Mission planning and scheduling for Earth observation space system

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Abstract: Planning and scheduling systems are needed to manage Earth observing satellites for satisfying the optimum usage of the constellation's resources. This is a combinatorial optimisation NP-hard problem which is solved in this paper using the constraint programming technique. The proposed system can deal with a heterogeneous constellation that consists of satellites with different manoeuvrability, placed in different orbits, and loaded with different payloads. The system's user can choose one of six optimisation objectives, three of them were not used before, for constructing the satellites' mission plan. Searching within the system is performed using one of five different search algorithms. The system produces plans with different planning horizons ranging from one track to more than one month. The obtained results depict that the proposed system behaves, comparatively, in a perfect manner even when dealing with a complicated case study consisting of three satellites, 2,500 targets, and one month planning horizon.

Keywords: Earth observing satellites; EOS; planning and scheduling; mission management; constraint satisfaction problem; heterogeneous constellation; agile satellites.

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1 Introduction

A mission planning and scheduling (MPS) system with high performance is required to output feasible optimised plans for a heterogeneous Earth observing satellite (EOS) constellation's mission. These plans should satisfy the received requests as much as possible in addition to performing the optimised usage of the constellation's resources considering all types of constraints applied on the operations environment.

In this paper, some advantages are included to improve the operational and scientific quality of the paper. The constraint programming technique is used as in Wang et al. (2015) but two more constraints are added. One arises from specifying the customer to the image resolution in his request and the second is the request end date or due date. The authors in Wang et al. (2015) considered the non-agile satellite constellation in their study, but in this paper, the agile satellite constellation is taken into consideration as in Xu et al. (2016) and Sun et al. (2012) in addition to the ability of planning the mission for the non-agile satellites also. Expanding the planning horizon from one day as used in Wang et al. (2015), Xu et al. (2016) and Sun et al. (2012), or one week as in Globus et al. (2002) to one month was another added challenge in the proposed system. Another more advantage in the proposed system is using a heterogeneous constellation as Globus et al. (2002) but with agile satellites instead of non-agile ones and including the stereo imaging capability.

The paper is structured as follows; a summary for the literature survey on the previous researches in this field is introduced in Section 2. The proposed MPS system formulation is in Section 3, which is divided into the problem model explained in Subsection 3.1 and the problem solver discussed in Subsection 3.2. The system architecture is presented in Section 4. The realisation of the proposed system is introduced in Section 5 with the aid of system snapshots. Five objectives in combination with five search algorithms are tested on nine case studies with different problem sizes using a personal laptop equipped with an Intel(R) Core(TM) i7-3612QM CPU @ 2.10 GHz and 6.00 GB RAM, with 64-bit operating system Windows 7. The proposed system's performance assessment results are presented in Section 6. Two performance metrics are used to evaluate the quality and the efficiency of the proposed system which are the normalised score (i.e. the normalised output value from the objective function) and CPU time respectively. Normalised score has been unified for all the tested objectives such that its value is better as it tends to 100. Some comparisons with other systems from CPU time point of view are introduced in this section. Finally, conclusions and future work are introduced in Section 7.

2 Literature survey

By a survey on the previous researches in EOS MPS systems, we collect the most commonly used approaches in the problem modelling (Table 1), the most commonly used search algorithms in problem solving (Table 2), the most commonly used problem constraints (Table 3). In addition, we gather the different case types from the constellation type point of view (Table 4) and the most common used planning horizons (Table 5).

Table 1 Most commonly used approaches

#	*Approach*	*Used by reference*
1	Constraint satisfaction problem (CSP)	Bensana et al. (1996, 1999), Li and Wang (2008) and Wolfe and Sorensen (2000)
2	Integer linear programming (ILP)	Wang et al. (2015, 2009), Bianchessi et al. (2007), Wang (2007) and Bensana et al. (1997)
3	Window constrained problem (WCP)	Wolfe and Sorensen (2000)
4	Graph theory	Lemaitre et al. (2002)
5	Knapsack problem	Vasquez and Hao (2001) and Cordeau and Laporte (2005)
6	Mathematical programming	(Xu et al., 2016)
7	Constraint programming	Wang et al. (2015) and Lemaitre et al. (2002)
8	Constraint-based interval	Dungan et al. (2002) and Lemaitre et al. (2002)

This paper presents a MPS system that can be used with different number of satellites, different payload types, different planning horizons, different search algorithms, different orbit types and taking into consideration almost all the system constraints. In addition, it can deal with a heterogeneous constellation from the orbit point of view i.e., a constellation that includes inclined and sun synchronous orbits simultaneously. Up to the best of our knowledge, this case was not used in literature before.

