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Research Article

Predictive Assessment of the Development of Unmanned Aviation System

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Abstract

This paper shows the method of using a variational model for forecasting trends in the development of unmanned aerial systems for various purposes. The predictive assessment of development prospects is determined by solving a variational problem. Several variants of formulations of variational problems are investigated. A variant of a specific task is determined by the purpose of the aviation system under study and the goals of its development. The priority development goal is determined by when the system is supposed to be used for its intended purpose in the future. As a result, it is shown that the development of various types of aircraft as part of a promising system should be treated as the development of a complex technical system. This should consider not only all the features of the joint functioning and its constituent parts but as well as the fact that the unmanned aerial vehicle itself is the element of a complex system of a higher order. And the problem as a whole requires the professional approach of specialists with different competencies.

Keywords: remotely piloted aircraft system (RPAS), unmanned aerial system (UAS), power-to-weight ratio, variational model, optimal control, payload.

1. Introduction

At the present stage of creating unmanned vehicles, aviation equipment, structural materials, developing technologies, and expanding the scope of tasks to be solved, it can be noted that the market for the use of unmanned aerial systems is in the process of formation, although the first unmanned aerial vehicles began to appear in the 30s years of the 20th century. Every year the number of market participants is constantly growing, the geography is expanding, and the number of applications by industry is increasing.

Remotely piloted aircraft system (RPAS)is an integrated set of unmanned aircraft vehicles (UAV) and related flight support equipment (ground control station, ground handling facilities) that differ in their type, parameters or purpose, or both and operate to achieve a single goal.

Recently there has been an increase in the need for the use of UAVs in the RPAS by government and commercial entities to solve emerging problems. These systems allow you to solve problems in the most difficult places on the open surface. Research is actively conducted, based on which new niches of their needs and demand are identified, and development forecasts and requirements are formed.

In the future, we see a variety of application-specific types and relatively small series production. This will allow for a flexible response to market needs.

The articles [1-4] provide materials on the study of the needs of the unmanned aerial vehicles market, but nowhere is a forecast estimate given.

There is extremely limited information in the scientific literature on market research for unmanned aerial vehicles. Studies [24-26] are devoted to general trends in the assessment of flight safety.

The study [24] uses machine learning algorithms to predict the risk of incidents in unmanned aerial systems. The study [25] presents a new approach to demonstrating the compliance of aviation systems with safety requirements.
The study [26] aims to explore the current state of the unmanned aerial systems market and future concepts with a particular interest in safety risk management. This manuscript aims to summarize some of the regulatory aspects currently available related to drone safety investigation and reporting and therefore outline some potential directions for future research.

Problem statement

Aeronet analytical center conducted a study of trends in the development of unmanned aerial systems Fig. 1, revealing the growth trends in the demand for RPAS for various purposes in foreign countries.

The study also revealed a fundamentally different situation in the field of low take-off weight and large unmanned aerial vehicles. Fig. 2 and Fig. 3 show the classification given by AUVSI (Association for Unmanned Vehicle Systems International) for existing and under-development unmanned aircraft systems, which is based on the take-off weight of the UAV [5].

In a scientific and technological direction, the problem of the creation of essentially new bearing systems for aircraft that will have sharp gliders on take-off and landing, to carry out long flights and maneuver with big overloads allowing effectively and reliably solve tasks at the achievement of unique properties is actual. It is necessary to use new power units that are more cost-effective and based on different physical principles, elements, and devices for storage and supply of fuel, and energy using different types of fuel and power.

According to the type of carrier system in the horizontal flight of the entire set of UAVs currently, the greatest use in the UAS received:

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- Aircraft-type UAVs -AT. B as a supporting system is used the supporting surface - the wing, there can be several wings (in the particular case of a glider integrated into the aerodynamic scheme, functionally combining the wing and fuselage) [6,7].

