

Cost-effectiveness analysis of the implementation of transport and technological cycles in the swarm use of agricultural UAVs

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Abstract. The article presents an approach that provides a comprehensive analysis of the cost-effectiveness of the implementation of transport and technological cycles in the swarm use of agricultural UAVs. A generalized "effect-cost" assessment is presented for ensuring the transport process within the framework of acceptable implementations of the transport-technological cycle. It is shown that for swarm applications of UAVs in precision agriculture, cost-benefit analysis is also directly related to the microprocessor performance of the UAV swarm. The cost-effectiveness model proposed in the work is based on a previously obtained solution to the problem of optimal performance of a UAV swarm used for spraying crops. The results of improving the cost function are presented using a model example that illustrates the proposed approach. It is noted that the presented problem statement helps developers clearly identify alternatives and formulate additional questions that need to be answered to make a decision.

1 Introduction

In the practice of using UAVs in precision agriculture, there are various approaches to assessing the effectiveness of the implementation of transport and technological cycles (TTC) of UAVs. It is noted in [1] that for UAVs, target efficiency is a system characteristic determined by the framework of the functional operations of the TTC. An analysis of works [2-5] shows that a direct description of the entire set of UAV actions within the framework of complex TTC operations is difficult due to their diversity and the large number of system elements performing these actions. For agricultural UAVs, when analyzing the TTC, it is possible to identify typical operations, for each of which it is possible to develop both universal and standard mathematical models. In particular, works [6-9] propose a GERT-

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network modeling of the UAV TTC, on the basis of which an analysis of the costs and time characteristics of the implementation of the UAV TTC is carried out.

Considering the assessment of the target efficiency of the UAV TTC, we will introduce an assessment of the efficiency of one UAV operating under the conditions of a typical TTC, which we denote by E_1 . If one UAV is not effective enough to carry out a flight mission for precise processing of agricultural objects, then a swarm of several UAVs interacting with each other is necessary. We will assume that all UAVs participating in the swarm and performing TTC operations operate under the same conditions and have the same efficiency indicator values. In this case, standard TTC operations and corresponding standard models can be introduced. The use of GERT network models that describe the probabilistic-time characteristics of the TTC allows us to reduce the high degree of uncertainty in the parameters of the UAV and the external environment to the uncertainty of these models. The TTC specification methodology outlined in [10] makes it possible to take into account the experience of specialists when forming models, implement a cost-benefit analysis and consider the problem for several possible implementations of the TTC (allowable within the framework of GERT-like nodal logic) when deciding on the implementation of flight missions by a swarm of UAVs.

2 Materials and methods

The transport and technological cycle, from the point of view of the intended purpose of an agricultural UAV, consists of transporting a given target cargo. This cargo for spraying UAVs is a solution of pesticides or fertilizers intended for spot application on the cultivated fields. Consequently, the efficiency of the TTC can be considered as a generalized characteristic of the target quality for the delivery of the target cargo to the required point in space. It should be noted that the task of delivering a target cargo using a UAV to the desired area of space and performing the assigned task can be assessed by the total integral indicator of target efficiency E_{com} . An integral part of this indicator is the probability of effective operation of the UAV denoted as E_1 . The value of the indicator can be estimated using the following equation:

$$E_{com} = E_1 TR, \quad (1)$$

where TR is an indicator of the UAV's transport excellence. As noted in [11], the indicators for assessing the transport excellence of UAVs can be based on various physical quantities, for example, work, energy, productivity, operating time or other characteristics of operations for transporting fertilizers or pesticides.

Note that it is necessary to link these characteristics with the main design parameters of the UAV. In [1], transport excellence is proposed to be assessed from the perspective of "effect – costs", where the effect is a characteristic (result) of the TTC, that is, the process of transporting the target cargo with a mass of M_z , and costs are the resource required to implement the transport function of the TTC. This resource is estimated by a value proportional to the total energy required to transport the target cargo:

$$TR = M_z W^2 D, \quad (2)$$

where W and D are the average speed and flight range of the UAV, respectively.