Table 2 Most commonly used search algorithms

	Search algorithm	*Used by reference*
Exact algorithms	Branch and bound	Bensana et al. (1997, 1996, 1999)
	Pseudo dynamic	Bensana et al. (1996)
	Russian dolls	Bensana et al. (1997)
	Branch and price	Wang et al. (2015)

Table 2 Most commonly used search algorithms (continued)

	Search algorithm	*Used by reference*
Approximate algorithms	Greedy search (GS)	Bensana et al. (1997), 1996), Lemaitre et al. (2002), Frank et al. (2001), and Dungan et al. (2002)
	Tabu search (TS)	Bensana et al. (1997, 1996, 1999), Vasquez and Hao (2001), Cordeau and Laporte (2005), Wang et al. (2009) and Bianchessi et al. (2007)
	Priority dispatch	Wolfe and Sorensen (2000)
	Look ahead	Florio (2006), Wolfe and Sorensen (2000) and Bianchessi and Righini (2008)
	Genetic algorithm	Li and Wang (2008), Wolfe and Sorensen (2000), Globus et al. (2002, 2004), Wang (2007) and Sun et al. (2012)
	Ant colony	(Xu et al., 2016)
	Simulated annealing	Lemaitre et al. (2002), Globus et al. (2002, 2004) and Wang et al. (2009)
	Hill climbing (HC)	Globus et al. (2002, 2004)
	Column generation	Wang et al. (2015)

Table 3 Most commonly used problem constraints

Type	*Name*	*Used by reference*
Temporal constraints	Observation window	Cordeau and Laporte (2005), Bensana et al. (1999, 1997), Lemaitre et al. (2002), Dungan et al. (2002), Globus et al. (2002, 2004), Frank et al. (2001), Bianchessi et al. (2007), Florio (2006), Wang et al. (2011, 2009), Wolfe and Sorensen (2000), Li and Wang (2008), Tangpattanakul et al. (2015), Sun et al. (2012), Wang (2007) and Xu et al. (2016)
	Transition time	Wang et al. (2015, 2011), Bensana et al. (1996, 1999, 1997), Vasquez and Hao (2001), Lemaitre et al. (2002), Dungan et al. (2002), Globus et al. (2002), Bianchessi et al. (2007), Bianchessi and Righini (2008), Tangpattanakul et al. (2015), Sun et al. (2012) and Xu et al. (2016)
	Image duration	Vasquez and Hao (2001), Cordeau and Laporte (2005), Bensana et al. (1999, 1997), Dungan et al. (2002), Globus et al. (2002, 2004), Bianchessi et al. (2007), Wang et al. (2011, 2009), Wolfe and Sorensen (2000), Li and Wang (2008), Tangpattanakul et al. (2015), Sun et al. (2012) and Xu et al. (2016)
Request constraints	Cloud cover	Wang et al. (2015) and Globus et al. (2002)
	Stereo	Bensana et al. (1996), Bianchessi et al. (2007) and Tangpattanakul et al. (2015)
	Resolution	Sun et al. (2012)
	Download	Wang et al. (2015, 2011), Dungan et al. (2002), Globus et al. (2002), Frank et al. (2001), Florio (2006), Bianchessi and Righini (2008), Wang (2007) Wang (2007) and Bensana et al. (1997)
	End time	Not listed

Table 3 Most commonly used problem constraints (continued)

Type	*Name*	*Used by reference*
Resource constraints	Onboard memory	Wang et al. (2015, 2011), Bensana et al. (1996, 1999, 1997), Vasquez and Hao (2001), Cordeau and Laporte (2005), Lemaitre et al. (2002), Dungan et al. (2002), Globus et al. (2002, 2004), Bianchessi and Righini (2008), Li and Wang (2008), Wang (2007), and Xu et al. (2016)
	Energy	Wang et al. (2015, 2011), Lemaitre et al. (2002); Globus et al. (2002), Li and Wang (2008) and Xu et al. (2016)
	Duty cycle	Globus et al. (2004) and Xu et al. (2016)
	Revisit	Globus et al. (2002) and Florio (2006)

