Applying partial domination in organizing the control of the heterogeneous robot group

S Yu Misyurin$^{1,2}$, A P Nelyubin$^2$ and M A Potapov$^3$

$^1$ National Research Nuclear University MEPhI, Moscow, Russia
$^2$ Mechanical Engineering Research Institute of the RAS, Moscow, Russia
$^3$ Institute of Computer Aided Design of the RAS, Moscow, Russia

E-mail: nelubin@gmail.com

Abstract. The article discusses the formulation of the problem of multicriteria design of a robotic system consisting of a group of robots, with the aim of achieving specified targets. A new approach to organizing the control of such robotic systems based on the partial dominance of decisions over target indicators is proposed. Illustrative examples of the application of the approach for UAV groups are given.

1. Introduction

The article discusses a special formulation of the problem of design of groups of robots interacting with each other. Such robotic systems include groups of mobile robots designed to search, explore or research work in hard-to-reach or completely inaccessible areas (in space, under water, underground, with high radiation, etc.) [1–4]. In particular, groups of unmanned aerial vehicles (UAVs) [5-7].

In practice, there are many situations where there are goal system characteristics (or targets) that need to be achieved or surpassed. As such a goal may be the characteristics of an enemy system in a military confrontation or a rival in another type of competition. It may also be the characteristics necessary for a robotic system to perform a specific task. Moreover, in such tasks, target indicators are often considered barrier constraints, so their failure to lead to a qualitatively worse solution. But the available resource and other constraints often do not allow us to achieve or dominate the goal with feasible solution variants.

In recent publications, the topic of interaction of robots in a group and control of these groups is widely presented, both from the technical point of view [1], and from the side of control algorithms and multicriteria optimization [8-10]. The multi-agent approach [8], the adaptation [9], and genetic algorithms [9-10] are also being studied. In a number of papers [11–12], attention is paid to algorithms for coordinated movement of groups of robots. Basically, the emphasis is either on the development of the element base with a detailed study of engineering issues, or on special optimization algorithms that solve specific problems of increasing the efficiency of existing or developed systems. This indicates a higher level of development of foreign technology and infrastructure.

We propose an approach to solving such problems using a coordinated control of a group of heterogeneous robots, i.e. differing in functionality, structure, and technical parameters. At the same time, we use special methods of multicriteria analysis and introduce the concept of zones of partial dominance, allowing to achieve specified targets under limited resources. In [13-14], the foundations
of a multicriteria approach to the design of complex robotic systems capable of adapting to dynamically changing operating conditions were laid. This work is a continuation of this study.

2. General problem formulation

Consider the following mathematical model of a multicriteria problem of robotic system design in the presence of a goal:

\[ \langle X, K, Z, G \rangle \]

Here \( X \) is the set of feasible solutions (designs); \( K = (K_1, \ldots, K_m) \) is the vector criterion consisting of \( m \geq 2 \) partial criteria; \( Z \) is the vector criterion \( K \) range or scale; \( G = (G_1, \ldots, G_m) \) is the goal (target) vector in the criteria space \( Z \).

The solution variant \( x \in X \) is a set of parameter values that describe the design of a robotic system. The design of a separate robot includes technical parameters, the values of which can be determined (selected, adjusted) in a certain area of possible values. In the case of a system consisting of a group of heterogeneous robots, the design description also includes information on the composition and number of different robots, on the systems of group control and interaction between them.

Each partial criterion \( K_i \) is a separate characteristic (performance indicator) of the solution \( x \in X \), measured or evaluated on its scale \( Z_i \), i.e. \( K_i: X \rightarrow Z_i, \ i = 1, \ldots, m \). The scales \( Z_i \) can be ordinal or more advanced. For convenience, we assume that preferences increase along the scales \( Z_i \). Then the non-strict Pareto preference relation \( R^0 \) can be introduced on the set of feasible solutions \( X \) [15]:

\[ \forall x', x'' \in X: \ x' R^0 x'' \Leftrightarrow K_i(x') \geq K_i(x''), \ i = 1, \ldots, m, \]

as well as the strict Pareto preference (dominance) relation \( P^0 \):

\[ \forall x', x'' \in X: \ x' P^0 x'' \Leftrightarrow x' R^0 x'' \land K(x') \neq K(x''). \]

The set of Pareto optimal solutions form \( X \) is denoted by \( X^0 \). These solutions \( x^0 \in X \) are not dominated by any other solution from \( X \), i.e. not \( \exists x \in X: \ x P x^0 \).

The problem of designing a robotic system considered in this paper is to find such a solution \( x^* \in X \), which will provide the fulfillment of specified target characteristics:

\[ K_i(x^*) \geq G_i, \ i = 1, \ldots, m. \]

The problem formulation (1) differs from the classical problem of goal programming. First, the problem (1) is not an optimization problem, but consists in finding feasible solutions. However, one can further optimize one of the criteria \( K_i \) or add a new one, for example, the time or cost of manufacturing the system. Secondly, the problem (1) does not allow a solution close to goal \( G \), but not reaching it, which can be considered as optimal when solving a goal programming problem. This key difference is due to the fact that in a number of practical situations in robotics it is not enough to get as close as possible to the goal, and it is necessary to achieve or exceed it.

3. The proposed approach to solving the problem

The problem of designing a robotic system is formulated by us in a general form, without specifying the type of constraints on the set \( X \) and the type of functions of the criteria \( K_i \). Therefore, the specific method for estimating the range of feasible values of the vector function \( K(X) \) in the space \( Z \) is not considered in this paper. For these purposes, you can use the methods of global multicriteria optimization (such as genetic algorithms [16]), parameter space investigation methods [17], methods for approximating the Edgeworth-Pareto hull [18]. Further, we assume that the region of feasible values of the vector function \( K(X) \) is constructed (estimated) and the boundary of the Pareto optimal solutions \( K(X^0) \) is picked out on it.