For a generalized "effect – cost" assessment, it is also proposed to add a component that takes into account the material resource that ensures the transport process within the framework of the acceptable implementation of the TTC. Such a resource is the mass of UAVs – M_{uav} . Thus, a generalized indicator reflecting target efficiency, transport excellence and resource costs within the acceptable implementation of the TTC can be presented in the following form:

$$E_{com} = \frac{M_z}{M_{uav}} W^2 D \quad (3)$$

Considering cost-effectiveness, the authors in [1] note that the quantitative assessment of technical excellence is based on the technical level of the product. The technical level, as noted above, is a relative characteristic based on a comparison of the values of indicators characterizing the technical perfection of a product with the corresponding values of the base sample or prototype. In general, the technical perfection of a spraying UAV can be achieved both by simply increasing the mass (volume of spray solutions) and by increasing productivity, including such a component as the microprocessor performance of the UAV [12].

For UAV swarm applications in precision agriculture, cost-benefit analysis is also directly related to the microprocessor performance of the UAV swarm [13]. The previously performed analysis of optimal performance makes it possible to implement acceptable TTCs for given values of system parameters. Taking into account the dependence of parameters and their sensitivity to changes in their values allows us to obtain several acceptable implementations of TTC, differing both in implementation efficiency and in time and resource costs [14, 15].

3 Results

3.1 Cost effectiveness model

So, based on the generalized “effect-cost” assessment (3), we can take into account the material resources that ensure the implementation of the UAV TTC, but the question remains open regarding the assessment of the cost effectiveness of providing the required microprocessor performance of a UAV swarm. The proposed cost-effectiveness model is based on a previously obtained solution to the problem of optimal performance of a swarm of UAVs used for crop spraying [16].

The problem of finding the optimal microprocessor performance of a UAV swarm is formulated as follows. For the existing values of system parameters S , P , M and T , determine the number of processors N required to obtain maximum performance $P(N, S, P, M, T)$. Here:

S — microprocessor speed, thousand operations/s;

P — internal processor overhead, thousand operations/s;

M — interprocessor overhead ratio, thousand operations/s;

T — number of operations to process one message, thousand operations per message.

If the number of UAVs in a swarm were unlimited and the only goal was to maximize productivity, then the above formulation would be ideal. However, in most cases, UAVs for precision farming systems are purchased in conditions of limited financial resources, and these funds are required to satisfy other goals related to the organization of UAV transport and technological cycles, including both the onboard and ground segments. Therefore, it is preferable to have a model that relates indicators such as productivity to costs in dollars or in units of some other limited resource. This model is called a cost-effectiveness model.

We will illustrate the approach using the following model example. At the same time, we note that it is quite simple to transform the productivity model into a cost-effectiveness model. For the productivity formula considered in [13], this can be done by replacing N with the cost function $N(C)$ - the number of UAVs that can be purchased by spending C dollars:

$$P(C) = N(C)[S - P - M(N(C) - 1)]/T. \tag{4}$$

In the model example, we assume that since 25 UAVs will be manufactured and each costs \$400, we find that adding one UAV to the basic swarm structure will cost \$10 thousand (\$25·400 = \$10,000). Therefore, when measuring C in thousands of dollars, we obtain $N(C) = C/10$ and then

$$P(C) = C/10[S - P - M(C/10 - 1)]/T. \tag{5}$$

Thus, the cost-effectiveness curve corresponding to (5) can be obtained by simply changing the scale along the x-axis for the optimal performance model, as shown in Figure 1.

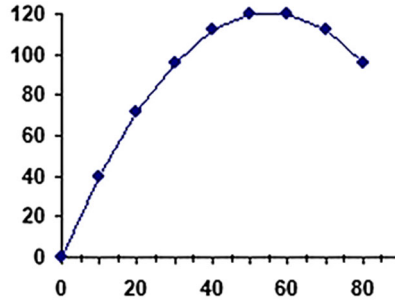


Fig. 1. Cost-benefit curve at \$10,000 per item.

