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AUTOMATIC TAKE-OFF CONTROL SYSTEM

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Abstract

The purpose of the work is to present a solution that will significantly contribute to the technological development of the European defence sector. The proposed solution brings up the issue of controlling autonomous vehicles. This paper presents the concept of an algorithm that allows for automatic take-off of an unmanned aircraft. Arguments, which justify the need for developing and applying such a system, are presented. The socio-economic and environmental aspects of the project are also discussed. The automatic take-off algorithm complements the existing aircraft flight control systems. The considered solution takes into account take-off as a manoeuvre made of three phases. The aircraft control on a runway is possible due to the data fusion from the INS and GNSS systems. The data fusion may be supported by using the runway image processing system. The concept of the automatic take-off algorithm is presented along with the most appropriate testing methods, including software-in-the-loop and hardware-in-the-loop simulations.

Keywords: automatic take-off control system, unmanned aerial vehicles, defence technology, data fusion, image processing

1. Introduction

The modern world is a world of innovative technologies. Their influence on contemporary civilization is without a doubt. Nowadays, dynamic changes affect defence strategies and military tactics, organization and equipment. These changes lead to increased requirements involving advanced combat systems. Such systems should be able to use already existing potential efficiently, give opportunity for further development, and provide a solution to the upcoming challenges.

Aviation became a fundamental part of the military power after World War I. Air forces are not only used for combat, but also provide transport, evacuation, and rescue services, or carry out covert missions against terrorism. These tasks are performed both for the army as well as for civil purposes. The development of unmanned aerial vehicles (UAVs) could potentially revolutionize the way that air forces will be used in the future. While the performance of earlier operations with the use of autonomous aircraft showed great promise, their full capabilities are largely unknown. However, it is clear these technologies will enable air forces to use their power more efficiently and that means lower operational costs and lower risk for the human pilot. For these reasons, we are convinced of the relevance of autonomous aircrafts in Europe's defence and security.

The development of UAVs raises the possibility of conducting military operations in a more efficient and less risky fashion in comparison to human–controlled flights. Today's aircrafts are highly automated machines. Diverse stabilization and control systems take over more and more tasks, previously performed purely by pilots. These systems are being implemented especially in the control areas, in which the human abilities of perception and correct decision making are found to be insufficient. Avionic solutions are already taking over many pilot's duties such as managing a stable flight on the desired path or carrying out a smooth touchdown. However, even UAVs demand the active presence of the flight operator, who schedules the approach, performs take-off and taxiing. The indispensable factor in achieving complete flight automation is to supplement control systems in these flight areas, which are still fully human–dependent. The most important of them is the take-off phase.

2. Overview of the system and its principles

The algorithms providing the automatic take-off manoeuvres will be developed within this project. They will complement other flight control systems. In the development of the algorithms, the following design principles were adopted:

- The automatic take-off system begins its operation when the aircraft is preconfigured for flight and positioned on the active runway.
- The aircraft brakes are released.
- The system does not provide control of the flaps.
- The system provides aircraft control unit up to 50 ft. after lift-off.
- The aircraft is equipped with a measuring system that provides information about forces exerted on the landing gear wheels.
- The aircraft is equipped with: INS (Inertial Navigation System and GNSS (Global Navigation Satellite Systems)/EGNOS (European Geostationary Navigation Overlay Service).
- The aircraft is equipped with an on-board camera that records the view of the runway (as an optional feature).

An aircraft will be controlled by two autopilot channels: longitudinal and lateral, with appropriate control surfaces: ailerons, elevator, rudder as well as engine thrust. Additionally, the system counts the landing gear's contact force. The algorithms will be implemented in a real avionic system, tested in–the–loop using general aviation aircraft. Developed control rules will imitate human pilot behaviour. Figure 1. shows a general diagram of the control system.

