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Agile mission optimization for a constellation of earth observation satellites

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Abstract. Today's Earth Observation Satellites (EOSs) have complicated missions with an agility capability. For this reason, a great importance for satellite mission optimization problem has been arisen. In this paper, a multi-objective equation has been formulated which contains three selected objectives (Gain, image quality and time execution). There are three constraints (Target exclusiveness, due date and transition time) which have been selected and presented by three equations. Satellite Tool Kit (STK) has been used to simulate the relation between satellites and customers' targets. The output opportunities from STK have been saved in an excel sheet and they will be used as inputs for our problem. Genetic Algorithm (GA) has been used as one of the optimization techniques to solve this problem and it has been applied by using Matlab program and its graphical user interface. The result from solving our problem is a plan which contains selected targets numbers, satellite numbers, target's gain, shooting time, combined angle, target's objective function value and the total objective function value. In this paper, a case study has been presented assuming there is a constellation of four (4) satellites (Superview constellation), thirteen (13) random targets and the required output is an optimum daily plan for shooting.

1. Introduction

Thousands of satellites have been operated, since the first satellite had been launched 62 years ago. The technologies of mission control system for satellite have been also developed, with an expectation of high complicated missions. Today's earth observation satellites have complicated missions with an agility capability. Mission planning and scheduling problem of earth observation satellite has been discussed in many papers. Each paper has its own specific conditions. These conditions include types of satellite's operation (imaging, downloading or both) [1], maneuverability of satellites (not agile or agile) [2,3], number of tasks (single or multi) [2], number of satellites (single or constellation) [4,5], and number of ground stations (single or multi) [5,6].

There are many objectives, related to EOSs mission optimization problem, which have been discussed in many papers. Such as maximizing the total amount of downloaded data [6], the profits of the scheduled targets [7,8], the total priority of selected targets [9,10], the profit of satellite [4,11], the quality values [12], the observation income and completing dynamic tasks as many as possible [13,14]. From all previous objectives, gain, image quality and time execution have been selected to be



determined and summed in one equation. This multi-objective equation has been formulated using weighted sum method and normalization.

There are many constraints which have been discussed in many researches such as energy [5,6], capacity [7,15], data buffer limits, time of each interval [5,6], target exclusiveness [7,10], due date [16] and transition time for consecutive targets [15,17]. From all previous constraints, target exclusiveness, due date and transition time have been selected to be determined in our problem.

STK has been used as an orbit propagator to simulate the relation between satellites and customers' targets. The STK output report contains shooting opportunities (satellites shooting times and satellites shooting combined angles) which have been saved in an excel sheet and they will be used as inputs for our problem.

There are many optimization techniques which have been used for solving EOSs mission optimization problem for agile earth observation satellites such as GA, Dynamic Programming (DP), Ant Colony Optimization (ACO)...etc. GA has been used in this paper. Matlab program and its graphical user interface have been used as a tool for applying genetic algorithm optimization technique.

The next section contains a detailed explanation for satellite mission scheduling. Section 3 determines scheduling scenario including customers, orbit propagator (STK), objectives, constraints, model structure and output plan sequentially. At section 4, our case study will have a detailed explanation. At section 5, results will be discussed.

2. Satellite mission scheduling

In general, the meaning of mission scheduling is to make a plan contains a timetable to perform requested missions from users or customers. Distribution of the limited resources which can manage the tasks can be applied by mathematical techniques or heuristic algorithms. Proper distribution of resources is a very important factor to achieve mission operations goals successfully. The example of scheduling problem with each task and resource is shown in table 1 [18].

Table 1. Examples of scheduling problem

	Missions (Tasks)	Resources
Airport	Landing and Takeoff of planes	Runway
Satellite	Taking images	Memory, Power, Agility

In the field of satellites missions operations, the scheduling problem is to generate a conflict-free mission timeline, which contains tasks to be operated by each satellite. The scheduling process can be summarized as follows:

1. Making a schedule for each satellite to execute tasks in a regular sequence.
2. Arranging tasks for each satellite not to conflict with each other.
3. Making an optimized plan with the given objectives and constraints.

