Intelligent Multi-Agent based Automated Negotiation of Mission Scheduling for Satellite Constellation

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Abstract

As the number of satellites increases, a new operation concept and technology for a satellite constellation is required, different from the existing one for a small number of satellites. And for efficient operation of a satellite constellation, automation and optimization of the mission operating system is essential. A satellite constellation composed of several dozen or more satellites revisits less than tens of minutes even if a single ground station is operated, so there are significant limitations for the operator to manually assign a mission to each satellite and create a mission schedule. In particular, unplanned missions, such as emergency missions, must be planned by analysing communication schedules for multiple satellites within a limited time. So, the mission planning system, not the operator, has no choice but to perform it automatically. This paper proposes an intelligent multi-agent based automated negotiation technique for mission scheduling that identifies optimally which satellite can perform the corresponding mission among satellite constellation in real time and suggest the modified optimal mission schedule when an emergency mission is given to the mission planning system. Based on the characteristics of intelligent multi-agents, each procedure and function related to the mission scheduling is given to each agent, and each agent shares and determines the newly assigned mission to derive the modified optimal mission schedule. The automated negotiation technique for mission scheduling of a satellite constellation based on intelligent multi-agent is expected to contribute to the efficient operation of a satellite constellation because it can modify the mission schedule of a satellite constellation composed of multiple satellites in real time and derive the optimal result.
Keywords: Multi-agent system, Satellite constellation, Mission scheduling, Emergency mission

1. Introduction

Earth orbiting satellites equipped with various sensors and communication repeaters are becoming increasingly important in fields such as education, science, the economy, environmental protection, disaster response, security, spatial information, and daily life[1]. Due to the development of satellite production technology and the decrease in cost, the number of companies planning commercial small satellite constellations and the field of satellite image data application are expanding, and the commercial market is expected to grow by 58% over the next 10 years[2]. Companies such as SpaceX and OneWeb, which are driving the Space 4.0 era, are actively working to operate Mega-Constellations with more than 100 to 1000 satellites, resulting in increased research into automation and optimization of mission operating systems[3]. One of the latest research fields related to the automation and optimization of mission operating systems is automated mission scheduling by applying the concept of an agent with a certain level of intelligence individually, unlike existing multi-satellite mission scheduling techniques that lack independent mission classification and processing[4].

Based on the above background, this paper proposes a method of automatically assigning the mission of a satellite constellation that operates multiple satellites by using an agent with appropriate intelligence. Through the automatic negotiation process between each agent, this paper proposed an automatic negotiation method for intelligent agent-based mission scheduling that identifies the optimal satellite capable of performing the mission and derives the optimal mission schedule. The contribution of this paper is as follows:

1) The proposed method prioritizes missions based on factors such as the target request time, target imaging time, and deadline, allowing for the automatic allocation of multiple missions to multiple satellites.
2) In case of an emergency mission request, the method analyzes the optimal satellite for mission execution and adjusts the overall mission schedule to accommodate the new mission.
3) The method has been implemented using a simulation tool designed using the JADE platform, considering future scalability.

The paper is structured as follows: Section II provides an overview of mission scheduling of constellations and multi-agent systems. Section III outlines the problem statement and architecture of the proposed method. Finally, section IV presents and analyzes the simulation results.

2. Background Introduction

2.1 Mission Scheduling of Constellation

The mission scheduling for a satellite constellation, composed of multiple satellites, presents complex challenges that differ from the mission scheduling of a single satellite. Mission scheduling for an existing single satellite is performed in consideration of the time aspect of the area where the mission is performed and the availability of various satellite resources. On the other hand, mission scheduling for satellite constellation additionally includes the problem of allocating missions to each satellite[4]. That is, even if the mission for each satellite is properly planned, it is difficult to say that it is optimal when viewed from the perspective of the satellites as a whole constellation. Optimization studies related to mission planning have been studied by applying various techniques such as Dynamic Programming, Branch and Bound, the Greedy Search, Simulated Annealing, Tabu Search, and Genetic Algorithm. However, most of the above studies have the disadvantage that they need to have a sufficient understanding of the entire system to implement the heuristic technique, modify the model even for small changes, and are not sufficient to solve the dynamic problem in which new constraints occur[5]. Recently, research on optimizing mission scheduling for a satellite constellation using Multi-Agent Systems has been actively conducted as a solution to these limitations.