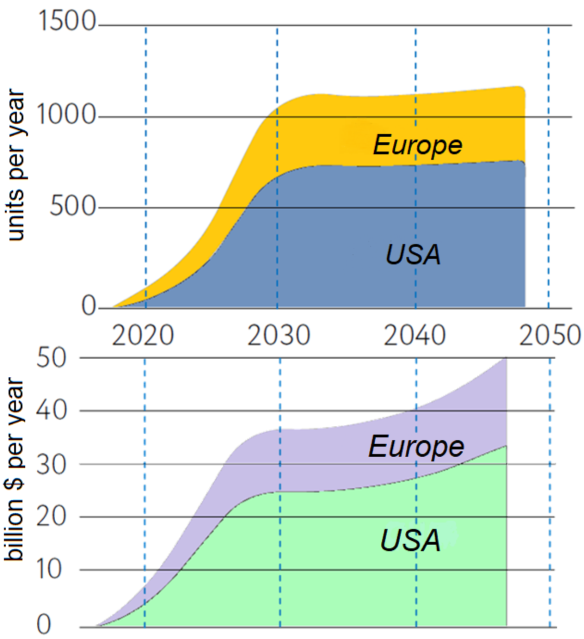

Fig. 1. Market growth forecast for RPAS development, 2018-2050

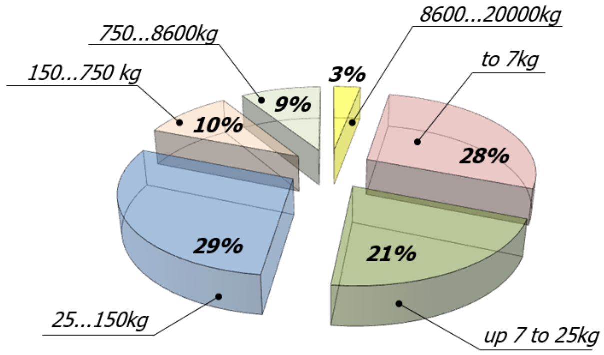

Fig. 2. Aircraft type UAV distribution diagram by take-off mass.

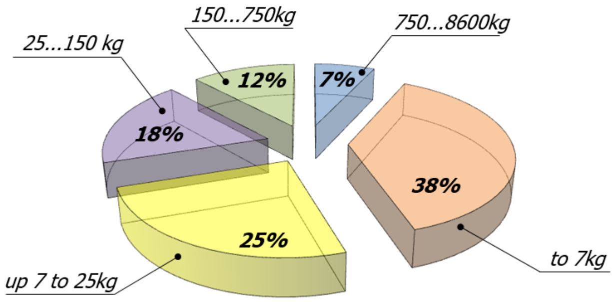

Fig. 3. The diagram of distribution of the UAV of helicopter type by take-off mass.

The diagram shows that most of the aircraft-type UAVs have a mass of less than 150 kg, with such categories as micro, mini and small UAVs having a fairly close percentage. It can be explained by their high demand in the military market (O_F^S) and civil (O_T^C) UAVs as they are relatively multifunctional and yet low cost and high availability.

- UAVs -HT helicopter-type. The supporting system uses a supporting screw (or two screws arranged in a coaxial, longitudinal, or transverse direction) of the flight variable pitch, which has an autorotating mode (this is the negative pitch mode, which promotes the unwinding of the supporting screw). The diagram shows that helicopter-type UAVs are also distributed unevenly by the specified categories. The categories of heavy helicopter-type UAVs are not revealed, less than half of all the UAVs of this type weigh up to 7 kg. This can be explained by the high demand in the civil market (O_T^C) UAVs.
- UAVs -MT multi-copter type. Three or more fixed pitch screws are used as the supporting system. In most cases, it has a device to stabilize the aircraft in flight, which is designed to ensure flight stability at lateral and vertical gusts of wind. It is controlled by changing the screw speed. UAVs -MT does not have a tilt changer, or a screw pitch change system. Auto rotation mode is not implemented.

Among all existing systems, the most common unmanned aerial vehicle for take-off and landing can be distinguished:

1. horizontal take-off and landing, using the wing (in this particular case - the wing forming structure integrating the wing and the fuselage) as a supporting system on take-off and landing;
2. vertical take-off and landing, using different types of propulsors (propellers, propellers, propeller ring devices, jet nozzles) at take-off and landing as a bearing system that creates lifting force;
3. combined UAVs that use takeoff and landing as a supporting system to create a lifting force, a combination of the wing (glider) and propulsor (propulsors).