In this work, a multi-objective equation has been formulated with three chosen objectives (Gain, image quality and time execution), three constraints (target exclusiveness, due date and transition time) have been taken in consideration, the mission optimization problem has been solved and an optimized plan has been resulted to satisfy customers.

3. Scheduling scenario

The mission scheduling scenario can be explained by the following sections:

3.1. Customers

Each customer prepares its own requests for shooting with specific conditions. Each request may contain one or more spot target.

3.2. Orbit propagator

Satellite Tool Kit (STK) will be used to simulate and get access windows (Number of access time and shooting start time), target name and shooting combined angles between each satellite and each target as shown in figure 1.

Abu_Zenima-To-02 Combined angle				
Target	Access	Start Time (UTC)	Stop Time (UTC)	Duration (sec)
	1	15 Sep 2018 09:02:24.754	15 Sep 2018 09:02:29.238	4.483
Global Statistics				
Min Duration	1	15 Sep 2018 09:02:24.754	15 Sep 2018 09:02:29.238	4.483
Max Duration	1	15 Sep 2018 09:02:24.754	15 Sep 2018 09:02:29.238	4.483
Mean Duration				4.483
Total Duration				4.483

Abu_Zenima-To-03 Combined angle				
Target	Access	Start Time (UTC)	Stop Time (UTC)	Duration (sec)
	1	15 Sep 2018 09:02:23.286	15 Sep 2018 09:02:30.702	7.416
Global Statistics				
Min Duration	1	15 Sep 2018 09:02:23.286	15 Sep 2018 09:02:30.702	7.416
Max Duration	1	15 Sep 2018 09:02:23.286	15 Sep 2018 09:02:30.702	7.416
Mean Duration				7.416
Total Duration				7.416

Figure 1. An example of STK access report

3.3. Objectives

We considered three objectives in our case. These objectives are gain, image quality and time execution.

3.3.1. *Gain objective.* It means getting the maximum gain for each selected request. This doesn't mean that the selected requests have the absolute maximum gain but have the highest gain among the requests that have the opportunity to be included in the plan. This objective has been expressed as profit or quality which transfers to money for commercial companies [3,7].

3.3.2. *Image quality objective.* It means getting the best resolution from all requests opportunities. This means that the plan will include the feasible requests that can be shot at the minimum combined angles to increase the image quality [2].

3.3.3. *Time execution objective.* It means shooting requests as soon as possible. This means that the plan will include the feasible requests that can be shot at the nearest time by any of the constellation's satellites [16].

All these objectives have been chosen because they are common in most of commercial companies which use their constellations of satellites such as Airbus Company, China's commercial aerospace companies and European Space Agency. All these objectives have been summed together in one equation using the weighted sum method and normalization formulating a multi-objective equation. Equation (1) shows the multi-objective equation.

$$\text{Minimize } [\sum_{i=1}^n \sum_{m=1}^k \omega_T \cdot t_{im} \cdot X_{im} + \sum_{i=1}^n \sum_{m=1}^k \omega_Q \cdot \theta_{im} \cdot X_{im} - \sum_{i=1}^n \sum_{m=1}^k \omega_G \cdot G_i \cdot X_{im}] \quad (1)$$

where:

T : The set of targets. $\{T_1, T_2, \dots \dots T_n\}$
 Sat : The set of satellites $\{Sat_1, Sat_2, \dots \dots Sat_k\}$

For each target $T_i \in T$

1. n : The number of targets. $i \in [1, 2 \dots n]$
2. G_i : The gain for each target (Priority, Urgency, Cost ...etc.)

For each satellite $Sat_m \in Sat$

k : The satellites' number. $m \in [1, 2 \dots k]$

Decision Variables

$$X_{im} = \begin{cases} 1, & \text{If the target } T_i \text{ is scheduled to } Sat_m \\ 0, & \text{Otherwise} \end{cases}$$

ω_T : The weight of the execution time objective

ω_Q : The weight of the image quality objective

ω_G : The weight of the gain objective

3.4. Constraints

There are three constraints in our case. These constraints are request exclusiveness, request due date and transition time.