2.2 Multi-Agent System

Agent is defined as a computational entity that can be viewed as perceiving and acting upon its environment and that is autonomous in that its behaviour at least partially depends on its own experience sometimes[6]. However, the definition of an agent varies depending on the researcher applying it. What they all have in common is that the agent recognizes its surroundings through its sensors and responds to its environment through actuators. Agents have a certain level of intelligence and react independently to their surroundings, resulting in characteristics such as autonomy, cooperation, honesty, adaptability, and scalability[7].

The intelligence level of Agent is largely divided into 4 types, as shown in Fig 1[8]. I_1 is the highest level of intelligence, performing system-level planning and interaction based on its knowledge of the entire system.

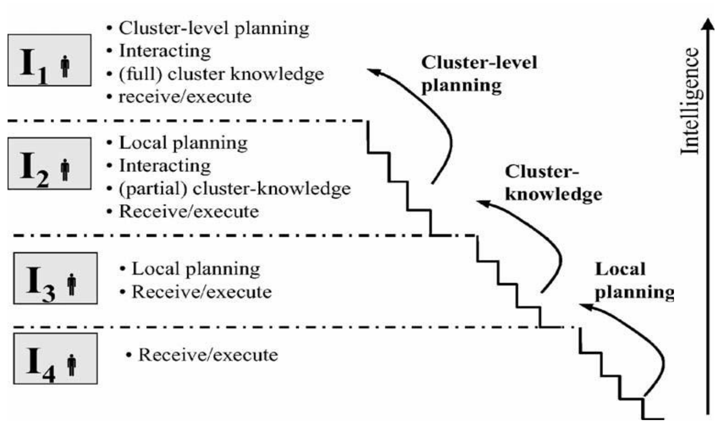

Fig. 1. Intelligence Level of Agent[8]

Conversely, I_4 is the lowest level of intelligence, simply repeating a given function. In addition, since each agent functions independently and interacts with other agents, various agent organization can be configured, as shown in Fig

2[8]. Since the characteristics of the system vary depending on the organization of the agent, it is necessary to select the organization by considering time, resources, and information exchange.

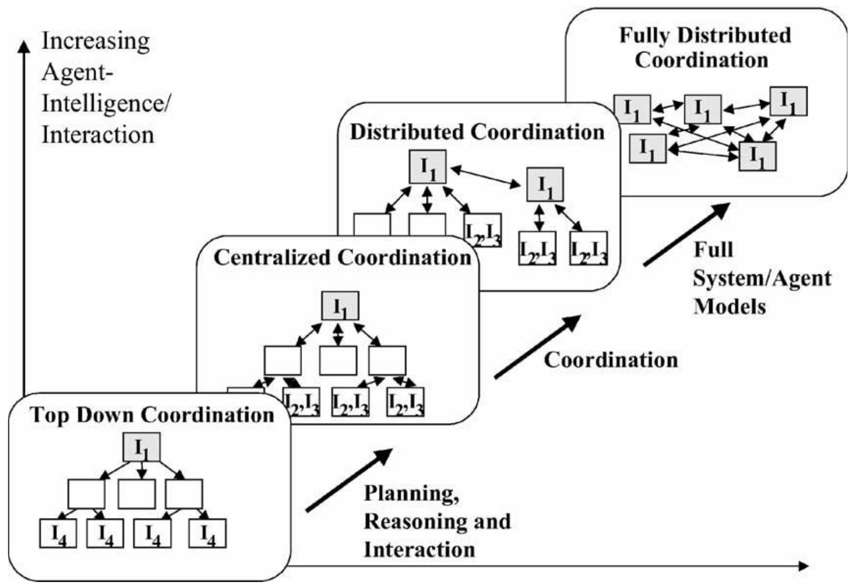

Fig. 2. Organization of Agent[8]

2.3 JADE(Java Agent Development Framework)

Since the concept of Agent was first introduced in the 1980s, it has continued to develop, and the early 1990s, the framework for Agent has been developed. In the late 1990s, Agent Communication Language(ACL) was developed as a standard for communication between agents and is applied to most agent frameworks[9].