To expand the geography of the UAS application it becomes necessary to have ultra-short almost vertical take-off and landing. At the same time, it is necessary to preserve flight characteristics, in particular flight range and specified mass of target load, the set of which determines the economic efficiency of the aviation system.

The attractiveness of vertical take-off and landing is obvious, especially if the devices can take off and land automatically, because it becomes easier to work with UAVs in confined spaces and from hidden positions, the process of launching and returning is simplified, less space is needed, etc. As in the case of manned aircraft, vertical take-off and landing always limit speed, range, and load capacity. Convertible aircraft allow for combining the advantages of vertical take-off and landing and cruise flight with wing support [8, 9, 10].

One of the most important indicators of UAVs is their take-off power capacity. The statistics Fig.4, shows a clear connection of this parameter with another important flight and technical parameter as the maximum duration of the flight. It can be seen that to increase the maximum flight time of the UAV it is necessary to reduce the engine power. This, in turn, leads to an increase in run length and distance, which limits the possibility of basing.

A decrease in the energy capacity of aircraft limits the geography of the tasks to be performed under climatic conditions, which reduces its competitiveness in the market. In areas with relatively high wind loads (more than 8 m/sec), the use of UAVs with an energy structure of less than 0.2-0.25 kW/kg is problematic - it is impossible to maintain the given parameters of the flight route [11,12].

Hybrid solutions of different types are implemented for the effective performance of tasks, many of which combine a propeller driven by an internal combustion engine for a cruising flight, and four or more vertically installed propellers for vertical flight modes. In more complex constructions such solutions are used, for example, swivel wings, pushing or pulling propellers with variable tilt, or even landing on the tail, to maintain the specified mass of the target load, if necessary, the placement of additional support systems [13].

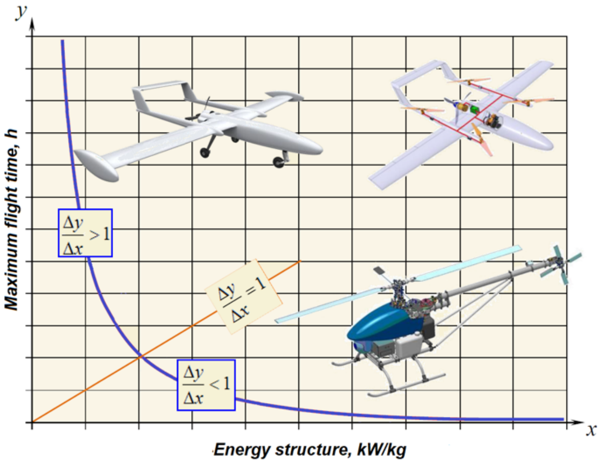

Fig. 4. Influence of takeoff energy structure on the flight duration of UAVs

2. Methods of Research into the Development of Promising Rpas

With the selected types, methods, and conditions of UAV applications, the properties of UAVs are determined by: the number of n UAV variants; the vector of the i-th variant $x = \{x_i\}, i = 1, 2, \ldots, n$; by the criteria of their functional and economic efficiency. The evolution of UAS consists of the development, production, and implementation in the aviation market of new competitive unmanned aerial systems with the required level of efficiency.

A forecast of UAS evolution in the future periods of time $0 \leq t \leq T$ has a vector function $x(t) = \{x_i(t)\}$. The task of the study is to find the optimal forecast, i.e., the trajectory of UAS evolution – . $x_{opt}(t)$ If the solution to the problem turns out to be $x_{nopt} = 0$, it would mean the system doesn't need the UAS of option n, it's unpromising.