Table 4 Case types

#	*Satellites types*	*Sat's no.*	*Used by reference*
1	EOS	1	Bensana et al. (1996, 1999, 1997), Vasquez and Hao (2001), Cordeau and Laporte (2005) and Li and Wang (2008)
2	EOS	>1	Wang et al. (2015, 2009), Dungan et al. (2002), Globus et al. (2002, 2004), Frank et al. (2001), Wolfe and Sorensen (2000), and Wang (2007)
3	Agile EOS (AEOS)	1	Lemaitre et al. (2002) and Tangpattanakul et al. (2015)
4	AEOS	>1	Bianchessi et al. (2007), Florio (2006), Bianchessi and Righini (2008), Wang et al. (2011), Sun et al. (2012) and Xu et al. (2016)
5	Heterogeneous payloads	--	Globus et al. (2002), Wang et al. (2011) and Li and Wang (2008)
6	Heterogeneous agility	--	Globus et al. (2002)

Table 5 Planning horizons

#	*Planning horizon*	*Used by reference*
1	Less than one track	Lemaitre et al. (2002)
2	One track	Bensana et al. (1999)
3	Multiple tracks < one day	Wang et al. (2015), Bensana et al. (1999), Dungan et al. (2002), Li and Wang (2008) and Wang (2007)
4	One day	Wang et al. (2015, 2009, 2011), Bensana et al. (1996, 1997), Vasquez and Hao (2001), Cordeau and Laporte (2005), Frank et al. (2001), Bianchessi et al. (2007), Florio (2006), Bianchessi and Righini (2008), Wolfe and Sorensen (2000), Globus et al. (2004), Tangpattanakul et al. (2015), Sun et al. (2012) and Xu et al. (2016)
5	Two days	Globus et al. (2002)
6	> Two days (< one week)	Bianchessi and Righini (2008)
7	One week	Globus et al. (2002) and Florio (2006)

3 Problem formulation

What we meant by problem formulation is to define a model and a solver.

3.1 Problem model

The main parts of the problem model are the following:

1 Input data

Let R be the set of input requests. For each $r \in R$, let G_r be its gain and A_r its surface area. Let I be the set of images obtained from R by the geometric cutting up process. *A* spot request is the one that can be imaged in one shot while the polygonal request is the large target that should be cut up into spot targets.

The data associated with each request determines the target geometrical description (spot or polygon), validity period or data delivery end time (end_r), demand time (the date of request), angular constraints (required resolution), shooting type (stereoscopic or mono), and gain.

Let us assign for each image $i \in I$:

E_i its earliest shooting start time

L_i its latest shooting start time

D_i its duration of shooting, a positive value

A_i its surface area.

For each possible pair of images (i, j), let M_{ij} be the transition time between shooting the two images i and j. If a transition from i to j is not possible, they cannot be shot consecutively. Let B defined as the set of pairs of images (i, j) such that i and j are images for the same image with opposite pitch angles. In addition, let S be the set of pairs of corresponding stereoscopic images.

2 Decision variables

One of these variables determines the decision of selecting or not selecting an image. It takes a binary value (0, 1). The other is the selected time for imaging start time that lies within the observation time window. They are:

X_i is one if the image $i \in I$ is selected, and zero otherwise

t_i the shooting start time of image i if selected.

3 Constraints

The MPS system has many constraints that can be categorised as temporal constraints that concerning with time aspects, resources constraints that are forced by the system's resources specifications, and the request constraints that appear from the request demanded parameters. The whole constraints implemented in the system are as follows:

a Observation time window constraint:

$$\forall i \in I : (X_i = 1) \Rightarrow (E_i \le t_i \le L_i) \quad (1)$$

b Transition time constraint:

$$\forall(i,\ j)\in I:\left(X_i,\ X_j=1\right)\Rightarrow\left(t_i+D_i+M_{ij}\le t_j\right) \tag{2}$$

c Request end time constraint:

$$\forall i\in I,\ I\subset r,\ r\in R:\left(X_i=1\right)\Rightarrow\left(t_i<end_r\right) \tag{3}$$

d Shoot a mono image once constraint:

$$\forall(i,\ j)\in B:X_i+X_j\le 1 \tag{4}$$

e Stereo image constraint:

$$\forall(i,\ j)\in S:X_i=X_j \tag{5}$$

f The stereo pair pitch angles constraint:

$$\forall(i,\ j)\in S:Pitch_i=-Pitch_j \tag{6}$$

g The stereo pair roll angle constraint:

$$\forall(i,\ j)\in S:Roll_i=Roll_j \tag{7}$$

h The stereo pair satellite constraint:

$$\forall(i,\ j)\in S:Satellite_i=Satellite_j \tag{8}$$

i Memory limitation constraint:

$\forall$ planning horizon

$$\forall i\in I:\sum_i X_i\le N_{\max} \tag{9}$$

where $N_{\max}$ is the maximum allowable number of selected images for this planning horizon.

j Payload duty cycle constraint:

$$\forall(i,\ j)\in I:t_j-\left(t_i+D_i+M_{ij}\right)\ge t_P \tag{10}$$

where t_P is the payload duty cycle (technological break).