3.4.1. Target exclusiveness constraint. It means shooting any request just once as shown in equation (2). This constraint is very important for reserving satellites resources [7].

3.4.2. Request due date constraint. It means shooting time for each request doesn't exceed its due date as shown in equation (3). This constraint is very important for customer who has our priority and interest [16].

3.4.3. Transition time constraint. It means the time between each two consecutively selected targets doesn't conflict with the agility of the shooting satellite as shown in equation (4). This constraint has an important relation between target and satellite agility [16].

$$\forall i \in [1, 2, \dots n], \sum_{m=1}^k X_{im} \leq 1 \quad (2)$$

$$\forall X_{im} = 1, t_{im} \cdot X_{im} \leq Dead_{T_i} \quad (3)$$

$$\forall X_{im} = 1, t_{im} \cdot X_{im} + D_{im} + M_{ij_m} \leq t_{jm} \cdot X_{jm} \quad (4)$$

where:

$Dead_{T_i}$: The dead time for target T_i

Decision Variables

$$X_{jm} = \begin{cases} 1, & \text{If the target } T_j \text{ is scheduled to } Sat_m \\ 0, & \text{Otherwise} \end{cases}$$

For two consecutive targets i and j

1. θ_{im} : The combined angle for shooting target T_i by Sat_m
2. t_{im} : The shooting time for target T_i by Sat_m
3. t_{jm} : The shooting time for target T_j by Sat_m

4. D_{im} : The duration for shooting target T_i by Sat_m
5. M_{ijm} : The transition between consecutive targets T_i and T_j by Sat_m

3.5. Model structure

Genetic algorithm is being applied by using MATLAB program. The default main GA parameters are being used. Such as, population type (Double Vector), population size (50), scaling function (Rank), selection function (Stochastic Uniform), crossover fraction (0.8), mutation function (Constraint Dependent), crossover function (Constraint Dependent) and migration fraction (0.2). There will be an input data for our model such as customers' requests, access windows times, shooting combined angles, requests priorities and due date for each request. The objectives and constraints are included in our model. The architecture of our model describes that we receive inputs from customers which refers to requests that may be one spot target or more, then those spot targets and our constellation satellites and planning horizon get in the STK, the output from STK contains the spot targets shooting opportunities, these opportunities enters the satellites mission scheduling system which apply genetic algorithm, objectives and constrains to them and the output is an optimized plan for shooting targets satisfying our customers. Figure 2 shows the satellites mission scheduling architecture system for our model.

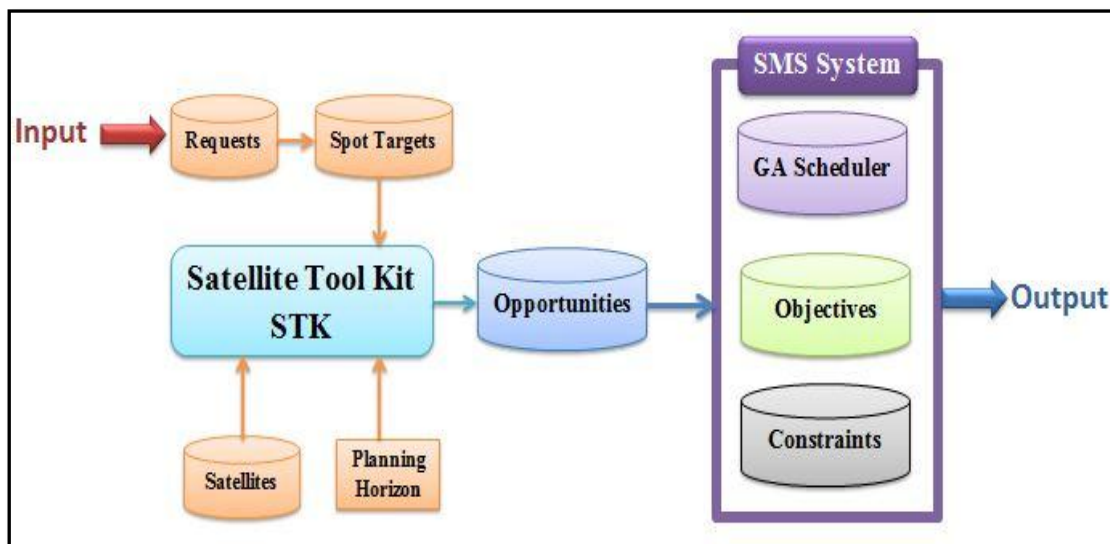


Figure 2. Satellites Mission Scheduling System Architecture

The workflow for our model can be described as follows:

1. Receive the input requests while each request contains one or more spot target. The spot targets appear in a table in section 4 containing the spot target name, Location, Gain and Validity date. The gain refers the priority for each target and it has four levels as level (1) refers to the standard request, level (2) refers to the priority request, level (3) refers to the high priority request and level (4) refers to the urgent request. Each priority level has its own credit that refers to money. The validity date is considered an important constraint for me as shooting the request after that date has no meaning or benefit for the customer. The spot targets have been chosen randomly just for explaining the algorithm.

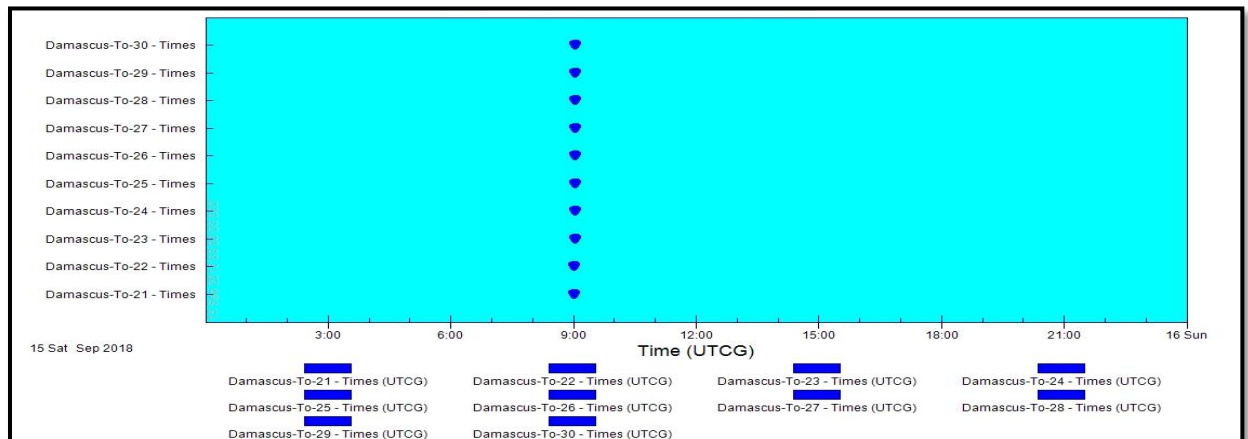


Figure 3. An example of STK graph access report

2. STK will calculate the access times between each satellite from the constellation and all targets. Figure 3 represents an example of STK graph access report, shows that approximately at 9:00 UTC, Damascus can be shot by this satellite with different combined angles (From 21° to 30°).
3. The output report of STK (access times and combined angles) will be saved as excel sheet and the proposed system will read the data in that excel sheet automatically. The data will be taken as inputs for the proposed system beside other inputs.
4. The weight for each objective will be chosen according to decision maker depending on the previous experience.
5. The inputs data will be entered to the proposed system.
6. The proposed system will run getting the daily output plan for shooting.

3.6. Output plan

The output from our model is an optimized plan which satisfies customers and saves satellites resources. This optimized plan contains the target number, the satellite number, the target gain, the shooting time, the combined angle, the result (the fitness value at each target with its parameters) and the objective function value for all chosen targets.

4. Case study

Our case study is a one day planning horizon (from 15/9/2018 at 00:00:00 to 16/9/2018 at 00:00:00) with a Superview constellation and (13) random spot targets. This constellation consists of (4) Chinese satellites (superview_1, superview_2, superview_3 and superview_4). Each one is inclined by 97.6° at 530 Km height. Parameters of customers' requests are collected together as shown in Table 2. The weight factors for each objective in our case study are $\omega_T=0.2$, $\omega_Q=0.3$ and $\omega_G=0.5$. The decision maker has a great experience so the gain weight seems to be the greatest one as the gain importance as it refers to money.