The optimal trajectory of UAS evolution is by solving a variation problem. Several variants of formulation of variation tasks (models) are possible. The variant of the problem is determined by the type of the UAS under study and the goals of its further improvement. The type of UAS and the purpose of its evolution are determined by when the system is expected to be used for its intended purpose in the future. On this basis, all UAS can be divided into three types:

1. Special UAS (Special UAS), the application of these aircraft systems is assumed at some future point in time $t = T$ (T - depth of prediction).These include unmanned monitoring aircraft systems (monitoring of emergency zones, natural disasters, and their consequences), and various combinations of these systems, the impact of which is expected in the period ahead T. Time is peaceful, and time $t \geq T$ – is an emergency period. The goal of SUAS development is to obtain a system capable of delivering the greatest impact during an emergency, in a situation of severe interference, or in the absence of sustained communication and global navigation system signals.

2. Transport UAS (TBAS), the use of which is expected at any point in time in the future $0 \leq t \leq T$. These include unmanned aerial vehicle systems (delivery of medicines, mail, collection, etc.), and various combinations of these systems, the impact of which is expected from the time of their formation in the future period. The goal of TBAS evolution is to have a system capable of producing the greatest effect in peacetime.

3. Combined UAS (CUAS), the application is intended for both peacetime and emergencies. CUAS is the integration of elements of special and transport systems into a single whole. The purpose of CUAS development is to obtain an optimal aviation system capable of showing the greatest effect in times of peace and emergency.

Variation models of forecasting were considered in several works by Professor, Doctor of Technical Sciences Myshkin L.V. [14, 15].

This article shows a variation model to predict the development of the CUAS. It is accepted that the stepwise process of UAS evolution is described by the system of differential equations:

$$\frac{dx_i}{dt} q_i(x,t) u_i(t) - \omega_i(t) x_i(t) = Q_i(x, u_i) \quad (1)$$

$i = 1,2,\ldots,n$

with restrictions on management functions, representing the proportion of the funds allocated at the time of production t for i-th UAV (UAV$_i$):

$$0 \leq u_i(t) \leq 1, \quad \sum_{i=1}^{n} u_i(t) = 1 \quad (2)$$

where: coordinate variables $-x_i(t) \geq o; g(x_i(t)) \geq 0-$; initial conditions:

- at: $t = 0 \; x_i = x_i^0(0)$, $i = 1, 2, \ldots, n^0$; n^0 , – number of variants UAV$_i$;
- at: $t = t_{R\&D}$ (end of development time UAV$_i$) $x_i = x_i(t_{R\&D}) = 0$, $i = n^0+1, n^0+2, \ldots, n$ $(n-n^0)$ number of new versions UAV$_i$.

In equations (1):

$$q_i = \frac{f(t) - \sum_{i=1}^{n} C_0^0 i(x_i t) x_i(t)}{C_i(x_i t)}$$

,

where: $f(t) = \frac{dC^c(t)}{dt}$ – UAS development intensity; $C_i(x_i, t)$ – the cost of creation (development and serial production) UAV$_i$; $C_{0\,i}^0 = C_i^0 - a\, C_i^S \omega_i^S; C_i^0, C_i^s$ and ω_i^S – the cost of operation per unit of time, sales and intensity of UAV$_i$ sales abroad, α – share of UAS development revenue;
$\omega_i = \omega_i^s + \omega_i^A$the total intensity of UAV$_i$ waste due to sale $\omega_i^s$and accidentω_i^A.

Determining the optimal trajectory (optimal prediction) $x_i(t)$comes down to determining the optimal management $u_i(t)$ and subsequent integration of equation (1).

As a function O_k^C of finding the optimal $u_i(t)$ CUAS management, we choose a weighted sum of criteria that take into account the functioning of the system in peacetime (i.e.

O_k^C TUAS functionality) and during an emergency (i.e. O_F^S SUAS functionality) [16, 17, 18]:

$$O_C^C = \beta_T k_T O_T^C + \beta_F k_F O_F^C, \tag{3}$$

where: β_T and β_F , $\beta_T + \beta_F$ =1 the coefficients of the importance of transport and special tasks performed by CUAS; $\mathrm{k_T}$, k_F – dimensionless ratios $k_T O_T^C$ and $k_F O_F^C$,, which is necessary because the dimensions O_T^C and O_F^C different (dimensions O_T^C – kilograms-kilometers of TUAS cargoes, O_F^C,– the number of objects viewed (determination of the fire area) by SUAS).