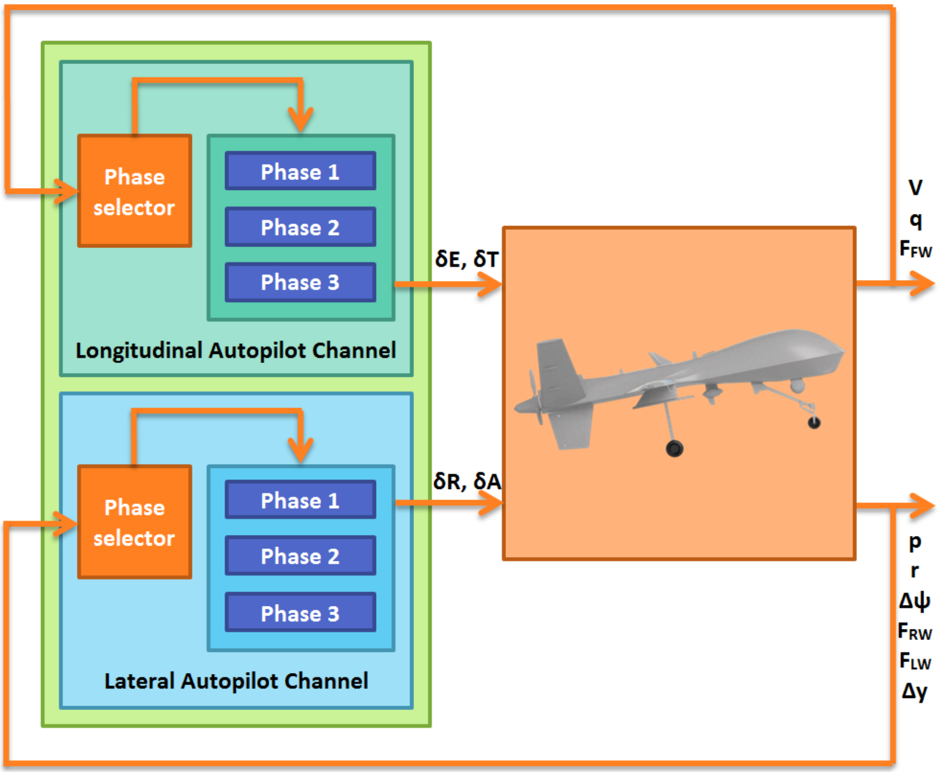

Figure 1. A general diagram of the control system

Internal routing signals are divided into two sections:

- inputs: heading ψ, flight track, indicated airspeed V, angular speeds in aircraft's 3-axes p, q, r, deviation from runway centreline Δy, pitch angle ϑ, contact forces (front–wheel pressure force F_{FW}, right–wheel pressure force F_{RW}, and left–wheel pressure force F_{LW}) and wind forces
- outputs: throttle setting δ_T, aileron displacement δ_A, elevator displacement δ_E, rudder displacement δ_R, and front–wheel turn δ_{FW}.

The take-off operation is marked by a large variability of flight parameters as well as a large variability of the control surfaces efficacy η as shown in equation (1):

$$\begin{cases} t = 0 \rightarrow v = 0,\ \eta = 0 \\ t > 0 \rightarrow v > 0,\ \eta \gg 0 \end{cases} \tag{1}$$

At the stop (indicated air speed $v = 0$), the efficiency of the control surfaces is equal to zero. During the start roll, the change of aircraft speed causes a fluent change of the control surfaces efficiency. While the speed increases, the efficiency rises to the value when a stable lift-off is possible. For that reason, the take-off of an aircraft can be split into several phases. Due to efficiency changes, in each phase, separate control rules have to be applied.

3. Take-off Control Phases

The considered solution takes into account take-off as a manoeuvre made of three phases: start roll, take-off roll, and lift-off roll & transition (Figure 2).

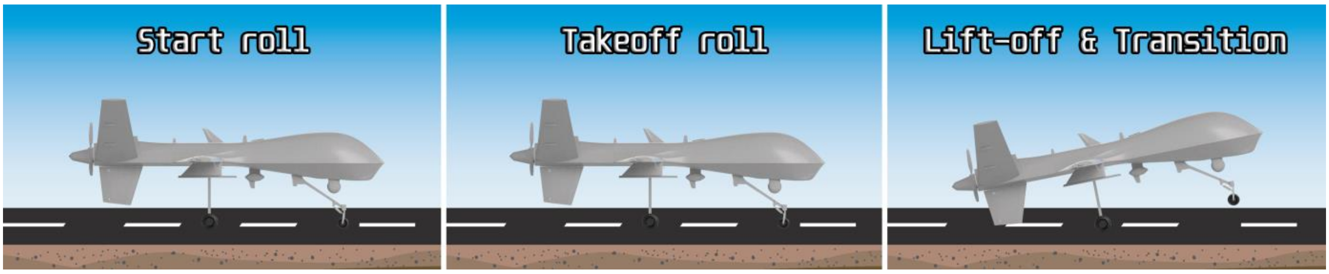

Figure 2. Take-off control phases

3.1 Start roll

Start roll is the first phase of the take-off. In this phase, the front wheel is responsible for maintaining control of the aircraft on the runway. The take-off algorithm does not allow for the possibility of wheels skidding. Maintaining the front wheel traction is executed with the elevator, which provides consistent front–wheel pressure force. The pressure is measured by a metering system installed in the aircraft.