As the field of agent technology progressed, various agent frameworks were developed. In this paper, the Java-based JADE was used because it is easy to implement, provides various functions, and is open source. JADE is one of the most used agent-oriented middleware today. It is a completely distributed middleware system with a flexible infrastructure that allows for easy extension through add-on modules. Additionally it fully complies with the FIPA specifications and includes both white pages and yellow pages, which act as database, as well as a set of graphical tools for supporting programmers, and so on[10]. Fig 3 shows the architecture of JADE

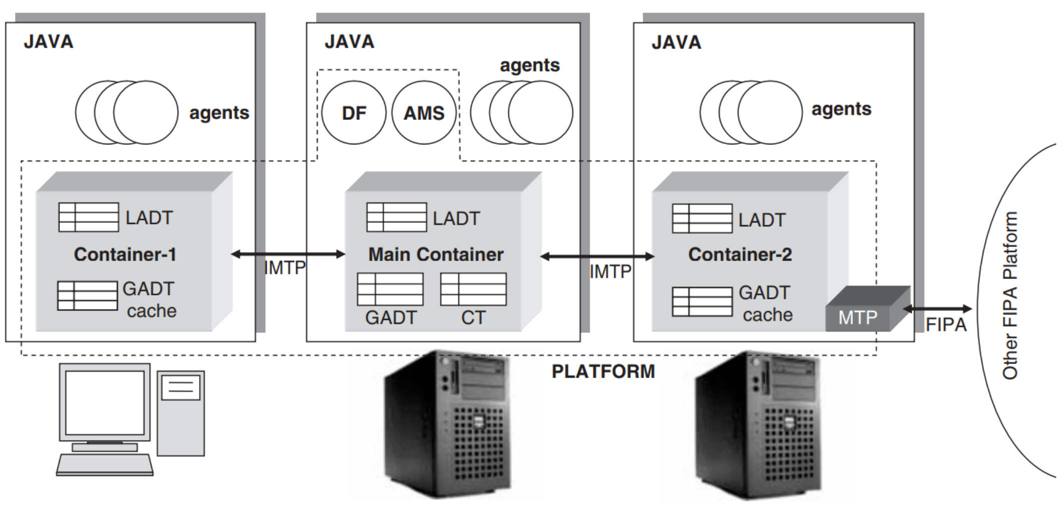

Fig. 3. Architecture of JADE[10]

3. System Description

3.1 Problem Statement

In this paper, a scenario is considered where a MCE(Mission Control Element) manages multiple targets to perform missions and multiple satellites that perform the same function. The mission assigned to the satellite considers the user requesting the target and the degree of urgency to receive the target result.

In this scenario, each target includes a mission request time, a priority index, and a deadline index. he priority index, which is assigned based on the requesting agency, is used to determine the priority for allocating the target. For instance, a government agency operating the satellite would have a higher priority compared to others and therefore, their requests would need to be fulfilled first. The deadline index is a constraint on the time available to complete the mission for each target and it must be completed before the specified time.

The MCE sequentially allocates the multiple targets to the multiple satellites in operation, taking into account the priority and deadline information. Each satellite checks if imaging for the target is possible and if so, calculates the target priority based on the priority index and deadline index and transmits it back to the MCE. The MCE then performs automatic negotiation based on the target priority of each satellite, selects the most suitable satellite to image the target, and allocates the mission. The satellite assigned the mission confirms that it does not overlap with existing missions before finally accepting the mission.

3.2 Automated Negotiation

Negotiation is a decision-making process in which two or more parties come together to find a solution that can meet their common goal. Automated negotiation refers to the process in which this function is performed by a single computer or a network of computers, without human intervention[11].