Factors k_T and k_F we construct in the form of inverse optimal values of TUAS and SUAS development functions:

$$k_T = \frac{1}{O_{T\,opt}^C};\ k_F = \frac{1}{O_{F\,opt}^S}; \tag{4}$$

Thus, the values $k_T O_T^C = \frac{O_T^C}{O_{T\,opt}^C} < 1$; $k_F O_F^S = \frac{O_F^S}{O_{F\,opt}^S} < 1$ dimensionless, dimensionless and functional O_C^C.

Let's define the functionalityO_T^C and O_F^S [1].

$$O_T^C = \int_0^T \sum_{i=1}^n a_i x_i dt, \tag{5}$$

where: a_i is the transport UAV*ᵢ* operating intensity.

For the case of consideration of a transport UAV a_i may have the form:

$$a_i = v_i \frac{m_{xi} L_i}{t_{pi}}$$

where: v_i – flying fraction of the day; m_{xi}– UAV$_i$ lading weight; L_i – range of flight; $t_{pi} = t_{f\,i} + t_{ina\,i}$– flight time, consisting of flight time and time inactive.

$$O_F^S = \int_0^T \sum_{i=1}^n \tilde{O}_i (q_i u_{i-} \omega_i x_i) dt \tag{6}$$

where: $\tilde{O}_i = \frac{\partial\, O_F^S}{\partial\, x_i}$ the criterion of efficiency of every UAV$_i$ functioning in the system.

Substitution (5) and (6) in formula (3) gives:

$$O_C^C = \int_0^T \sum_{i=1}^n \beta_F K_F \tilde{O}_i (q_i u_{i-} \widetilde{\omega}_i x_i) dt \tag{7}$$

where: $\widetilde{\omega}_i = k_i \omega_i$, $k_i = 1 - \frac{\beta_T k_T a_i}{\beta_F c \tilde{O}_{i\omega_i}}$;
k_T and k_T the factors are determined by formulae (4).

Included in k_T and k_T optimal values of the functions respectively $O_{T\,opt}^C$ characterizing the execution of CUAS only functions TUAS and $O_{F\,opt}^S$ characterizing the execution of CUAS only functions SUAS are determined from the ratio (1):

$$O_{T\,opt}^C = \int_0^T \sum_{i=1}^n a_i x_i \ \ (u_{i\,opt}) dt \tag{8}$$

where: $u_{i\,opt} = argmax O_T^C [\{x_i(u_i)\}]$;

$$O_C^C = \int_0^T \sum_{i=1}^n \tilde{O}_i \left[q_i \left(\{x_{i\,opt}\} \right) u_{i\,opt} - \widetilde{\omega}_i x_{i\,opt} \right] dt \tag{9}$$

where: $u_{i\,opt} = argmax O_F^S [\{x_i(u_i)\}, \{u_i\}]$.

Optimal management of CUAS development is determined by maximization of functionality (7) with limitations (1) and (2):

$$u_{i\,opt} = argmax O_C^C [\{x_i(u_i)\}, \{u_i\}] \tag{10}$$

Since the development functions of the CUAS (7) and CUAS (6) are structurally the same, as a solution (10) at (1) and (2) we use the solution (9) (taking into account the difference between ω_i and $\widetilde{\omega}_i$, $\tilde{O}_i$ and $\beta_F k_F \tilde{O}_i$), published in [15]. Bring him in:

$$u_{i\,opt} = \begin{cases} 1, & if\ \varepsilon_i = max \\ 0, & if\ \varepsilon_i \neq max \end{cases} for\ 0 \leq t \leq T \tag{11}$$

$$\text{where: } \varepsilon_i = \frac{\varphi_i(t)}{C_i} + \frac{\tilde{O}_i}{C_i} \tag{12}$$

ε_i – significance factor *i*-th UAV$_i$ (dynamic comparison criterion UAV$_i$ and UAV$_j$ $i, j - 1,2, \ldots, n$, i≠j).

