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COMBINED SYSTEM OF AUTONOMOUS CONTROL AND ORIENTATION OF MOVEMENT OF THE OBJECT IN 3D SPACE

Abstract. The paper presents an analysis of the developments of the "Rocketry Agency Student Rocket" project and identifies the main research directions for the development of this project. Prospects for the development of a research student project are the task of developing suborbital rockets with a flight altitude of 80, 100 or more kilometers. Flights to such altitudes are impossible without the use of monitoring and control systems, so an essential and high-priority task is development of a flight monitoring and control system for suborbital rockets with taking into account the caliber of the D-150 and D-300 launch vehicles. The analysis of modern monitoring and control systems has been carried out, the advantages and disadvantages of these systems have been determined. The most attractive for use for suborbital rockets with the given caliber are autonomous guidance and television guidance systems. It is determined that the use of such control systems is impossible, both in terms of the dimensions of the design itself, and the price category of the system as a whole. A new combined system of autonomous control and orientation of movement of volume in space, which is built on a combination of capabilities of television, inertial and mechanical systems, has been developed. regarding the determination and maintenance of the main vertical of the flight path of a suborbital rocket with a given caliber of the D-150 and D-300 launch vehicles.

Keywords: automatic control systems, aircraft, suborbital rocket, optical sensors, microcontroller, inertial systems, software algorithms.

Introduction. To date, there are many tasks where an accurate assessment of the position of the physical body (object) in space is required. Starting with ships and airplanes, robotics, car safety, and ending with the creation of augmented reality, where the assessment of the movement and orientation of the observer is necessary for the correct display of virtual objects in relation to him or her. The use of various instruments and technical measuring devices is an integral part for assessing the position of the object in space. The development of systems and intelligent control is a relevant topic, due to the constant progress in the development of electronic components. Development of electronic components tends to miniaturization; in addition, microelectromechanical technologies are characterized by low mass, size,

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low electric power consumption, as well as high demand and low cost. All this is the driving force of technological progress and, accordingly, the development of automatic and intelligent control systems. The scope of application of modern radio electronics in control systems is extremely wide: the creation of strapdown inertial navigation systems (SINS), the creation of new stabilization, orientation and navigation systems, the possibility of improving unmanned aerial vehicles, autonomous robots, etc. It should be noted that, despite a number of advantages, microelectromechanical devices are not highly accurate, this is due to the accumulation of errors during integration. The inertial measurement module (IMM) of the strapdown inertial navigation system (SINS) performs the task of determining the angular velocities and linear accelerations of a moving object in a given coordinate system. As a result of algorithmic processing of signals received from IMM and SINS, parametric signals are formed that contain information about navigation parameters of the moving object (roll, pitch, velocity). Due to the errors inherent in modern digital meters, as well as errors caused by the digital processing of received signals (integration, etc.) performed by the computing core, errors in determining the orientation parameters tend to accumulate. Therefore, this topic is very relevant in the creation of rocket and spacecraft, namely in the development of information and measuring technologies for monitoring, controlling and orienting an object in space.

On the basis of the Faculty of Physics and Technology of Oles Honchar Dnipro National University, since 2018, the project "Student Rocket" of the "Rocketry Agency" has been operating at the initiative of an international entrepreneur in the field of space technologies Maxim Polyakov to increase the level of practical training of highly qualified specialists for the rocket and space industry of Ukraine.

Figure 1 - pad of the test site of Pavlograd Mechanical Plant

This project forms a scientific research ecosystem that not only involve students and mentors, but also has the necessary financial, technical and technological support from the Public Organization "Association Noosphere", the National Center for Aerospace Education of Youth named after A.M. Makarov, the State Enterprise "Southern Machine-Building Plant named after A.M. Makarov" (Yuzhmash), Pavlograd Plant, R&D Flight Control, etc. To date, this project continues its development in the direction of creating suborbital rockets. Uultralight rockets with flight altitudes of 2 and 7 km have been designed and developed, and ultralight suborbital rockets with flight altitudes of 20 and 40 km have been developed and worked out. Research work in the student project has different directions, for example, studies of possible applications of suborbital launch vehicles, their main characteristics and the use of such rockets [1-7]; particularities of the development of solid fuel engines [8-10]; rocket fuel research [11]; studies of experimental measurements of statistical quantities [12]; research in the field of non-destructive testing of rocket and space objects [13, 14] and others. Fig.2 shows a photograph of ultralight rockets worked out at the test site of the Pavlograd Mechanical Plant.