Figure 4 and figure 5 show the locations of the (13) targets. They are distributed but not scattered.

The input data will be entered as shown in figure 6. Gain and dead time will be entered for each target. Weights for gain, quality and time will be entered also. Then press the start button. The proposed system will run after pressing start button getting the daily output plan for shooting as shown in figure 7.

Table 2. Table of targets parameters

Serial	Target Name	Location (Lat., Long.)	Validity Date Date/Time	Gain
1	Abu Zenima	29.05, 33.10	16-09-2018 00:00:00	1
2	Adis Ababa	9.024, 38.75	16-09-2018 00:00:00	4
3	Amman	31.95, 35.93	16-09-2018 00:00:00	2
4	Ankara	39.92, 32.86	16-09-2018 00:00:00	3
5	Baghdad	33.34, 44.39	16-09-2018 00:00:00	1
6	Casablanca	33.59, -7.61	16-09-2018 00:00:00	3
7	Damascus	33.5, 36.3	16-09-2018 00:00:00	4
8	Darnah	32.77, 22.64	16-09-2018 00:00:00	2
9	Khartoum	15.59, 32.53	16-09-2018 00:00:00	1
10	Makka	21.43, 39.83	16-09-2018 00:00:00	3
11	Masqat	23.61, 58.59	16-09-2018 00:00:00	1
12	Tel Aviv	32.06, 34.77	16-09-2018 00:00:00	2
13	Tunis	36.80, 10.18	16-09-2018 00:00:00	4

5. Results and discussion

Before start the discussion, we have to know that the targets opportunities are shown in table 3.

For our case study, it is noticed that the output optimized plan has nine (9) chosen targets to be executed from the thirteen (13) entered targets according to the proposed objectives, constraints and weights for gain, quality and time. It is good to mention that the output optimized plan contains also the result (the fitness value at each target with its parameters) and the objective function value for all chosen targets. The smaller the better are these results, as our multi-objective equation has minimization objectives.

All the previous selected targets examples are the fittest from point of view for our proposed satellites mission scheduling system. As choosing the others opportunities may make a conflict with other selected targets. This conflict may be in transition time.