Let us estimate the relative position of the region \( K(X^0) \) and the goal \( G \). If some of the variants from \( X^0 \) dominate the goal \( G \) with respect to Pareto relation, then we can choose any of these variants as the solution to problem (1). Figure 1 illustrates this case on example of two criteria.
In the general case, the Pareto frontier $K(X^0)$ is divided into zones (regions, sets) of partial dominance and a zone of complete dominance by a goal (see figure 2). In the zones of partial dominance, the solutions we have provide an advantage in terms of some criteria over the corresponding criteria of the goal. As a rule, the measure of the set of complete dominance of a goal is substantially less than the sum of sets of partial dominance.

Solution variants in the field of complete domination by goal are inferior by all the criteria. However, as a rule, it is in this area that the optimal solutions to the problem of goal programming are found. The proposed approach is based on the use of partial dominance zones depending on the operating conditions of the designed system, determining the relative importance of the criteria $K_i$. Under some conditions, one group of criteria will be more important, and it will be preferable to choose solutions that dominate the goal for this group of criteria. Under other conditions, the second group of criteria will be more important, and other solutions from another zone of partial dominance will be preferable.

Thus, the problem (1) can be solved by constructing the structure of a group of heterogeneous robots, taking into account zones of partial dominance of the goal. Namely, you should choose the designs of robots from different zones of partial dominance and organize the mechanism of distribution and switching functionality between them, ensuring the implementation of a common goal.

4. Illustrative examples
Let us consider two examples to illustrate the described formulation of a multicriteria problem and the proposed approach to its solution.
**Example 1.** The mission is to transport containers with a payload using a UAV group crossing the enemy’s territory, where the UAV detection and eliminating systems are located. On each UAV, you can install an anti-radar protection system that actively damps the signals of the enemy’s radar. Such a protection system can have a different level of effectiveness: low, medium, high. Wherein, the higher the level of efficiency, the heavier the system. The limited resource in this example is the UAV load capacity. The design problem is to choose the load configuration of all UAVs, so as to maximize the payload, measured in the number of containers, and the level of anti-radar protection. Figure 3 shows 3 Pareto optimal UAV loading variants in the space of these two criteria: (0, high), (1, medium), (2, low).

![Figure 3. Solution variants to the example 1 problem.](image)

The goal \( G \) in this example is determined by the mission based on the following considerations: 1) to perform the task of transporting cargo, the payload of the UAV must be at least 1 container; 2) at the same time, the level of anti-radar system should be higher than medium to ensure that the UAV will not be detected. Thus, there is no such solution for loading the UAV that would satisfy all the \( G \) targets, i.e. dominate the \( G \) by Pareto relation. The goal programming problem solution in this case will be loading (1, medium) for each UAV, which is dominated by the goal \( G \) and will lead to a high risk of detecting the group of UAVs.

Consideration of the zones of partial dominance in this example suggests a comprehensive solution consisting in the use of heterogeneous UAVs with (0, high) and (2, low) loads and the organization of their interaction in a group in order to accomplish a common task. More specifically: UAVs (0, high) can cover UAVs (2, low) by their anti-radar protection, while flying near the UAVs (2, low) transport only payload.

**Example 2.** The problem is to form a group of combat aircrafts to confront enemy aircraft with specified characteristics. The technological base (engines, electronic equipment) is the constraint in this problem and does not allow production of aircrafts that are superior to those of an opponent, both in maneuverability and in the maximum developed speed. Figure 4 shows the space of these two criteria, the values of which are normalized from 0 to 1. The \( AD \) curve shows the Pareto frontier of the feasible structures of the aircraft produced in the space of these two criteria. The goal \( G \) is characteristics of the enemy aircraft. Solution variants on the \( BC \) curve are completely dominated by the opponent’s aircraft and will lose to him under any conditions.
Therefore, it is proposed to use solutions in the zones of partial dominance – on the $AB$ and $CD$ curves. Consider the dependence of the relative importance of the criteria $\alpha$ from the environmental conditions. For illustration, we take a simple dependence on the altitude $H$ of the battlefield above sea level: the closer to the surface, the more important is maneuverability, and vice versa, the higher, the more important is the maximum speed of the aircraft. For each solution $x$ on the Pareto frontier, we can determine the value $\alpha_x$ of the coefficient of relative importance of the criteria, at which the solution $x$ will be optimal when using any convolution of criteria [15]. Then, using the dependence $\alpha(H)$, one can estimate the altitude $H^x$, at which the solution $x$ will be optimal: $\alpha(H^x) = \alpha_x$. Then the complex solution of the problem of organizing the battle will be the formation of two groups of aircrafts from different zones of partial dominance $AB$ and $CD$, and the distribution of aircrafts from the zone $AB$ above a certain level $H^B_x$, and aircrafts from the zone $CD$ below a certain level $H^C_x$.

5. Conclusion
We have proposed a new approach to organizing the control of robotic systems consisting of groups of heterogeneous robots, based on the partial domination of decisions over target indicators. By organizing such a coordinated operation of a group of robots and ensuring the transfer of control to that part of the robots that currently partially dominates the goal, it is possible to ensure the regime of complete domination of the group of robots in the overwhelming amount of operating space. The integrated control provides, in general, complete domination over the goal with limited resource capabilities to increase the ranges of characteristics of each robot.

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