4 Optimisation criteria

The proposed MPS system is designed to use one of six objectives to obtain a feasible optimised output plan. It is worthy mentioned that the proposed MPS system has a modular nature where more optimisation criteria can be added using the same constraints and the same search algorithms. Also, the constraints may be changed or modified independently as well as the case with the search algorithms.

The six implemented objective functions, whose outputs are normalised and used as the normalised score metric for performance evaluation, are:

Let X_i be the selection decision variable, equals one if selected and zero otherwise,

a Gain maximisation objective function:

$$\forall i\in I:\ f(x)=\max\left(\sum_i G_i*X_i\right) \tag{11}$$

G_i is the gain of image $i \in I$ (the set of images).

b Area maximisation objective function: (not used before)

$$\forall i \in I: f(x) = \max\left(\sum_i A_i * X_i\right) \tag{12}$$

$$A_i = D_i * W_s * S_v \tag{13}$$

where

A_i is the surface area of the strip

D_i is the shooting duration

W_s is the satellite's swath

S_v is the satellite's speed.

c Image quality maximisation objective function:

$$\forall i \in I: f(x) = \max\left(\sum_i (R_{worst} - R_i) * X_i\right) \tag{14}$$

R_i is the resolution of image $i \in I$

R_{worst} there solution at maximum roll and pitch angles.

d Execution time minimisation objective function: (not used before)

$$\forall i \in I: f(x) = \min\left(\sum_i t_i * X_i\right) \tag{15}$$

t_i is the shooting start time.

e Waiting time minimisation objective function: (not used before)

$$\forall i \in I: f(x) = \min\left(\sum_i (t_i - d_i) * X_i\right) \tag{16}$$

d_i is the request demand time.

f Satellites' load balance objective function:

$$\forall (i, j) \in I \text{ and } \forall (y, z) \in Sat: f(x) = \min\left(\sum_{i,j,y,z} abs\left(X_{iy} - X_{jz}\right)\right) \tag{17}$$

where

I, Sat are the images set and satellites set, respectively

X_{iy}, X_{jz} equal one when image i or j is assigned to be shot by satellite y or z respectively, zero otherwise.