In this paper, the Kasbah System's buyer negotiation strategy parameters were used to determine the priority, which was used as a value criterion for negotiation[12, 13]. The priority was determined by considering various factors such as the requesting agency, the time of target request, the time of imaging, and the deadline for imaging the target. The priority was divided into three types: Linear Priority, where the priority increases in direct proportion, Root Priority, where the priority starts high but has a fixed upper limit of under 100, and Square Priority, where the priority initially increases slowly but then rapidly rises after a certain period. The variable used to increase priority was based on the target request time, imaging time, and deadline. It represents how much time is left for imaging considering the entire time period from target request to the deadline, with a higher value for the variable as the imaging time gets closer to the deadline. The negotiation function for each priority parameter is shown in Equation (1).

$$\text{(Root Priority)} \quad f(x) = (3/4)\sqrt{x} \times 100$$
$$\text{(Linear Priority)} \quad f(x) = x \times 100$$
$$\text{(Square Priority)} \quad f(x) = (4/3\, x)^2 \times 100$$

$$x = \left(T_{Image} - T_{Request}\right) / \left(T_{Deadline} - T_{Request}\right)$$

T_{Image} : Imaging Time of Target (Julian Date)
$T_{Request}$: Request Time of Target (Julian Date)
$T_{Deadline}$: Deadline of Target (Julian Date) (1)

3.3 Agents Organization

The overall composition of the system described in this paper consists of two types of agents: the MCE Agent and the Satellite Agent. The number of Satellite Agents can be determined based on the number of satellites required by the system. The MCE Agent monitors the created Satellite Agents and allocates the mission through interaction with each individual Satellite Agent. This composition is similar to the Contract Net Protocol (CNP), but the functions of each agent are implemented in a self-sufficient manner for future scalability.

First, the MCE Agent manages the entire system target list and mission plan with I_1 level intelligence. It requests the priority of the target to all Satellite Agents, compares the received priorities, and allocates the mission to the Satellite Agent with the highest priority. After receiving the mission allocation confirmation from the Satellite Agent, it reviews the next target. The Satellite Agent has I_3 level intelligence, calculate the priority of the received target from the MCE Agent, and when they receive a mission allocation request, they compare it to their existing mission and decide whether to accept the mission. The MCE Agent and Satellite Agents are composed of a Distributed Organization, and each Satellite Agent operates independently and performs its functions autonomously.

Two types of messages are exchanged between the MCE Agent and the Satellite Agent. The first is the Target Message, which the MCE Agent initially delivers to the Satellite Agent. The Target Message includes the target ID, the target request time, the target location (Lat/Lon), the priority index, and the deadline index, as shown in Table 1.

The second type is the Reply Message, which the Satellite Agent delivers to the MCE Agent. As shown in Table 2, the Reply Message includes the corresponding Satellite Agent ID, the imaging time of the target, the calculated priority, and the Allocation Result, in addition to the Target Message. The Allocation Result is divided into 5 types. When the priority of the target is requested, the possibility of performing the mission can be displayed as 'Possible' or 'No Access Found'. And when a mission allocation request is received, it can indicate whether it has accepted the mission by 'Accept', return the existing mission by 'Target ID', or reject the mission by 'Reject'. The MCE Agent manages missions based on the Allocation Result information contained in the Reply Messages received from the Satellite Agent. The composition of each agent is shown in Figure 4.

Table 1. Example of Target Message

Target ID	Request Time	Latitude	Longitude	Priority Index*	Deadline Index**
target1	1 Jan 2023 00:00:00.000	-11.074512	-141.132496	3	1
target2	1 Jan 2023 00:00:00.000	23.923244	34.339826	2	2
target3	1 Jan 2023 00:00:00.000	26.389176	-23.311201	1	3
:	:	:	:	:	:

* Priority Index : (1) Root Priority / (2) Linear Priority / (3) Square Priority
** Deadline Index : (1) up to 1 Day / (2) up to 3 Days / (3) up to 7 Days

Table 2. Example of Reply Message

Target Message	Reply SAT ID	Imaging Time	Priority	Allocation Result*
target1 ~~	SAT2	1 Jan 2023 09:00:30.378	17.367262855435543	Possible
target2 ~~	SAT3	0 000 0000 00:00:00.000	0	No Access Found
target3 ~~	SAT1	1 Jan 2023 17:17:30.484	24.061723858013757	Accept
target4 ~~	SAT2	1 Jan 2023 17:17:30.484	80.524685592311457	Target27
target5 ~~	SAT3	0 000 0000 00:00:00.000	0	Reject
:	:	:	:	:

* Possible : Possible to accept (Possible to imaging)
No Access Found : No Access Time to target (Impossible to imaging)
Accept : Accept Mission without any Modify
Target# : Accept Mission but Return Existing Mission of Target#
Reject : Cannot Accept Mission(No Access Time or Lower Priority than Existing Mission)

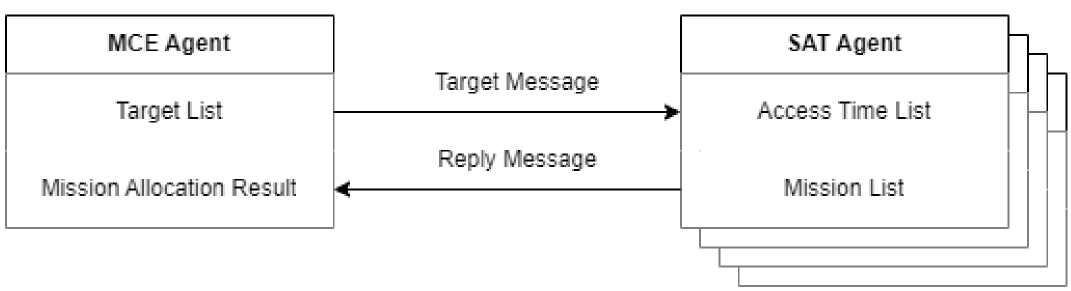

Fig. 4. Relationship between Agents

3.4 Overall Architecture

The overall architecture is shown in Figure 5. The process starts with the MCE Agent checking the target list and converting it into Target Messages which are then sent to all Satellite Agents. Each Satellite Agent checks the access time for the target in the Target Message. If there is an access time, the priority is calculated using the request time and deadline included in the Target Message, and a Reply Message is created including the "Possible" Allocation Result. If there is no access time, a Reply Message is created including the "No Access Found" Allocation Result. The MCE Agent then compares the priorities included in the Reply Messages received from each Satellite Agent and selects the Satellite Agent that sent the highest priority. The MCE Agent then sends a mission allocation request to the selected

Satellite Agent. If all the Reply Messages from the Satellite Agents include the "No Access Found" Allocation Result, the Target Message for the next target is sent to all Satellite Agents.

Upon receiving the mission allocation request, the Satellite Agent checks whether the imaging time overlaps with any existing mission. If there is no existing mission or the imaging time does not overlap, the mission is accepted and the result is replied to the MCE Agent by including the "Accept" Allocation Result in the Reply Message. Overlap of imaging time was determined based on a 30-minute interval.