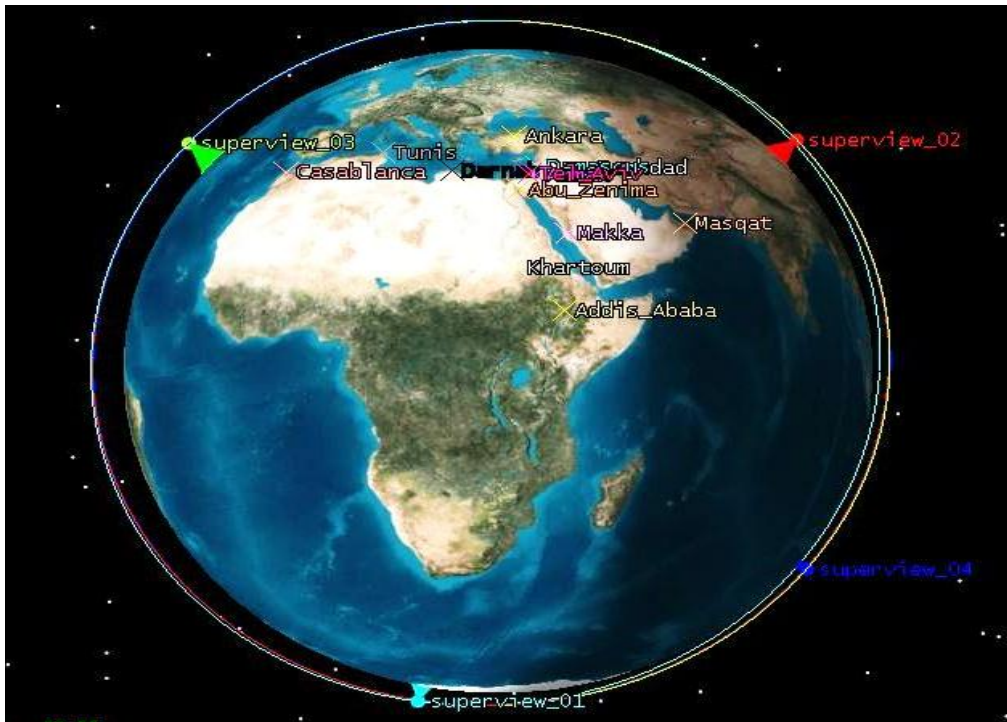


Figure 4. The constellation of satellites and spot targets



Figure 5. The spot targets

Figure 6. Mission scheduling system inputs

	Request_Number	Satellite_Number	Gain	Shooting_Time	Combined_Angle	Result
1	11	2	2	15-Sep-2018 06:50:57	21	0.2148
2	7	2	2	4 15-Sep-2018 08:23:31	26	-0.1269
3	4	4	4	3 15-Sep-2018 08:42:33	24	-0.0152
4	12	1	1	2 15-Sep-2018 09:01:29	11	0.0231
5	1	4	4	1 15-Sep-2018 08:45:01	21	0.2148
6	3	2	2	2 15-Sep-2018 08:23:58	26	0.1231
7	9	2	2	1 15-Sep-2018 08:28:16	27	0.2548
8	13	4	4	4 15-Sep-2018 10:18:35	7	-0.2535
9	6	2	3	3 15-Sep-2018 11:33:44	8	-0.1219

	Objective Function Value
1	0.3133

Figure 7. Mission scheduling system output

Table 3. Table of targets opportunities

Target Number	Target Name	Satellite Number	Combined Angle	Shooting Start Time
1	Abu Zenima	1	2	9:02:25 AM
		4	21	8:45:02 AM
2	Adis Ababa	3	14	8:04:12 AM
3	Amman	1	1	9:01:30 AM
		2	26	8:23:58 AM
		4	4	8:44:27 AM
4	Ankara	1	25	8:59:36 AM
		4	24	8:42:34 AM
5	Baghdad	4	10	7:57:43 AM
6	Casablanca	2	8	11:33:44 AM
7	Damascus	1	21	9:01:01 AM
		2	26	8:23:31 AM
		4	24	8:44:05 AM
8	Darnah	3	13	9:32:57 AM
9	Khartoum	1	27	9:05:45 AM
		2	27	8:28:16 AM
		4	30	8:48:48 AM
10	Makka	3	28	8:00:54 AM
11	Masqat	1	30	7:28:26 AM
		2	21	6:50:58 AM
12	Tel_Aviv	1	11	9:01:30 AM
		4	14	8:44:33 AM
13	Tunis	1	10	10:35:31 AM
		4	7	10:18:35 AM

6. Conclusion and future work

Satellites Mission Scheduling Problem for a satellites' constellation is considered an NP problem. There is no doubt that genetic algorithm is a very effective optimization technique which has been used for solving this type of problems. Matlab program, its graphical user interface and STK play an effective role in our proposed model. A multi-objective equation has been created to combine a very important objectives (Gain, image quality and time execution). There are three important constraints (Target exclusiveness, transition time and due date) have been taken in consideration. The proposed model has been run with the proposed case study and output a logic optimized plan. This optimized plan contains the target number, the satellite number, the target gain, the shooting time, the combined angle, the result (the fitness value at each target with its parameters) and the objective function value for all chosen targets. Applying our multi-objective equation by the proposed model is very effective in decreasing the load of satellites mission scheduling problem, saving satellites' resources and satisfy customers' needs.

Some facilitation was considered in the proposed Satellites Mission Scheduling System to simplify the implementation for the current time. For more precise SMS system, this facilitation should be eliminated. Therefore, as a future work, some contributions are recommended for the AEOs SMS systems. According to constraints, take into consideration other constraints, energy, storage capacity, intervals' time for ground station and data rate constraint, beside the proposed three constraints. According to satellites constellation, take into consideration another satellites with different specifications instead of the proposed constellation.

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