Figure 2 - Ultralight rockets at the noosphere Engineering School Space laboratory that have been worked out at the test site of the Pavlograd Mechanical Plant

The plans for the development of the research student project "Rocketry Agency" include the development of suborbital rockets with flight altitudes of 80 km, 100 km, or more. For flights to such altitudes, one of the urgent and priority tasks is the development of flight monitoring and control systems.

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Problem Formulation. The development of a rocket monitoring and control system is an integral part of the entire design project, so it is impossible not to take into account the design features of the rocket, namely the mass and size characteristics, and of course it is necessary to take into account the capabilities of launch vehicles for delivering the payload to different altitudes. In the student project "Rocketry Agency", as mentioned above, the general task of creating suborbital rockets with flight altitudes of 80 km or more is considered, which means that the diameter of the body of the launch vehicle will increase significantly and, accordingly, tasks regarding the development of new rocket engines and control systems for new generations of rocket technology of this project will be relevant. In this paper, we will dwell on the review of existing modern approaches to the intelligent control systems of suborbital rockets, taking into account the caliber of the D-150 and D-300 launch vehicle, the use of which allows reaching flight altitudes of over a hundred kilometers. Modern composite materials and new approaches to innovative types of fuel make it possible to manufacture a rocket engine with small mass and size characteristics, but at the same time having an increased specific impulse and operational output power. It is this ratio of mass and power that makes it possible to create launch vehicles of the D-150 and D-300 caliber (the diameter of the body of the launch vehicle). The caliber of the D-150 launch vehicle can deliver a payload weighing up to 300 grams. at altitudes of up to 150 km, and the D-300 launch vehicle, a payload weighing up to 3 kg. Thus, modern technologies used to create small rockets and spacecraft opens a way to reach the heights of low-Earth orbits in the future.

High output power of the engine and huge g-force values at launch lead to the possibility of instant destabilization of the angular attitude of the rocket body. This behavior of the launch vehicle, designers try to compensate by the aerodynamic stability characteristics, but this approach does not ensure full control of the attitude of the launch vehicle (compensation for wind loads) throughout the flight path (to ensure maximum altitude, a straight vertical line at the point of launch is chosen as the main trajectory). It is wind loads that are the strongest obstacle for unguided launch vehicles of this caliber in the process of reaching maximum altitudes. To compensate for them, it is necessary to install high-speed automatic orientation and flight control systems.

Most commonly, aerodynamic rudders are used as control actuators. At high starting speeds and extremely short flight times, the control algorithm reduces to a guidance algorithm. Guidance is the process of changing the trajectory of a guided rocket aimed at reducing the distance between it and the guidance point [15]. The motion of a flying vehicle while maintaining minimum deviation from the trajectory is called a flight. In the process of guiding the rocket, the control signals are generated in different ways, but recently the control is based on the predicted value of the current flight – the accuracy of guidance, built taking into account the hypothesis of the movement of the target. In the assumption of the straightness of the motion of the target, the current flight is a vector perpendicular to the tangent to the trajectory of the rocket relative to the point of guidance and equal in its absolute value to the distance from the point to the tangent.

The difference between the real behavior of the launch vehicle and its behavior according to the hypothesis, taking into account the external disturbance acting directly on the launch vehicle and interfering with the exact reproduction of the given control, leads to the need to build a closed automatic control system that uses the current flight as a regulation error.

