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Decentralized autonomous planning of cluster reconfiguration for fractionated spacecraft

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ABSTRACT

Autonomous cluster operation such as cluster reconfiguration is one of the enabling technologies for fractionated spacecraft. By virtue of the multi-agent system theory, this paper presents an organizational architecture for fractionated spacecraft, which not only enables autonomous cluster operations but also facilitates its non-traditional attributes. Within this organizational architecture, a decentralized framework is proposed to solve cluster reconfiguration problems based on primal and dual decomposition, where sub-gradient methods are adopted to include reconfiguration cases with non-differentiable objectives. Two typical constraints are considered: final configuration constraints representing coupling variables and collision avoidance constraints representing coupling constraints, both of which are non-convex. General schemes are proposed to convexify those constraints via the linearization and convex restriction technology. Then final configuration constraints are tackled by primal decomposition, while collision avoidance constraints by dual decomposition. To the end, multi-level primal and dual decompositions are employed to solve reconfiguration problems with both coupling variables and coupling constraints. For illustration an example of in-plane cluster reconfiguration is solved and compared with the centralized approach the solution is optimal.

1. Introduction

Fractionation is the design concept of a distributed space system that deploys its functionalities, such as computation, communication, data storage, payload and even power generation, onboard several independent spacecraft that share those functionalities through a wireless network. The spacecraft hosting one or several shared functionalities is called a module. For such a fractionated system, new modules with more advanced technology may be added to the original system to enhance future value, which allows evolvability for future changing needs. Besides, existing functionalities can be re-organized to meet new mission requirements, which exhibits adaptability. Furthermore, modules that fail or are near the end of life can be replaced by new modules instead of putting the whole mission at risk, which shows maintainability. Apart from aforementioned evolvability, adaptability and maintainability, fractionated spacecraft shall allow survivability and responsiveness to evade debris-like threats. Apparently, any of the above non-traditional attributes requires the original configuration to change accordingly. Thus, the cluster reconfiguration capability is of paramount importance and is crucial for fractionated spacecraft.

However, modules that fly in the cluster of fractionated spacecraft operate in an open and dynamic environment, where internal or external changes cannot be characterized accurately beforehand. Due to this reason, fractionated spacecraft can be regarded as a distributed real-time and embedded (DRE) system. In such systems autonomous

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operation is required to make the system adapt to changing mission goals and environmental conditions [1]. Once operations of fractionated spacecraft are performed autonomously in space, more complex goals can be accomplished. Meanwhile, the workload of ground station as well as the cost of operating spacecraft after launch will be reduced.

This paper addresses the autonomous reconfiguration problems of fractionated cluster in the presence of final configuration constraints and collision avoidance constraints. In our study, for a cluster with n modules, the reconfiguration problem is defined as the design of open-loop optimal controls to transfer those n modules from their current locations to n new locations in the target cluster. Very often, such an open-loop control is required to be propellant-optimal to minimize the global propellant expenditure. The propellant-optimal control is commonly solved by direct or indirect methods [2,3]. Direct methods transcribe the optimal control problem into a parameter optimization problem [4], while indirect methods use the analytical necessary conditions derived from the calculus of variations [5]. For reconfiguration problems with path constraints (for example, collision avoidance constraints) and/or terminal constraints (for example, final configuration constraints), indirect methods become inadequate as the solution of the two point boundary value problem (TPBVP) that constitutes the first-order necessary conditions for optimality gets quite difficult [3,5]. On the contrary, direct methods are more promising because the reconfiguration problem is directly transcribed into a parameter optimization problem, which can be solved by a well-known nonlinear programming (NLP) solver [2,3].

However, reconfiguration problems still post stringent challenges to direct methods, especially for clusters with a large number of satellites, in at least the following five aspects. First, the size and complexity of the reconfiguration problem increase dramatically with respect to the number of modules in the cluster, because for each satellite the history of independent variable (e.g. time) is discretized into finite points, where both states and decision variables (e.g. control) exist. Second, the objective of the reconfiguration problem may be non-differentiable, for example, objectives including the l_1-norm of control vectors. Thus, ordinary gradient methods are not applicable anymore. Third, there may be non-convex constraints, such as collision avoidance constraints and final configuration constraints, which are long-recognized difficulties for optimization problems. For large-scale reconfiguration problems, decomposition is a general approach to break the original problem into several much smaller subproblems. The fourth and fifth challenges are related to the decomposition of reconfiguration problems. Fourth, constraints of the reconfiguration problem may be non-separable, for example, collision avoidance constraints, which prevents the decomposition. Last but not the least, coupling commonly exists between subproblems which complicates the reconfiguration problem. There are two types of coupling: coupling variables such as final configuration constraints and coupling constraints such as collision avoidance constraints. Note that coupling may be convex or non-convex, separable or non-separable. Note also that reconfiguration problems with both coupling variables and coupling constraints are much more complicated than problems with only one of these.

The purpose of this paper is therefore to develop decentralized algorithms by taking into account previous challenges for reconfiguration problems of fractionated clusters, potentially with a large number of modules. This paper firstly presents an organizational architecture for the fractionated cluster. There are three layers within the organizational architecture, namely, the planner, allocator and local controllers. The planner belonging to the higher level layer decomposes abstract high-level goals into cooperative tasks that satisfy temporal and resources constraints. And then the allocator from the middleware layer assigns the generated tasks to each module, which in the end accomplishes the assigned tasks with the onboard controller that belongs to the lower level layer.

Within this organizational architecture, a decentralized framework is proposed to solve complex reconfiguration problems based on primal and dual decomposition. In this framework subgradient methods are adopted to include general reconfiguration cases with non-differentiable objectives. The reconfiguration problem is formulated as an optimal control problem, and then transcribed into an NLP based on a direct method. Two typical constraints are of great concern: final configuration constraints representing coupling variables and collision avoidance constraints representing coupling constraints, both of which are non-convex. Besides, collision avoidance constraints are non-separable. The linearization and convex restriction technology is employed to convexify all these constraints, and the collision avoidance constraints are approximated by affine constraints that are separable. Then the NLP problem becomes separable and convex, which are proper for primal and/or dual decomposition. After that, final configuration constraints are tackled by primal decomposition, while collision avoidance constraints by dual decomposition. To the end, multi-level primal and dual decompositions are employed to solve reconfiguration problems with both coupling variables and coupling constraints.

The remainder of this paper is organized as follows. In Section 2, the organizational architecture is presented with an introduction of both a software and hardware testbed. In Section 3, the propellant-optimal reconfiguration problem is formulated as an optimal control problem, where the final configuration constraints and collision avoidance constraints are defined, respectively. In Section 4, the optimal control problem is transcribed to an NLP. This is followed by the approximated transformation of the NLP to a separable convex optimization. In Section 5, primal decomposition is presented to treat the coupling variables in the final configuration constraints. In Section 6, dual decomposition is presented to tackle the collision avoidance constraints. In Section 7, the multi-level primal and dual decomposition is presented to solve reconfiguration problems with both final configuration constraints and collision avoidance constraints. Finally, conclusions are drawn.

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