If for a while $\Delta\, t_i \in [0, T]\ \varepsilon_\iota(t) > \varepsilon_\iota(t)$, then UAV$_i$ rather than UAV$_j$ and CUAS is formed from a mixture of UAV$_j$ and UAV$_i$. The transition from production UAV$_j$ on UAV$_j$ happens at a point in time $\mathrm{t_{trans}}$, derived from the equation $E_i(t_{trans}) = \varepsilon_\iota(t_{trans})$.

Functions $\varphi_i(t)$ are determined by the integration of related equations:

$$\frac{d\Phi_i}{dt} = -Q_0 - \sum_{i=1}^n \frac{\partial\, Q_i}{\partial\, x_i}, i = 1,2, \ldots, n \tag{13}$$

subject to boundary conditions at t=T: $\Phi_1(T) = \Phi_2(T) = \cdots = \Phi_\nu(T)$=0.

In the equations:
$Q_0 = \sum_{i=1}^n \beta_F K_F \tilde{O}_i (q_i u_{i-} \widetilde{\omega}_i x_i) dt$; $Q_{i=} q_i u_{i-} \omega_i x_i$ – the right parts of development equations (1).

Thus, the task of determining optimum control $u_{i\,opt}(t)$ it comes down to determining the values of the significance ratios UAV$_j$ $\varepsilon_i(t)$ and therefore to the integration of conjugated equations (13). To solve the problem, you need to know the criterion of CUAS efficiency $O_F^S(\{O_i\})$ and everyone UAV$_i$ $O_i(t)$ when performing their task during an emergency, the intensity of operation UAV$_i$ $a_i(t)$ in the performance of the CUAS transport task in peacetime, the cost of creating $C_i(t)$, sales C_i^S, annual operation $C_i^O(t)$, sales intensity ω_i^S and accidents ω_i^A UAV$_i$ types, as well as the law of investment $C^I(t)$ for the development of UAV systems of each type [19, 20].

All these characteristics generally depend on future time $t$and most of them are based on the number of x_i UAV$_i$.

Assuming that the CUAS can be formed of two types of unmanned aerial vehicles: UAV$_1$ and UAV$_2$ (*i*=1, 2), for which the options O_i, a_i, C_i, C_i^S, C_i^O, $\widetilde{\omega}_i$ constants,
$O_F^S = O_1 x_1 + O_2 x_{2,}\ \tilde{O}_i = \frac{\partial\, O_F^S}{\partial\, x_i} = O_i, C^I = C_O^I + ft$ where $f = \frac{dC^I}{dt} = const.$

The application of ratios (11), (12), and (13) will make it possible to find the best management option.

$$u_1(t) = \begin{cases} 1, 0 \le t \le t_{trans}, \varepsilon_1(t) > \varepsilon_2(t) \\ 0, t_{trans} \le t \le T, \varepsilon_1(t) < \varepsilon_2(t) \end{cases}$$
$$u_2(t) = \begin{cases} 0, 0 \le t \le t_{trans}, \varepsilon_2(t) > \varepsilon_1(t) \\ 1, t_{trans} \le t \le T, \varepsilon_2(t) < \varepsilon_1(t) \end{cases}; \quad (14)$$

The transition time from UAV₁ to UAV₂ production is calculated by the formula:

$$t_{trans} = T + \frac{C_2}{C^0_{0\ 2} - C_2(\tilde{\omega}_1 - \tilde{\omega}_2)} ln \left[\frac{\frac{O_1}{O_2} - \frac{C^0_{0\ 1}}{C^0_{0\ 2} - C_2(\tilde{\omega}_1 - \tilde{\omega}_2)}}{\frac{C_1}{C_2} - \frac{C^0_{0\ 1}}{C^0_{0\ 2} - C_2(\tilde{\omega}_1 - \tilde{\omega}_2)}} \right] \quad (15)$$

where: $C^0_{0\ i} = C^0_i - aC^S_i \omega^S_i$.