Random errors in measuring the current flight suggest the development of modern guidance systems taking into account the statistical assessment of the measured values [12]. Thus, the guidance process consists in measuring the relative coordinates of the rocket and the target, statistically assessing the current flight, forming a given control on it and reproducing the latter by the rocket. In practice, it is convenient to replace the estimation of the current flight with the estimation of some quantities associated with it by a linear operator, for example, an assessment of the angular velocity of the rocket-target line, linear mismatch, etc.

Thus, in order to solve the formulated problem, it is necessary to analyze modern monitoring and control systems, taking into account the parameters of suborbital rockets with the caliber of D-150 and D-300 launch vehicles.

Autonomous guidance systems. There are autonomous guidance and tele-guidance systems. Autonomous guidance systems differ in that the coordinates of the end point are determined in advance and in the guidance process, only measurements of the absolute coordinates of the launch vehicle are used to compensate for initial errors and current disturbances. In homing systems, the relative coordinates of the end point are measured by a device installed directly on board the rocket - on-board measuring equipment.

In tele-guidance systems, the absolute or relative coordinates of the launch vehicle and the end point are measured either from some remote point (ground station, telecommand and telemetry point) or directly from the body of the launch vehicle itself using an external reference center. According to the obtained data, the current flight is evaluated and a signal is formed, which is either transmitted

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through the communication line as a given control to the launch vehicle from the ground center, or calculated directly on the launch vehicle itself.

Each of the above systems has its advantages and disadvantages, but for D-150 and D-300 caliber launch vehicles, it is reasonable to use the following types of systems: an autonomous control system (CS) or a tele-guidance CS.

Types of autonomous guidance systems of the guidance system:

a) Autonomous gyroscopic systems - systems based on the property of the gyroscope to maintain its position in space. Therefore, it is possible to build a reference coordinate system, relative to which the angular deviations of the rocket are measured. With the help of signals of deviation of pitch, yaw and roll angles, it is possible to both stabilize them and control them with the help of special software.

b) Autonomous inertial systems. Acceleration sensors are positioned in such a way that their sensitivity axes coincide with the measuring reference system (RS). By integrating, it is possible to find the magnitude of the velocity and the distance traveled in any direction. The trajectory is laid in the basis RS, therefore, to determine the current value of the coordinates, it is necessary to combine the measuring RS with the basis RS.

The advantage of such systems is that both systems measure angles or linear coordinates regardless of external disturbances (wind). But such systems also have drawbacks, such as the accumulation of errors over time due to the deviations of gyroscopes and errors of linear acceleration sensors. This disadvantage is especially affected by integration, that is, when determining linear movements.

c) Autonomous astronavigation systems infer the location of the object by measuring the angles of two celestial objects from the location of the aircraft (AIRCRAFT). The Sun, stars, Moon, Earth can be used as celestial objects. Thus, the aircraft should have two autonomous sextants located on a gyro-stabilized platform, the measurements from which coincide with the basis CS.

The advantages of such systems include the fact that the accuracy of measurements made with sextants does not depend on the guidance time. But there is a drawback to such systems, namely, the accuracy of measurement decreases in the case of a short guidance time.

d) Autonomous electro- or magnetometric systems make it possible to determine guidance by the physical parameters of the medium (magnetic, electric and gravitational fields of the earth). Partially and in a simplified form, these systems are used in aviation.

The advantage of such systems is that their accuracy of measurement does not depend on the guidance time. Their disadvantage is that the very parameters of the Earth's fields that are used for measurement, are not stable and depend on the perturbations on the Sun.

e) Autonomous correlation systems have recently become widespread. The principle of operation of such a system is that a representation or a map of the terrain around the target or under the entire flight route is preinstalled in the computing device. Then, during the flight, one or another method (radar, television, infrared beams or laser beams) is used to determine the contour or map of the area above which the aircraft currently is located. By comparing the preinstalled and aquired contours, the deviation of the aircraft from the specified route is determined and the aircraft is controlled in such a way that both contours coincided.