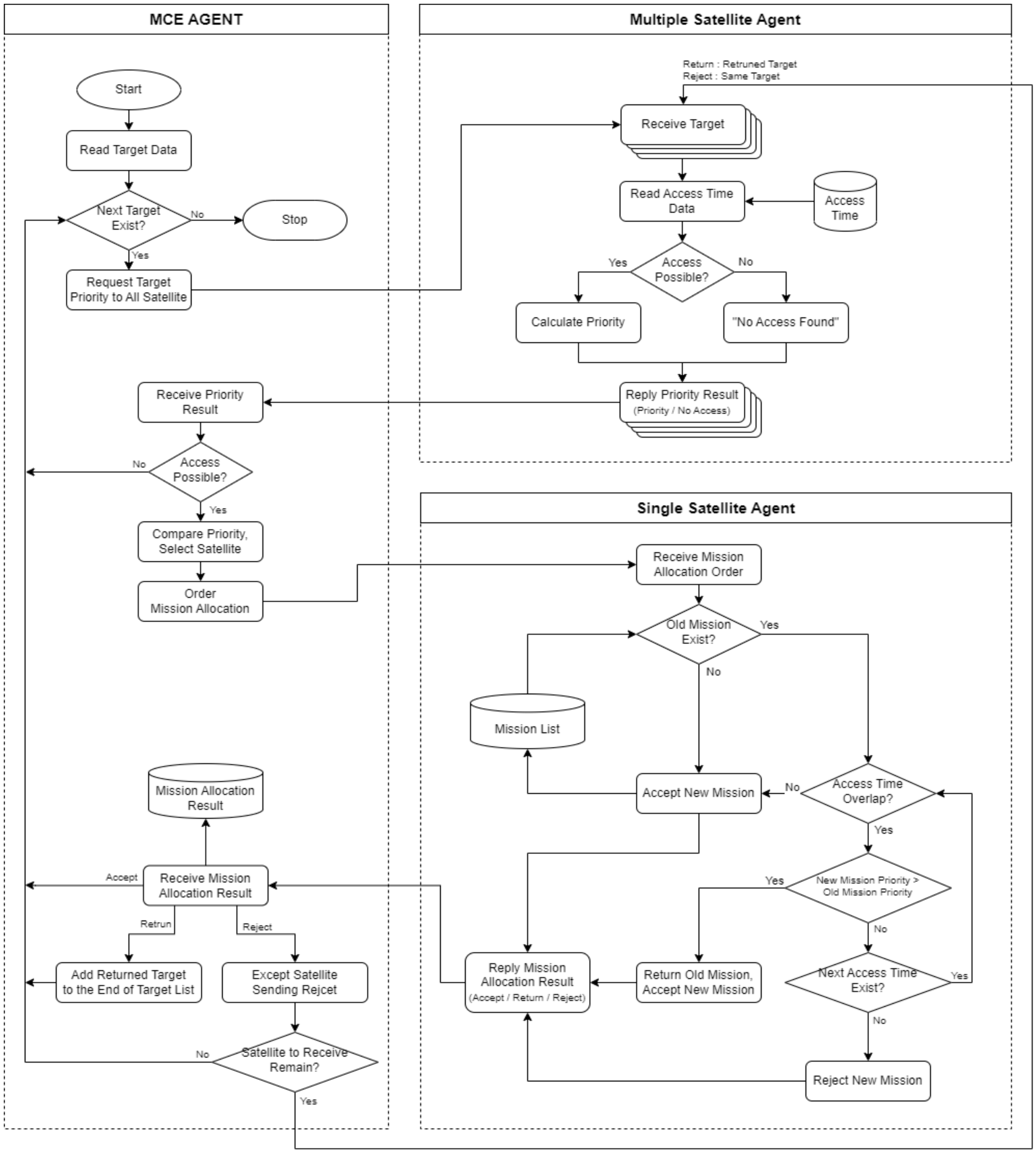

Fig. 5. Overall Architecture

However, if the imaging time does overlap with an existing mission, the priorities of the two missions are compared. If the priority of the existing mission is low, the new mission is accepted, and the existing mission is returned to the MCE Agent. The Reply Message includes the target ID of the existing mission and is forwarded to the MCE Agent.

The MCE Agent adds the returned target to the end of the target list and starts the allocation process for the next target. If the priority of the existing mission is high, the existing mission is maintained, and the next access time of the target requested for allocation is checked. This process is repeated to determine if the imaging time overlaps and to compare priorities. If the next access time does not exist, the Reply Message includes the "Reject" Allocation Result and is forwarded to the MCE Agent. Upon receiving the "Reject" Allocation Result, the MCE Agent transfers the rejected mission(target) to the remaining Satellite Agents except for the one that sent the corresponding Reply Message and restarts the mission allocation process.

When all of the above procedures are completed, the mission allocation procedure for the next target starts, and when the mission allocation for all targets in the target list is completed, the entire process is finished.

4. Simulation Results

4.1 Design of Simulation

In order to verify the results of automated negotiation between agents, a satellite constellation consisting of 3 satellites was set up, as shown in Table 3. Each satellite assumed to be located at a 600km altitude, and had a RAAN(Right Ascension of Ascending Node) spaced equally at 120° intervals. All satellites were equipped with a SAR(Synthetic Aperture Radar) payload, and the incidence angle of the SAR was the same as that of a typical SAR satellite.