While the speed increases, the efficiency of the rudder rises. The rudder's task is to maintain the aircraft in the runway centreline at acceleration. During the start roll, a constant value of thrust $\delta_T(t)$ is held. Control in the first phase is also maintained with the use of ailerons, which compensate for the gusts of wind by holding an equal value of pressure forces on the left and right wheels of the main landing gear.

The first phase of the take-off is described by the following control rules (2)(3)(4)(5):

1) elevator control

$$\delta_E(t) = K_E(F_{FWC} - F_{FWM}) \tag{2}$$

where: K_E – signal gain

F_{FWC} – constant front–wheel pressure force (value estimated from engineering knowledge)

F_{FWM} – measured front–wheel pressure force (from pressure sensor)

2) aileron control

$$\delta_A(t) = K_A(F) \quad (3)$$
$$F = F_{RW} - F_{LW} = 0 \quad (4)$$

where: K_A – signal gain
F_{RW} – right wheel pressure force
F_{LW} – left wheel pressure force

3) rudder control

$$\delta_R(t) = [-K_R \cdot \Delta y]_{-\delta_{max}}^{+\delta_{max}} \quad (5)$$

where: K_R – signal gain
Δy – lateral deviation from runway centreline
$\pm\delta_{max}$ – limits imposed on the rudder incline

3.2 Take-off roll

A clear transition from the first phase ending to the second phase beginning is nearly impossible. The transition between these phases is commonly called a fuzzy transition. The first and second phases are described by the same control rules (as above). The ailerons are still compensating for wind influence while the rudder holds the aircraft on the runway centreline.

In the first phase, the pressure force on the front wheel is consistent, whereas, in the second phase, the front wheel is steadily relieved of weight by the control system. This progresses until the aircraft reaches the rotation speed $V1$ and the front wheel is raised off the runway surface. Detection of zero pressure force on the front wheel means the aircraft then goes forward into the third take-off phase.

3.3 Lift-off and Transition

In the third and last phase of the take-off, elevator efficacy is high enough to enable changes in the pitch angle. The proper value of the pitch angle is adjusted and maintained by the flight control system. Pitch angle θ rises in time and the controller adjusts its value in a keep-up manner. In this way, any aircraft movement oscillations do not occur and the control error is minimized over time. Pressure forces on the main landing gear are monitored and held equally, as in the equation (6):

$$F = F_{RW} - F_{LW} = 0 \quad (6)$$

In this phase, keeping to the runway centreline is performed by rudder displacement. The control system makes use of the PID controller, which control rule equation (7) is as follows:

$$\delta_R(t) = K_R \cdot \Delta y + K_D \frac{d}{dt}\Delta y + K_I \int_{min}^{max} \frac{d}{dt}\Delta y \quad (7)$$

where: K_R – proportional gain
K_D – derivative gain
K_I – integral gain
Δy – lateral deviation from runway centreline

The system provides aircraft flight control up to 50 ft. after lifting the entire landing gear [1][7][8].

4. Holding on runway centreline

Aircraft control in the lateral autopilot channel is in charge of holding the aircraft on the runway centreline. This is a difficult task due to disturbances such as gusts of wind or an uneven runway surface. It is necessary for the control system to eliminate the lateral deviation Δy in the shortest possible time without excessive overshoot. Controlling this based on the measurement of the magnetic heading alone is insufficient. The blowing wind may carry the plane parallel to the centreline, as shown in Figure 3.