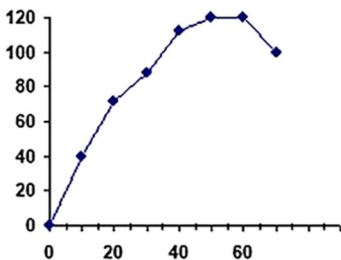
Using the concept of cost-effectiveness, one can more easily assess whether the option ($N = 5$ or $N = 6$) that maximizes system performance is the best way to allocate limited resources. Of course, option $N = 5$ is better than $N = 6$, but is it better than $N = 4$? After all, it may not be justified to spend \$10,000 to move to a larger UAV swarm structure with a slight increase in microprocessor performance (or message processing when controlling the UAV).

3.2 Cost function improvement results

Sometimes the choice of an appropriate option is simplified with an improvement in the cost function $N(C)$. For example, suppose it is possible to negotiate with UAV suppliers regarding the following (very simplified) price list with a “quantity discount” (providing for a reduction in price when purchasing a large batch of products):

- the price of each product from the first 25 is \$400;
- the price of each product over 25 is \$240.

For this case, the cost-effectiveness curve is shown in Figure 2, from which it can be seen that with a discount on the number of products, purchasing more UAVs for a precision farming system becomes more attractive.



N	C(N)	$\Pi(N)$
1	10	40
2	20	72
3	30	96
4	36	112
5	42	120
6	48	120
7	54	112

Fig. 2. Dependence of costs when purchasing products at a discount.

4 Discussion

So, the cost-effectiveness model consists of a sequence of formulas that determine the assessment of efficiency depending on the cost of money or some other limited resources.

Cost-effectiveness models typically consist of two parts:

- 1) cost model $C = C(F)$, which determines the cost of purchasing certain funds F ;
- 2) productivity model $P = P(F)$, which determines productivity when using means F .

This division is made mainly for convenience. It is usually more convenient to consider costs and performance depending on some intermediate data (such as the microprocessor performance of the UAV, the number of UAVs in the swarm, etc.) than to exclude such a relationship. In addition, if we consider the model of UAV transport and technological cycles as a whole as a GERT-network model with many admissible implementations, then the specified method of dividing it is fully consistent with the modeling principle, since the functions of connecting costs and productivity with means (some resources) most likely will change independently of each other. At the TTC specification stage, work [10] provides several examples of such tools for which typical price lists can be found in the extensive literature (price list for UAV technical support, typical prices per minute of UAV operating time within the TTC, etc.).

You can also get additional information about the price structure for ground-segment computing equipment and services for servicing software and hardware systems.

At the same time, concluding a favorable price agreement does not completely solve the problem of determining the appropriate number of UAVs to be purchased for swarm use in agriculture. However, the cost-effectiveness model makes it possible to clarify this problem, since the cost-effectiveness formula $P(C)$ shows what productivity can be obtained at a given cost and how to determine this desired performance.

5 Conclusion

Thus, the presented problem statement helps developers clearly identify alternatives and formulate additional questions that need to be answered to make a decision [17]. Let's assume that we can find some alternative way to use resources to increase microprocessor performance (direct these resources to simplify the communication system and on-board control equipment and reduce interprocessor overhead). The answer to the question of how to choose the best alternative relates to the area of cost-benefit comparison.

There is often a need to determine the importance of message processing speed in swarm applications of UAVs. It is known that, as a rule, specialized computers based on digital signal processors or PC/104, MicroPC computers running real-time operating systems (QNX, VME, VxWorks, XOberon) are used as on-board control equipment for UAVs [18]. In this case, the task is to harmonize various cost estimates and their importance within the framework of a single decision-making criterion for choosing the right alternative, which affects the determination of the number of purchased UAVs. Getting an answer to this question falls into the realm of multi-objective decision making.

It is also possible that there is not enough information regarding certain system parameters to make a satisfactory decision. There is a need to answer the question of what funds should be spent on obtaining additional information and conducting analysis in order to reduce the likelihood of choosing the wrong decision? Getting an answer to this question belongs to the field of risk analysis and statistical decision theory.

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