Table 3. The Orbit Parameter of Satellites

SAT ID	Altitude (km)	Eccentricity	Inclination (°)	RAAN (°)	Payload (Incidence Angle, °)
SAT 1	600	0	45	0	SAR (20 ~ 55)
SAT 2	600	0	45	120	SAR (20 ~ 55)
SAT 3	600	0	45	240	SAR (20 ~ 55)

A total of 1,000 targets were selected as shown in Table 4. It was assumed that all requests were made at the same time, and Latitude, Longitude, Priority Index, and Deadline Index were all randomly assigned. Target 1001 is a target that assumes an emergency mission and was not used at the time of initial allocation.

Table 4. Target List

Target ID	Request Time	Latitude	Longitude	Priority Index	Deadline Index
target1	1 Jan 2023 00:00:00.000	-11.074512	-141.132496	3	3
target2	1 Jan 2023 00:00:00.000	23.923244	34.339826	3	3
target3	1 Jan 2023 00:00:00.000	26.389176	-23.311201	3	1
target4	1 Jan 2023 00:00:00.000	34.658768	167.369562	3	1
target5	1 Jan 2023 00:00:00.000	18.319851	-40.499360	1	1
:	:	:	:	:	:
:	:	:	:	:	:
target996	1 Jan 2023 00:00:00.000	-26.995669	52.581975	1	1
target997	1 Jan 2023 00:00:00.000	-1.815879	114.362055	2	1
target998	1 Jan 2023 00:00:00.000	38.992357	55.856634	1	3
target999	1 Jan 2023 00:00:00.000	-9.792124	165.260570	3	2
target1000	1 Jan 2023 00:00:00.000	41.561309	132.744933	2	3
target1001*	1 Jan 2023 12:00:00.000	38.9481	126.943	0	1

* target1001 : Emergency Target (Priority Index of ‘0’ means that the Priority has 30 points more)

The simulation was divided into two parts. Initially, 1,000 targets were allocated to each satellite as missions. After the mission allocation, emergency target was additionally requested. It was reviewed whether the mission was allocated to an appropriate satellite and whether the previously allocated mission was appropriately modified. The computing parameters are Intel Core i7-11700 processor 2.50 GHz CPU and 32 GB RAM memory configuration.

4.2 Result and Analyse

(a) Initial Mission Allocation

The initial mission assignment results for 1,000 targets are shown in Tables 5 and 6. Table 5 presents only a few examples, but it shows that all missions were considered. Table 6 lists only some examples of missions allocated to SAT1, but the imaging time of each mission were allocated without overlap. The results indicate that the missions were accepted, returned or rejected appropriately based on priority and access time, as per the planned algorithm.

Table 5. Initial Mission Allocation Result (MCE Agent)

Target ID	Allocated SAT	Imaging Time	Priority	Allocation Result
target1	SAT3	7 Jan 2023 15:48:28.358	73.14854869	target913 Returned
target2	SAT2	6 Jan 2023 22:52:13.166	69.16360744	Accept
target3	SAT1	1 Jan 2023 03:47:50.203	29.83265284	target613 Returned
target4	SAT2	1 Jan 2023 00:03:58.398	3.939632216	target50 Returned
target5	SAT2	1 Jan 2023 04:22:04.618	32.35518105	target3 Returned
target6	SAT1	7 Jan 2023 15:49:53.143	73.15393855	target148 Returned
:	:	:	:	:
target995	SAT3	3 Jan 2023 18:27:25.318	92.30143442	target777 Returned
target996	SAT1	1 Jan 2023 11:03:39.040	81.93218104	target274 Returned
target997	-	-	-	Reject
target998	SAT1	4 Jan 2023 15:09:16.960	92.22720753	target744 Returned
target999	-	-	-	Reject
target1000	SAT1	6 Jan 2023 08:59:12.105	76.77779514	target714 Returned

Table 6. Initial Mission Allocation Result (SAT1 Agent, Total number of missions : 226)

