Integrated control of a robotic group with partial dominance of decision variants

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Abstract. We consider the problem of multicriteria design of a robotic group, consisting of a group of robots, with the aim of achieving specified targets. A new approach to the organization of control of such robotic systems based on the partial dominance of decisions over target characteristics is proposed.

1. Introduction

In recent years, there have been many promising developments in the world in the field of robotic systems, consisting of groups of robots that interact with each other. Such systems include groups of mobile robots designed to carry out search, explore or research work in hard-to-reach or completely inaccessible areas (in space, under water, underground, with high radiation, etc.) [1–4]. Groups of unmanned aerial vehicles (UAVs) are increasingly used in the military field [5]. Other promising areas of application are security systems, smart home technologies [6], and surgery with microscopic robots.

In practice, there are many situations where there are goal system characteristics (or target indicators) that need to be achieved or surpassed. As such a goal can be the characteristics of the enemy system in military confrontation or a rival in another type of competition. It may also be the characteristics necessary for a robotic system to perform a task. But the available resource and other constraints often do not allow us to achieve or dominate the goal with feasible solution variants. We propose an approach to solving such problems through the use of integrated and coordinated control of a group of robots.

In [7–8], the authors laid the foundations for a new multicriteria approach to designing complex robotic systems capable of adapting to dynamically changing operating conditions. In particular, on the examples of groups of mobile robots. This work is a continuation of the developing multicriteria approach.

2. Problem formulation

For the formulation of a multicriteria problem of designing a robotic system, we will use the following mathematical model:

\[ <X, K, Z, G> \]
Here $X$ is the set of feasible solutions (designs); $K = (K_1, ..., K_m)$ is the vector criterion consisting of $m \geq 2$ partial criteria; $Z$ is the vector criterion $K$ range or scale; $G = (G_1, ..., G_m)$ 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 mechanism (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 many individual mechanisms (a group of robots), the design description also includes information on the composition and number of different mechanisms, 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. $K_i : X \rightarrow Z_i, i = 1, ..., m$. 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 $X$: \( \forall x', x'' \in X: x' R^0 x'' \iff K_i(x') \geq K_i(x''), \quad i = 1, ..., m, \)

as well as the strict Pareto preference (dominance) relation $P^0$: \( \forall x', x'' \in X: x' P^0 x'' \iff x' R^0 x'' \text{ и } K(x') \neq K(x''). \)

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:

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

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 [10]), parameter space investigation methods [11-13], methods for approximating the Edgeworth-Pareto hull [14]. 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). In Fig. 1 this case is illustrated by the example of two solutions.
Fig. 1. Trivial case where there are solution variants dominating the goal.

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 Fig. 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.

Fig. 2. Selection of zones 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 organizing a mechanism for switching between different zones of partial dominance depending on the operating conditions of the system.

For robotic systems consisting of a group of robots, such a switching mechanism may be the transfer of control between heterogeneous subgroups of robots with different characteristics. By organizing such an integrated (coordinated) functioning of a group of robots and ensuring the transfer of control to that part of the robots that at the moment partially dominates the goal, it is possible to ensure the mode of complete domination of the group of robots in the vast majority of operating space. A single integrated control provides, in general, complete domination over the goal with limited resource capabilities to increase the ranges of characteristics of each robot through the most effective control of a group of robots.

4. Conclusion
We have proposed a new approach to organizing the control of robotic systems consisting of groups of robots, based on the partial dominance of variants over target indicators. 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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