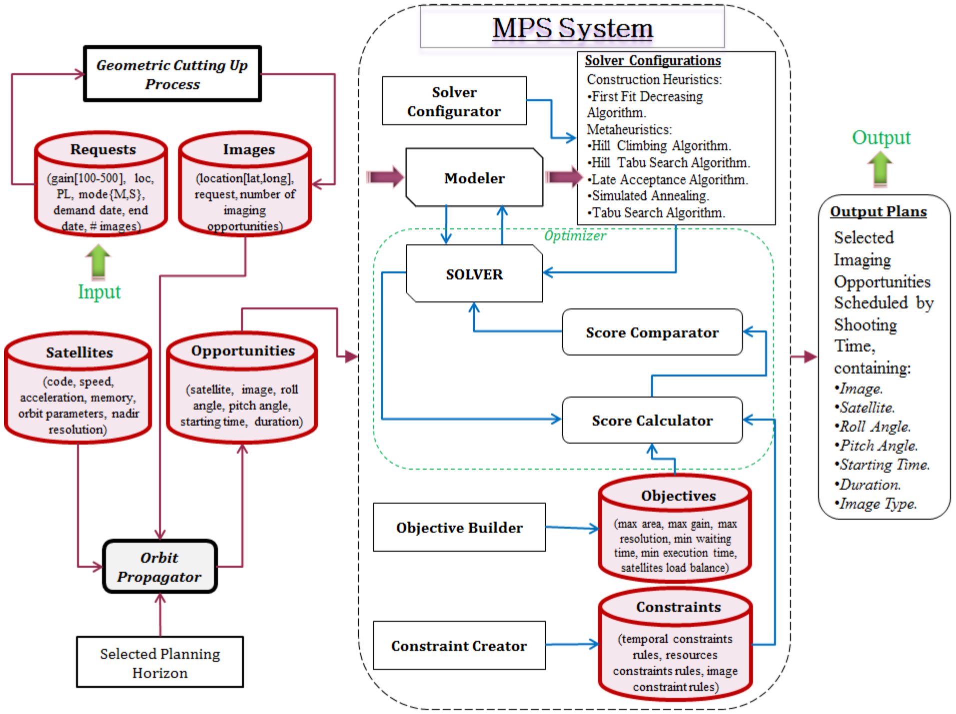
3.2 Problem solver

Depending on the modular nature of the proposed MPS system we can change, modify or add new algorithms. In this paper, we used the following five search algorithms: hill climbing (HC), late acceptance (LA), simulated annealing (SA), Tabu search (TS) and hill climbing Tabu search (HCTS).

4 Proposed system architecture

Each request will have one or more images after cutting up process according to its type (spot or polygon). Every resultant image will have a gain, imaging mode, payload type, demand time and end time that are inherited from the parent request of this image. With the help of an Orbit Propagator, the imaging opportunities for each image are calculated. An imaging opportunity has a roll angle determined by the orbit of the satellite, a pitch angle differs according to the start time of this imaging opportunity and a duration determined by both the roll and pitch angles. In addition, an imaging opportunity will also have an observation time window within which the shooting start time lies. Moreover, the satellite manoeuvrability is specified by its angular speed and angular acceleration that in turns define the transition time between two consecutive imaging processes. Of course, the start time of an imaging opportunity is affected by the satellite's transition time. Based on this, the proposed system architecture is built as in Figure 1.

Figure 1 Proposed system architecture (see online version for colours)



Geometric cutting up process is performed on input requests in the requests database. Each request has the following data:

1. a unique name defined as a string
2. a gain whose integer value ranging between [100,500]
3. an imaging mode defined by a string from the set {M, S}
4. a demand time defined as a timestamp

5 an end time determines the request validity
6 the target location defined by latitudes and longitudes
7 the payload defined by its type (Opt, SAR, IR).

Each resulted image from the geometric cutting up process is saved in the images database and has:

1 the request from which the image is cut up
2 a unique name defined as a string
3 image location defined by the centre point latitude and longitude.

The resultant images database is fed to the Orbit Propagator together with the constellation's satellites database and the selected planning horizon. Each satellite in the satellites database has:

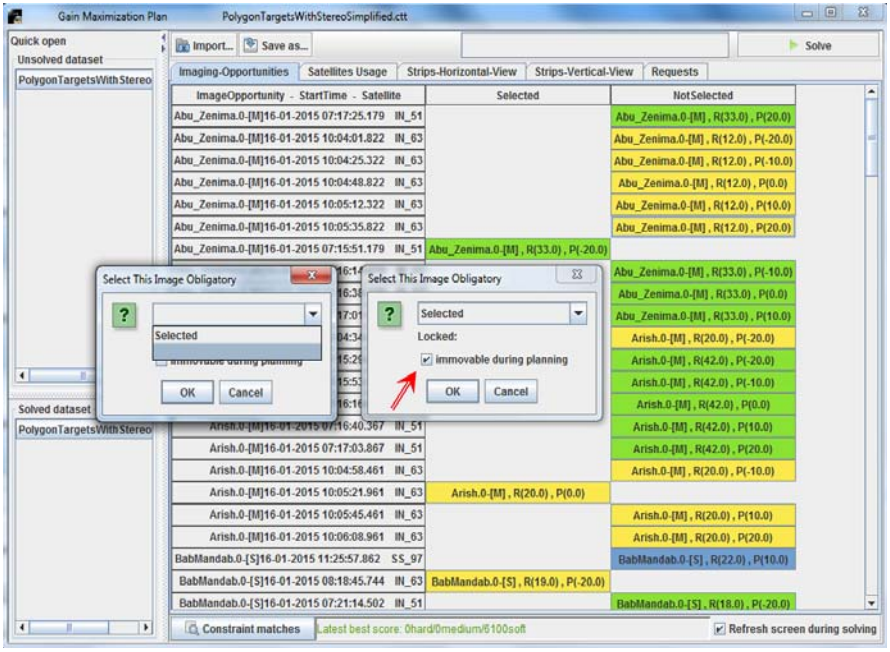
1 a unique name defined as a string code
2 onboard memory measured in MB
3 the ground resolution at nadir measured in metres
4 angular speed measured in degree per second
5 angular acceleration measured in degree/square seconds.