f) Strapdown inertial measurement systems (SIMS). The gyrostabilized platform (GSP), which protects accelerometers from the influence of angular movements of the object, has a number of drawbacks: being a precision electromechanical device, it is unreliable, consumes a lot of energy, has a large mass and dimensions, is expensive and its assembling is labor-intensive. Another way to build an inertial navigation system is to place accelerometers and gyroscopes directly on board a mobile object, and to assign the functions of the GSP to an on-board computing device. In the SIMS, the sensing elements are accelerometers and meters of attitude parameter (gyroscopes). They can be built on different physical principles. At the same time, the number of meters should be such as to provide information about the vector of proper acceleration of the point of the object in which the meters are mounted, and about the vector of absolute angular velocity characterizing rotation [4].

g) Autonomous combined systems. To improve the accuracy of guidance of autonomous systems, a combination of these systems is usually used. For example, a combination of inertial and astronavigation system. With the help of an inertial system, the speed is determined with a fairly high accuracy, but the path (or location) is determined with a big error; astronavigation system complements the inertial one by determining the location of the aircraft at some point in time with a higher accuracy. Note that almost all autonomous systems are combined systems. They are used in ballistic missiles, space launch vehicles and in space stations, and are also common in cruise missiles.

Remotely controlled guidance systems. Remote control is control at a distance by means of specially encoded control signals (radio, optical, audible, etc.). At

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that, the power of the control signals is much smaller than the power of the processes they control. In remote-control systems, signals controlling the rocket can be generated either at the command post (CP), or on the rocket, or jointly at the CP and on the rocket. In the remote-control system, the following are distinguished: command post (CP); a rocket in the form of a controlled object (OC), a target tracking line (TTL) (a channel for receiving target data), a line for monitoring the control object (LMCO) (a channel for transmitting data on the flight of the rocket), a command line (CL) (a rocket control channel). Note that TTL, LMCO, LCC, LCOS and CL can be based on different physical principles.

There are two types of remote control, depending on the method of tracking the target. The first type of remote control, when the CP receives control information from the ground control station (Fig. 3). The second type of remote control is schematically presented in Fig. 4., when the ground control station receives information about the object from the sensors on the launch vehicle, and then sends control information to the vehicle. Marking in Figs. 3, 4 and 5: GCP – ground control point; FV – flying vehicle; TP – terminal point – the point at the end of the flight; TDL – target designation line – a channel for receiving data on the destination point, TMCL – telemetry line from the controlled object - a channel for transmitting data on the flight of the rocket, a telecommand line (TCL) - an aircraft control channel).

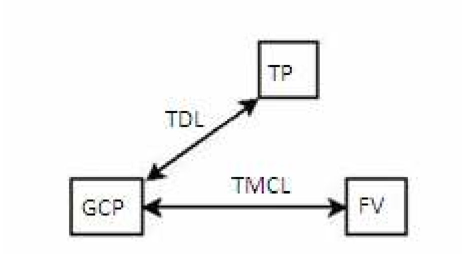

Figure 3 - Scheme of the first type of remote control

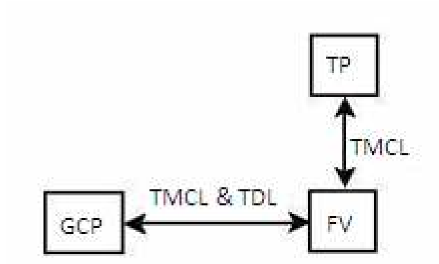

Figure 4 - Scheme of the second type of remote control

As a summary the results of the analysis, it can be concluded that for rockets of the D-150 and D-300 caliber, it is most optimal to use a combined control system, which is based on an autonomous remote control system and an autonomous inertial system.