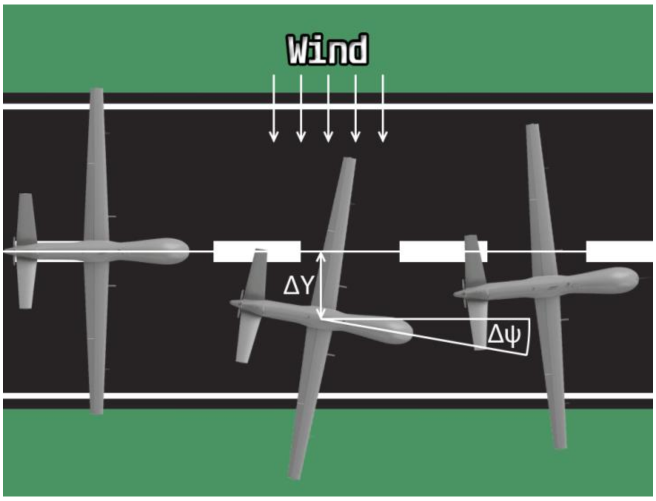

Figure 3. The influence of wind on the lateral deviation

The signal that can be best used to compensate for lateral deviation is the geostationary signal. Among all the current navigation systems, EGNOS is distinguished by the best parameters in this respect.

The European Geostationary Navigation Overlay Service (EGNOS) is Europe's regional satellite-based augmentation system (SBAS), used to improve the performance of global navigation satellite systems (GNSSs) such as GPS and Galileo. It has been deployed to provide safety of life navigation services to aviation, maritime, and land-based users over most of Europe. EGNOS uses GNSS measurements taken by accurately located reference stations deployed across Europe. All measured GNSS errors are transferred to a central computing centre, where differential corrections and integrity messages are calculated. These calculations are then broadcast over the covered area using geostationary satellites that serve as an augmentation, or overlay, to the original GNSS message.

Thanks to the functioning of EGNOS, the basic navigation parameters of the GPS and GLONASS systems are:

- accuracy, i.e., the ability of the system to determine the position of the measured object within the permissible system error with a probability of 95%,
- reliability, determining the level of confidence in the information provided by the system,
- continuity, i.e., the ability of the system (satellites) to work uninterrupted throughout its flight over the user's horizon,
- availability, defined as the likelihood of navigational services being provided at any time.

Typical GNSS systems operate on $10\,Hz$ frequency, which means that with aircraft speed equal to $v \approx 100\,kph$ and during time $\Delta t \approx 0{,}1s$, the lateral deviation will be equal to $\Delta y \approx \pm 2{,}5\,m$. The dispersion of measurements may turn out to be too large to control the aircraft without excessive oscillations and overshoot [10].

For this reason, the inertial navigation system (INS) will also be used. The INS is a self-contained navigation technique in which measurements provided by accelerometers and gyroscopes are used to track the position and orientation of an object relative to a known starting point, orientation and velocity. By processing signals from gyroscopes and accelerometers it is possible to track the position and orientation. INS can usually only provide an accurate solution for a short period of time. As the acceleration is integrated twice to obtain the position, any error in the acceleration measurement will also be integrated and cause a bias on the estimated velocity and a continuous drift on the position estimate by the INS. Nevertheless, inertial navigation allows for continuous positioning even in cases when the requested satellite is not available.

Determinately, the system's operation combines complementary data from EGNOS and INS for accurate aircraft positioning. This integrated system will be able to provide superior performance compared with each of the systems working separately. The main strengths and weakness of INS, EGNOS, and INS+EGNOS are summarized in Table 1.

In order to increase the accuracy of the aircraft positioning, there are several methods used to combine data from different sensors. In the literature, data fusion methods for integrated navigation are mostly implemented by Kalman filter (KF). However, in this project, the use of a complementary filter (CF) algorithm is proposed. The CF is an effective and versatile procedure for combining noisy sensor outputs. The CF filter has the advantages of a simple algorithm, low computational load, good real-time computations, and no need for initial conditions. When it is used in an integrated navigation system, CF can achieve close to the same filtering precision as KF.

Table 1. The main strengths and weakness of INS and EGNOS

INS	EGNOS
High position accuracy over the short term	High position accuracy over the long term
Accurate altitude information	Noisy altitude information
High measurement output rate	Low measurement output rate
Autonomous	Non-Autonomous
No signal outage	Possibility of signal loss
Affected by gravity	Not sensitive to gravity
Accuracy decreasing with time	Accuracy independent of time
INS + EGNOS	
High position accuracy	
Precise attitude determination	
High data rate	
Navigational output in case of GPS signal outages	
Cycle slip detection and correction	
Gravity vector determination	

Complementary filtering is meant to derive one single output by combining two (or more) different measurements with different noise properties. Focussing on one case, the EGNOS signal produces high–frequency noise while the INS results contain low–frequency noise. These data fusion techniques apply both low and high pass filters as expressed in equation (8).

$$H = H_{LP} + H_{HP} = \frac{1}{Ts+1} + \frac{Ts}{Ts+1} = 1 \tag{8}$$

where T is the time constant of the inertial element and determines the dynamics of the filter [5][11].