The integration of equations (1) at optimal controls $u_1(t)$ and $u_2(t)$ gives an optimal trajectory of CUAS development:

For $0 \le t \le t_{trans}$

$$x_1(t) = \frac{k_{11}}{k_{12}} - \frac{k_{11} - k_{12}x^0_1}{k_{12}} e^{-k_{12}t}$$
$$x_2(t) = 0 \quad (16)$$

where: $k_{11} = \frac{t}{C_1}$; $k_{12} = \frac{C^0_{0\ 1}}{C_1} + \omega_1$;
for $t_{nep} \le t \le T$

$$x_1(t) = x^{nep}_1 e^{-\omega_1(t - t_{nep})} \quad (17)$$
$$x_2(t) = \frac{k_{21}}{k_{22}} - \frac{C^0_{0\ 1}\ x^{nep}_1}{C_2(k_{22} - \omega_1)} e^{-\omega_1(t - t_{nep})} - \frac{k_{21}}{k_{22}} - \frac{C^0_{0\ 1}\ x^{nep}_1}{C_2(k_{22} - \omega_1)} e^{-k_{22}(t - t_{nep})}$$

where: $k_{21} = \frac{t}{C_2}$; $k_{22} = \frac{C^0_{0\ 2}}{C_2} + \omega_2$;for $t = t_{trans}$

An equally important indicator for predicting UAS development is the relative weight of the target load $\bar{m}_{tl} = \frac{m_{tl}}{m_0}$, where: m_{tl}– target load mass that determines the purpose of an unmanned aerial vehicle, m_0– the take-off weight of the UAV.

3. Results and Discussions

As a result of systematization and analysis of statistics on the world fleet of UAVs Fig. 5, it is visible, that the range of relative masses of target load with decreasing dimensionality of UAVs of different types on take-off mass essentially increases.

This can be explained by the large weight range of equipment for functional tasks (optoelectronic equipment, radiation detectors). Mass of onboard navigation complexes with high accuracy and reliability of navigation definition considering operation in many climatic zones. Mass of on-board systems (steering machines, power supplies, etc.) with different conversions coefficient of different types of energy, mass and overall efficiency, operating efficiency, reliability, and other properties.

There is a great discretion of the masses of the power unit with the electric propeller traction, with the accumulator, with the solid oxide fuel cell, with the gas-turbine generator of the electric power on board, with the hybrid generator, on the energy costs and power of the hoisting, marching and auxiliary engines [21, 22]. As a range of masses of drive reducers of screws and fans, mechanical transmissions for convertoplanes and UAVs with lifting ventilators.

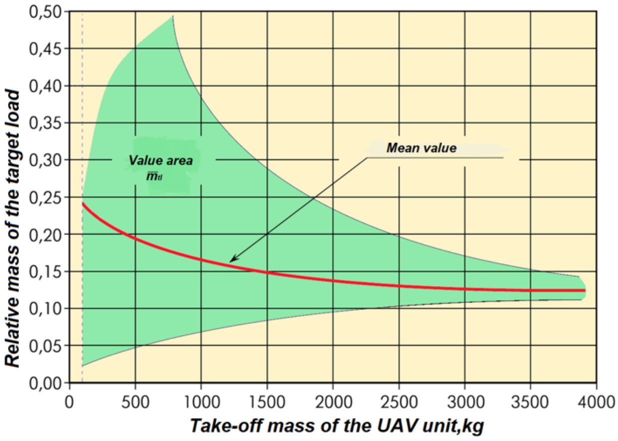

Fig. 5. Relationship between the relative mass of the target load and the take-off mass of the UAV unit

3. Conclusion

Thus, the presented methodology of unmanned aerial system development with the use of a variation model makes it possible to determine the optimal trajectory of development (type and quantity of UAVs) of a combined unmanned aerial system, which provides the greatest result of functioning in peacetime and during an emergency.

In some cases, under or over m_{tl} is conditioned by an arbitrary decision of the developers when choosing the type of UAVs, the dimensions of the body, and its manufacturing technology. Therefore, to optimize prospective UAS it is necessary to create target load sets for each type and dimension class of UAVs. In this case, it is necessary to consider the problems of integration of devices differ in terms of physical principles within a single payload complex installed on board the UAV for a particular flight. The desire to constantly use the multifunctional equipment set, regardless of the real need of a particular flight, leads to a marked decrease in the functional and economic efficiency of aircraft in the UAS.

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