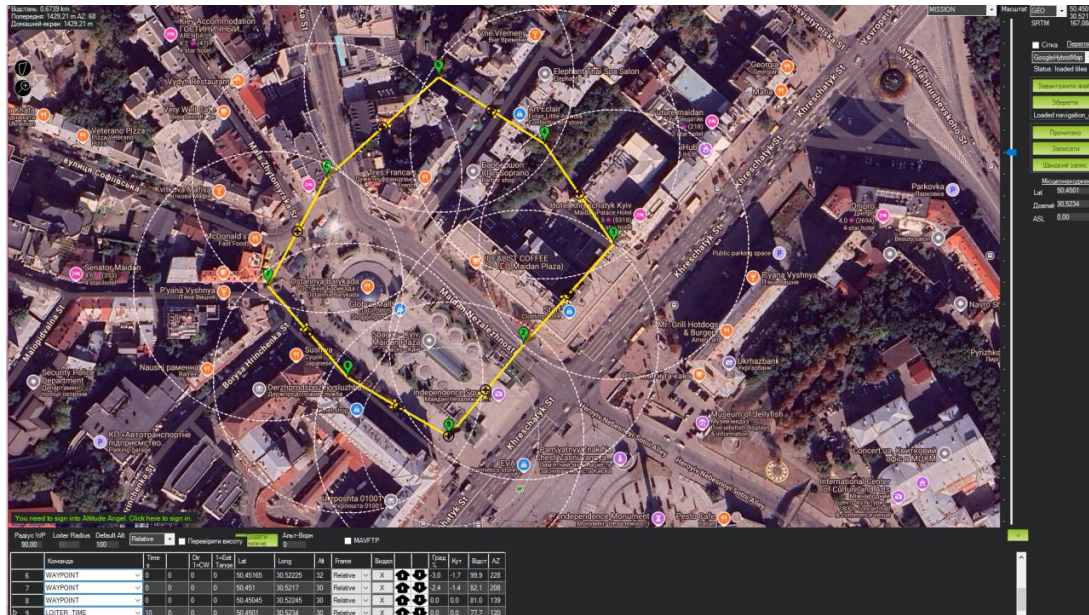


Fig. 4. Results of the simulation modelling of the navigation contour formation process

The obtained results confirm that the proposed correction mechanism reduces trajectory error accumulation and improves waypoint tracking stability under dynamic disturbances.

VI. CONCLUSIONS

This paper considered the problem of navigation contour formation of an autonomous aerial complex operating in a dynamic environment under conditions of external disturbances, instability of navigation parameters, and uncertainty of sensor information. The conducted analysis demonstrated that stable autonomous flight directly depends on the efficiency of trajectory stabilisation, adaptive correction of motion parameters, and coordinated interaction between navigation, computational, and executive subsystems.

In the course of the research, a structure of navigation support and an architecture of navigation contour formation of the autonomous aerial complex were proposed. The presented approach combines processes of spatial positioning, trajectory generation, motion parameter stabilisation, and synthesis of control actions within a unified navigation contour. The developed architecture ensures coordinated interaction between heterogeneous sensor modules and control subsystems during autonomous flight.

A mathematical framework for navigation contour formation was developed, including formalisation of trajectory deviations, a dynamic model of disturbed motion, synthesis of control actions, mechanisms of external disturbance compensation, and a stability criterion of the navigation contour. The proposed mathematical relationships make it possible to describe the dynamics of autonomous flight under conditions of dynamic environmental influence and instability of navigation measurements.

To evaluate the effectiveness of the proposed approach, simulation modelling of autonomous flight was carried out in Mission Planner. During the modelling process, the operation of the navigation contour was analysed under conditions of external dynamic disturbances and trajectory deviations. The simulation results showed that the trajectory deviation under external disturbances reached approximately 4–5 m, whereas after compensation it decreased to about 1–2 m.

Visual analysis of the obtained trajectories confirmed that the use of corrective control mechanisms significantly reduces trajectory errors compared to flight under disturbance conditions without compensation. In addition, the proposed approach demonstrated improved stability of route

tracking and more accurate passing of predefined control points during autonomous flight.

The practical significance of the obtained results lies in the possibility of applying the proposed approach in autonomous flight systems, trajectory stabilisation subsystems, adaptive navigation technologies, and spatial positioning systems of autonomous aerial complexes operating under conditions of uncertainty and dynamically changing environmental parameters.

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М. Ю. Войтех, В. В. Нечипорук. Формування навігаційного контуру безпілотного літального комплексу в динамічному середовищі

У статті розглянуто формування навігаційного маршруту безпілотного літального апарата, що функціонує в динамічному середовищі. Актуальність дослідження зумовлена необхідністю забезпечення стійкого автономного польоту за наявності зовнішніх збурень, невизначеності навігаційних вимірювань та часових затримок у процесах керування. Метою роботи є розробка математичного апарату навігаційного контуру керування, який забезпечує підтримання заданої траєкторії польоту та компенсацію динамічних відхилень. Запропоновано архітектуру навігаційного контуру керування, що поєднує оцінювання просторового стану, відстеження траєкторії, стабілізацію параметрів руху та синтез коригувальних керуючих впливів. Розроблений математичний апарат формалізує оцінювання траєкторних відхилень, формування керування, компенсацію збурень та оцінювання стійкості. Імітаційне моделювання в Mission Planner показало, що запропонований підхід зменшує просторові відхилення траєкторії та підвищує стійкість проходження заданого маршруту за умов динамічних збурень. Розроблений підхід може бути використаний у системах автономного польоту, навігації та стабілізації траєкторії безпілотних літальних апаратів.

Ключові слова: безпілотний літальний комплекс, автономний політ, стабілізація траєкторії, динамічні збурення, просторове позиціонування, адаптивне регулювання.

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