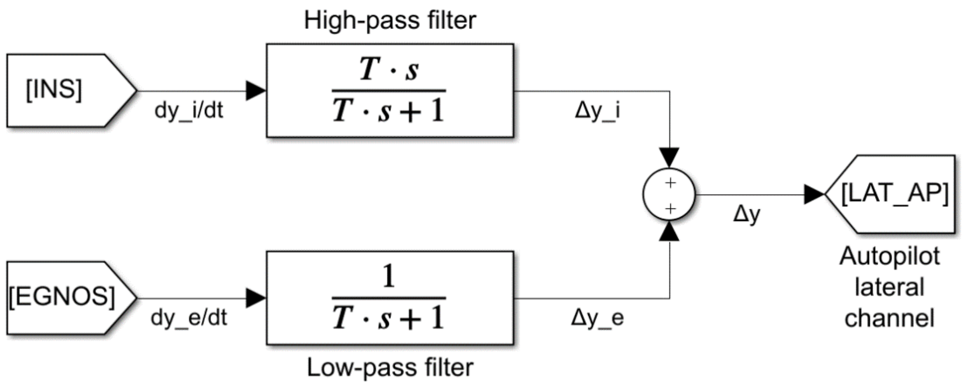

Figure 4. A diagram of a complementary filtering

Figure 4. shows a diagram of complementary filtering for data sourced from EGNOS and INS. Using this approach, advantages in the shape of low computation load, good stability, and steady-state accuracy are achieved, meeting the requirements of an integrated navigation system for an unmanned aircraft [2][3].

The runway image processing system (RIPS) is an additional element of the system for determining the lateral deviation, complementing the signals from GNSS and INS. It operates based on the picture recorded by the on–board camera. The use of RIPS is an option that allows even more accurate determination of the lateral deviation Δy. The camera signal can be added to the signals from the navigation systems.

The RIPS system calculates the coordinates of runway side-lines. This operation is accomplished by applying a linear Hough transform. The lines coinciding with the edges of the runway in the image are convergent and their intersection point is on the runway centreline. The distance between the designated intersection point and the vertical line, passing through the centre of the image, determines the level of deviation of the longitudinal axis of the aircraft from the runway centreline. The number of pixels between the point and the centreline specifies this level of deviation and is calculated in relation to half of the horizontal resolution of the image that is expressed as a percentage value. Figure 5. shows the image from the on–board camera, processed by the system.

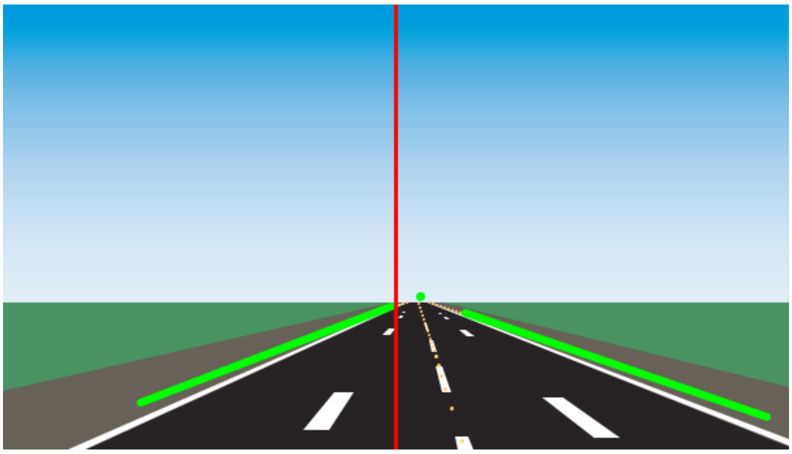

Figure 5. Runway image with marked lines

The lines that coincide with the edges of the runway and the intersection point of these lines have been drawn in green. The vertical red line passes through the centre of the on–board camera frame and coincides with the longitudinal axis of the aircraft. The determined value of the aircraft's lateral deviation from the runway centreline is positive when the aircraft is on the left side of the runway, while values below zero mean the position of the plane is to the right [9].

