JID:AESCTE AID:4575 /FLA [m5G; v1.236; Prn:29/05/2018; 9:59] P.1 (1-13)

Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Onboard mission allocation for multi-satellite system in limited communication environment

Zixuan Zheng, Jian Guo *, Eberhard Gill

Delft University of Technology, Netherlands

A R T I C L E I N F O

Article history:
Received 18 January 2018
Received in revised form 21 March 2018
Accepted 15 May 2018
Available online xxxx

Keywords:
Mission allocation problem
Multi-satellite system
Game theory
Negotiation mechanisms

A B S T R A C T

The purpose of this paper is to seek the suitable local objectives for each satellite to optimal the global mission allocation strategy with a global utility function. This paper uses a game-theoretical formulation for a multi-satellite system in which the satellites are viewed as a unique unit with their self-interests. To solve the problem, the first is to identify the utility functions for individual satellite, align them to form the global utility function which can represents the allocation requirements. The second is to design the suitable negotiation mechanisms that can be equipped on each satellite so they can pursue the optimization by their own interest. The Utility-based Regret play, the Smoke Signal play, and the Broadcast-based play are proposed as negotiation mechanisms for the team to cooperate under the distributed and decentralized system structure. The simulation results illustrate that using these mechanisms can help this multi-satellite system reaches a near-optimal allocation profile. The effectiveness of proposed mechanisms are demonstrated by comparing their simulation results with several existing mechanisms under different scale of participant number.

Abbreviations

MAS	Multi-agent System
MSS	Multi-satellite System
GPM	Global Precipitation Measurement
SBSS	Space-based Space Surveillance
MSMA	Multi-satellite Mission Allocation
MRTA	Multi-robot Task Allocation
WSN	Wireless Sensor Networks
UAV	Unmanned Aerial Vehicles
UGV	Unmanned Ground Vehicles
UUV	Unmanned Underwater Vehicles
MCTS	Monte Carlo Tree Search
GA	Genetic Algorithm
URP	Utility-based Regret Play
SSP	Smoke Signal Play
BBP	Broadcast-based Play
DSL	Discovering the Sky at the Longest Wavelengths mission
OBC	On-board Computer
ACL	Agent Communication Languages
KQML	Knowledge Query and Manipulation Language
FIPA	Foundation for Intelligent Physical Agents
UFP	Utility-based Fictitious Play
RMP	Regret Matching Play
P2P	Point-to-point
JADE	Java Agent DEvelopment Framework
AFP	Action-based Fictitious Play
RT	Respond Time
MBA	Market-based Auction

1. Introduction

As the rapid development of technology, many space applications that are impossible for a single satellite to achieve become feasible and attainable by using the Multi-satellite systems (MSS). A multi-satellite system consists of multiple satellites that interact in an area. They can either cooperate with others to accomplish a global goal, or they can be self-interested satellites to achieve their own goal through team negotiation. Each satellite in an MSS is considered as an agent, which acts autonomously, making decisions based on its knowledge. The objectives of these multi-satellite missions can be demonstration of technologies (Proba-3 [1], QB50 [2]), global precipitation estimation (Global Precipitation Measurement (GPM) Mission [3], TMPA [4]), Earth observation (GRACE [5]), ground surveillance (Space-based Space Surveillance (SBSS) [6]), etc. By using the MSS, these space missions are done in a more reliable, cheaper, and faster way compare with single satellite system. However, with the size growth for the MSS in

* Corresponding author.
E-mail addresses: Z.Zheng@tudelft.nl (Z. Zheng), J.Guo@tudelft.nl (J. Guo), E.K.A.Gill@tudelft.nl (E. Gill).

https://doi.org/10.1016/j.ast.2018.05.022
1270-9638/

Please cite this article in press as: Z. Zheng et al., Onboard mission allocation for multi-satellite system in limited communication environment, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.05.022

the future missions, the workload for ground operators is increasing for solving problems like the task allocation, group formation, cooperative object, fault detection and tracking. Therefore, employing onboard intelligence system is the future trend. Our research focused on how to enhance the onboard system of individual satellite so the entire MSS can automatically solve the Mission Allocation (MSMA) problems through negotiation and cooperation.