Combined autonomous control system. When developing a combined autonomous control system, the principle of the capabilities of television, inertial and mechanical systems was used to determine and hold the main vertical of the flight trajectory of the rocket. As the main system for monitoring the spatial position of the rocket, a system of optical digital cameras with serial data interfaces is used. Fig. 5 shows a diagram of a combined autonomous control system, where SINS is a strapdown inertial navigation system; OAPS is an optical automatic positioning system; MRACS is a mechanical rotation angle control system.

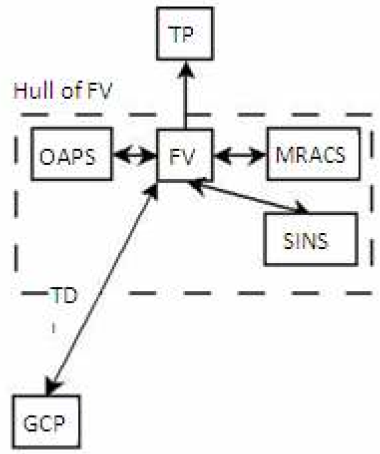

Figure 5 - Scheme of the combined autonomous control system

As a SINS, physically attached modules of accelerometers and gyroscopes (MEMS devices) of high accuracy at short time intervals will be used to correct the angle of inclination data obtained from the optical positioning system.

As a mechanical control system, a servo drive will be used, equipped with the necessary system of levers for obtaining the necessary forces to rotate the control aileron to the desired angle with a given accuracy.

Conclusions. In this paper, the features of rockets developed on the basis of the student project "Rocketry Agency" have been reviewed and the task of developing a system for determining and maintaining the main vertical of the flight path of the launch vehicle has been formulated. An analysis of the classical control and guidance schemes of low-orbit small-sized flying vehicle with rocket thrust has been carried out; the main advantages and disadvantages of such systems have been considered. The features of the existing control systems and the features of the use of such systems have been considered taking into account the characteristics and parameters of the launch vehicles of the student project, where the caliber of the launch vehicles is D-150 and D-300. The development of a combined automatic flight control system based on optical cameras with a parallel interface for information output, the use of an eight-bit controller and inertial position sensors is proposed. This method will reduce financial costs and required time owing to using ex-

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isting imported inertial position measuring sensors, reduce the mass and overall parameters of the system as a whole and make it possible to build a modular structure for the unification of units. The use of microcontroller technology with a large number of control interfaces will increase the reliability of the automatic control system and will be suitable for controlling any actuators for controlling the spatial movement of a flying vehicle without making structural changes in the scheme of the resulting module. Software implementation makes it possible to use new algorithms based on the cheapest equipment and small-sized flying vehicles.

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Комбінована система автономного управління та орієнтації переміщення об'єкту у просторі

Анотація. У статті проведено аналіз розробок проєкту «Студентська ракета «Rocketry Agency» та визначені основні науково-дослідні напрями розвитку цього проєкту. Перспективи розвитку науково-дослідницького студентського проєкту є задача розробки суборбітальних ракет з висотою польоту 80, 100 та більше км. Польоти на такі висоти неможливі без застосування систем управління та контролю, тому стає актуальним та пріоритетним питання розробки системи контролю та управління польотом саме для суборбітальних

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ракет з урахуванням калібру ракетоносію Д-150 та Д-300. Проведено аналіз сучасних систем управління та контролю, визначени переваги та недоліки цих систем. Найбільш приємними для застосування для суборбітальних ракет з заданим калібром є системи автономного наведення та теленаведення. Визначено, що застосування таких систем управління неможливо, як з точки зору габаритів самої конструкції, так і цінової категорії системи в цілому. Розроблена нова комбінована система автономного управління та орієнтації переміщення об'єкту у просторі, яка побудована за принципом можливостей телевізійної, інерційної та механічної систем щодо визначення та утримання основної вертикалі траєкторії польоту суборбітальної ракети з заданим калібром ракетоносію Д-150 та Д-300.

Ключові слова: системи автоматичного керування, літальні апарати, суборбітальна ракета, оптичні датчики, мікроконтролер, інерційні системи, програмні алгоритми.

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