5. Testing the system

The first stage of testing is mainly based on checking the developed algorithms. These tests can be described as software-in-the-loop (SIL). The test stand consists of a computer with installed MATLAB & Simulink software, in which the behaviour of the aircraft has been modelled. Through Ethernet communication, the control rules within the model are transmitted to the computer with the X-Plane flight simulator, where their accuracy is being analysed.

The second stage of testing includes hardware-in-the-loop (HIL) simulations. In HIL, the control laws are deployed to final hardware, while the power converter, plant, and feedback sensors are simulated. Also, there must be hardware to interface to the control law output and feedback sensor signals. HIL has been used for years in industries such as aerospace or automotive, where plants are especially complex. HIL can augment testing of physical plants to provide many advantages such as:

- Reduced cost to test (The high cost to execute tests on complex machinery like aircraft sub-systems can be reduced by using HIL as a complement).
- Reduced risks associated with failure (With complex plants, control system malfunction can lead to catastrophic failure, destroying equipment or presenting safety hazards. HIL can be used to validate controllers before running physical equipment).
- Testing fault models (HIL allows more robust testing of fault models. With HIL, faults can be induced through software and can be synchronized with a wide range of conditions).

At this stage, MATLAB's functions enable automatic generation of a source code for the real autopilot using the model of the developed system. Then, the tests can be carried out in the X-Plane flight simulator.

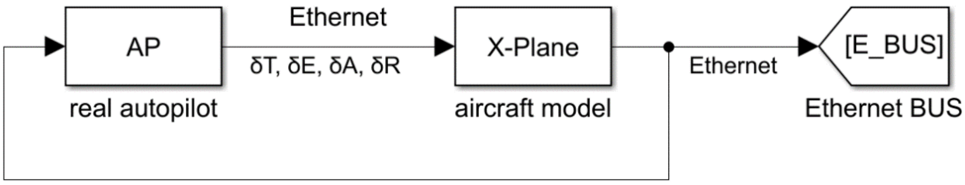

Figure 6. Hardware in–the–loop (HIL)

Figure 6. shows the signal going throughout the HIL simulation. The autopilot and the aircraft model communicate over the Ethernet. The enforced signals generated by the autopilot control the model. In the feedback loop, the information about the aircraft attitude returns to the autopilot and adjusts the module accordingly. After receiving satisfactory results, the programmed module can be finally tested on a real plane [6].

6. Conclusions and perspectives

Methods and tactics of air force operations depend mainly on factors such as social and political conditions, operational and tactical situations, spatial and temporal conditions, or environmental conditions. These are fundamental factors influencing the principles, possibilities, and methods of using aviation and shaping its further technical development. For this reason, it is so important to adapt the newly emerging solutions to contemporary world conditions. In the case of fully automated UAV technology, research provides a strategic future vision for autonomous UAV usage by highlighting its many advantages.

The presented take-off control algorithm completes existing autopilot systems and creates a coherent control environment. An automatic take-off process will enable pilots to focus on other tasks while managing the flight. It is particularly relevant in adverse weather conditions or during military operations, in which the pilot has to man multiple on–board combat systems. For applications in unmanned aerial vehicles, automation reduces the duration of the manoeuvre and adjusts it to the aircraft's structural capabilities. This system solves the "one operator – one machine" problem, which does not allow controlling multiple units at the same time.

Groups of UAVs could be used in airspace defence systems, supporting surface-to-air missile systems, which are unable to identify targets before interception. Autonomous aircrafts might be applied in reconnaissance missions replacing fighter jets and helicopters, and also significantly reducing time–span of the operations. Launching a group of autonomous aircrafts facilitates extending the operational area. The use of fully autonomous units brings a number of additional benefits, including economic and ecological aspects. The financial benefits come from the possibility of carrying out unmanned missions, implying a lower demand for pilots and the ability to control many machines by one ground operator. The green aspects are related to the smaller dimensions of aircraft (the lack of a pilot's cabin) which lead to a reduction in the use of construction materials in production. The smaller and more aerodynamic designs result in lower fuel consumption during missions [4].

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