Many academic studies reviewed some problems are similar to the MSMA problems, such as the Multi-robot Task Allocation (MRTA) problem [7,8], the Wireless Sensor Networks (WSN) deployment problem [9,10], the resources allocation problem [11,12], the weapon-target assignment problem [13], and many other problems related to Unmanned Aerial Vehicles (UAV) [14], Unmanned Ground Vehicles (UGV), and Unmanned Underwater Vehicles (UUV). Three types of approaches have been used to solve previous problems. The *Centralized approaches* are most widely used approaches, which typically requires one central controller to determine the mission assignment for each team member. Semsar and Khorasani [15] proposed a centralized solution for a cooperative multi-UAV system by using the game theoretic approach, but their assumptions can be invalid if the main controller is damaged and unable to control the rest UAVs. Kartal and Nunes [16] introduced a centralized approach for MRTA uses the Monte Carlo Tree Search (MCTS), which can find near-optimal solutions for nontrivial problems. Although using this method can generalize well across data sets and provide guarantees, it requires more time compare to other methods. Jose and Pratihar [17] used a centralized Genetic Algorithm (GA) with greedy initialization function for task allocation in a multi-robot system. However, this study only concerned about three robots, once enlarge the number, the convergence time will increase exponentially. One unique kind of centralized approaches for task allocation problem is called centralized auction. Several auctioning mechanisms can be used for this approach, such as the greedy auction [18], or the combinatorial auction [19,20]. This approach do not require the central auctioneer to keep track the internal model of other members, but the utility computation of each participant still rely on the main controller. The centralized approaches have the main advantage of performing optimization based on the overall objective function, which leads to a solution to be optimal or near-optimal. However, the centralized approaches also suffer from several weaknesses. Firstly, centralized approaches are strongly depend on the main controller, which makes them vulnerable to this point of failure. Secondly, they require steady communication between the main controller and the participants, which brings limitations on communication hardware and the mission coverage field. Thirdly, the demand on computational power of the main controller is high.

Many of the centralized approaches have focused on the analysis of mission allocation problem under stable operating environment. However, in our study, the mission operation environment is in deep space. Some unpredictable situations may occur to every member of the system, where centralized approaches are unreliable under these scenarios. Therefore, the MSS needs to solve the problem through the *Distributed approaches* and *Decentralized approaches*. Kose [21] used the reinforcement learning approach for solving the self-interested robot collaboration problems, but due to the limited communication, the system could converge on a sub-optimal solution. Zheng and Koenig [22] proposed a K-swaps mechanism to help the distributed algorithms exchange assigned tasks among agents to reduce the team cost. However, it is difficult to find the suitable value for K which can provide good performance on team cost and the computation time. Lang and Fink [23] presented a quota-based negotiation mechanism for minimizing the total cost for a multi-machine scheduling problem. Later on in [24], they re-designed this mechanism by implement simulated annealing. Raffard, Tomlin, and Boyd [25] introduced an optimal distributed approach uses dual decomposition technique for a group of cooperative agents. However, the negotiation procedure can only start when entire team is willing to cooperate. This assumption is not suitable for our case since satellites cannot establish the communication link with others all the time. Jin and Li [26] proposed a k-winners-takes-all (k-WTA) negotiation mechanism for multiple robots system under limited communication environment. However, in real-world application, the single point failure on the winner could cause algorithm pause and go backward to perform k-WTA again. Choi [27] proposed two decentralized auction-based approaches, the consensus-based auction algorithm and consensus-based bundle algorithm for a fleet of autonomous mobile robots. Gao [28] proposed an evolutionary computation decentralized approach using the genetic algorithm for solving the MRTA problems. However, it is time consuming for all the agents agree to regret the current assignment if a task has been bid. The main advantage of the non-centralized approaches is the strong robustness that can tolerant the low level system failure. The limitation of these approaches lay on the message communication between agents, if communication links are not sufficiently reliable, the outcome may degrade.

Unlike centralized approaches, both distributed approaches and decentralized approaches require cooperation and negotiation between participant agents. The main difference between these two kinds approaches is the topology of the MAS. In our study, the topology of the MSS is flexible due to changeable baseline between satellites in the different phase of the mission. All non-centralized approaches mentioned before either cannot guarantee the short allocation time and high success rate at the same time, or the negotiation strategies are too complicated that consume too much onboard memory and power. For our space mission, simple and reliable mechanisms are needed for different topology. The main contribution of this paper is to propose three negotiation & cooperation mechanisms for MSS to accomplish onboard mission allocation problems. Targeting different topology the MSS may face, we introduce the Utility-based Regret Play (URP) mechanism for the distributed structure, the Smoke Signal Play (SSP) and the Broadcast-based Play (BBP) mechanisms are for the decentralized structure.

The remainder of this paper is organized as follows: Section 2 formulates the MSMA problem along with some details about the organizational structure and decision-making theory; Section 3 illustrates the proposed three mechanisms; Section 4 presents simulation results to illustrate the performance of these mechanisms for solving the MSMA problem under the different structure. Finally, Section 5 concludes this paper.

2. Multi-satellite Mission Allocation problem

The MSMA problem can be divided into three sub-problems. Firstly, how to decompose the global goal into several sub-goals. Secondly, how to construct the organizational architecture based on different mission requirements. Thirdly, how to assign the subgoals to each satellite through the negotiation and cooperation mechanisms. Solving a mission allocation problem is a dynamic decision making procedure. It should be solved iteratively over time considering the changes of self-status or mission environment. Thus, choosing the suitable problem model and organizational architecture can lead to a more precise solution.

2.1. Organizational structures

The organizational structure provides a framework for activities and interactions between participant agents through the definition of characters, authority relationships and communication links [29]. In principle, the topology of the MSS usually follows three