Target ID	Allocated SAT	Imaging Time	Priority	Allocation Result
target861	SAT1	1 Jan 2023 00:29:23.684	10.71555776	target311 Returned
target242	SAT1	1 Jan 2023 01:04:55.599	15.92544272	target662/target954 Returned
target870	SAT1	1 Jan 2023 01:37:44.586	19.53993309	target932 Returned
target440	SAT1	1 Jan 2023 02:33:07.557	24.45706938	target315 Returned
:	:	:	:	:
target587	SAT1	7 Jan 2023 21:11:48.419	74.37164977	target420 Returned
target435	SAT1	7 Jan 2023 21:45:37.947	74.49844366	target721 Returned
target134	SAT1	7 Jan 2023 22:28:54.359	74.66033944	Accept
target913	SAT1	7 Jan 2023 23:13:15.535	74.82590999	target721 Returned

Table 7 shows summary of initial mission allocation result. 665 out of a total of 1,000 targets were assigned. In the process, 29,716 messages were transferred, and the total calculation time was 641.718 seconds. Missions not allocated to satellites could be identified in two ways. First, when the priority index and deadline index are low, the urgency of mission execution is low. And second, when many missions are concentrated in a short period of time, they are eliminated from the priority comparison. Therefore, it can be verified that the algorithm proposed in this paper considers both the target's priority and deadline to allocating missions.

Table 7. Summary of Initial Mission Allocation Result

Number of Satellites	Total Target	Allocated Mission	Message Transferred	Calculation Time (sec)
3	1,000	665	29,716	641.718

(b) Emergency Mission Allocation

The results of emergency mission allocation are shown in Tables 8 and 9. The emergency missions are allocated immediately because they have a higher priority than any existing missions. However, since emergency missions are allocated during a period when many missions are already concentrated, modification of the existing missions is inevitable. The results show that the existing missions were modified in the same way as the initial mission allocation process, considering both the priority and deadline of each target. Some existing missions were inevitably excluded in this process, and examining the target priority of the excluded missions reveals that they are lower than the non-excluded targets, indicating that the best choice was made in allocating the emergency mission.

Table 8. Emergency Mission Allocation Result

Target ID	Allocated SAT (From → To)	Imaging Time	Priority	Allocation Result
target1001	***SAT2***	2 Jan 2023 01:46:46.907	132.0718250	target136, target403 Returned
target136	SAT2 → ***SAT2****	3 Jan 2023 00:29:53.303	119.7484931	target892 Returned
target892	SAT2 → ***Reject***	-	-	Reject
target403	SAT2 → ***SAT2****	3 Jan 2023 01:38:34.226	122.574915	target553 Returned
target553	SAT2 → ***SAT3***	3 Jan 2023 09:15:23.561	79.52297878	target34 Returned
target34	SAT3 → ***SAT1***	3 Jan 2023 18:13:57.070	91.98961034	target20 Returned
target20	SAT1 → ***Reject***	-	-	Reject

* Imaging time is changed

Table 9. Summary of Emergency Mission Allocation Result

Number of Satellites	Total Target	Message Transferred	Number of Mission Modification	Calculation Time (sec)
3	1,001	81	6	1.082

5. Conclusion

Due to the development of satellite manufacturing technology and the decrease in cost, the number of satellites put into space will increase exponentially. In particular, in terms of the efficiency of mission operation and the increased applicability of satellite information, it is expected that there will be more cases of configuring Mega Constellations such as SpaceX and OneWeb or integrated operating existing satellites. In this case, automation and optimization of the mission operation system are essential because more considerations must be reflected in the manner of satellite mission planning.

In conclusion, this paper proposed an intelligent multi-agent based automated negotiation system for mission scheduling in order to effectively allocate missions to multiple satellites without human intervention. The proposed system considers the request time, imaging time, and deadline of targets, and calculates their priority, using which the satellites perform their mission plans through automated negotiation. The results of the simulation confirmed that the system effectively calculates the priority of targets, determines whether to replace existing missions, and allocates new missions as expected. For emergency missions, it was confirmed that the existing missions were modified and allocated as planned. In addition, the use of the agent concept established a foundation for realizing a mission plan that is closer to reality, taking advantage of the characteristics of agents such as independence and scalability.

In the future, it is expected that a more realistic multi-satellite mission planning method will be developed if the available resources of satellites, such as memory and power consumption, ground station communication schedules, weather conditions, and payload diversification, which were not considered in this paper, are implemented and considered as agents.

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