The proposed system can output feasible optimised plans for different planning horizons ranges from one track until one month. The Orbit Propagator outputs a number of imaging opportunities for each image. The opportunities database contains all the imaging opportunities from which a time-scheduled collection will be selected to produce an optimum output plan according to the used objective. The input to the MPS system is modelled via the modeller to be introduced to the SOLVER. A solver configurator is the module responsible to configure this SOLVER. A constraint creator is used to create the constraints used in the system and stored in the constraints database that will be input to the score calculator together with the objectives built via an objective builder. We build in the proposed system six objectives that are stored in the objectives database; one of them is selected before running the system. The SOLVER wades through the search space of solutions efficiently. It always elects feasible solutions before the algorithm termination criterion is fulfilled. Every solution is score calculated via the score calculator. This score is compared with the previous scores via a score comparator until reaching the optimum score. The optimum score is either the maximum or minimum one according to the selected objective. The SOLVER, the score calculator and the score comparator consist what is called the optimiser.

5 The proposed system realisation

The imaging opportunities for all the images are obtained from the Orbit Propagator. A sample of the opportunities with a specific colour for each satellite is illustrated in Figure 2. Some opportunities are located in the 'selected' column and others in the 'not selected' column. An option of adding or removing an image from the output plan intentionally with the ability of making this selection immovable during planning is also illustrated. If the 'immovable during planning' check box is not checked, the system is able to change this selection in case of finding a confliction with other images according to the used objective. This is done if the user presses the 'solve' button again after performing this manual change.

Figure 2 Selected imaging opportunities (see online version for colours)



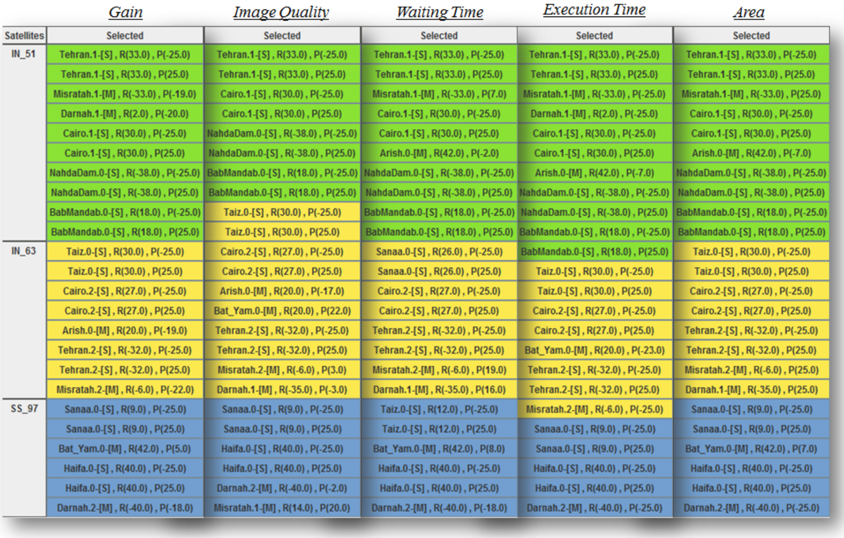
ImageOpportunity - StartTime - Satellite	Selected	NotSelected
Abu_Zenima.0-[M]16-01-2015 07:17:25.179 IN_51		Abu_Zenima.0-[M] , R(33.0) , P(20.0)
Abu_Zenima.0-[M]16-01-2015 10:04:01.822 IN_63		Abu_Zenima.0-[M] , R(12.0) , P(-20.0)
Abu_Zenima.0-[M]16-01-2015 10:04:25.322 IN_63		Abu_Zenima.0-[M] , R(12.0) , P(-10.0)
Abu_Zenima.0-[M]16-01-2015 10:04:48.822 IN_63		Abu_Zenima.0-[M] , R(12.0) , P(0.0)
Abu_Zenima.0-[M]16-01-2015 10:05:12.322 IN_63		Abu_Zenima.0-[M] , R(12.0) , P(10.0)
Abu_Zenima.0-[M]16-01-2015 10:05:35.822 IN_63		Abu_Zenima.0-[M] , R(12.0) , P(20.0)
Abu_Zenima.0-[M]16-01-2015 07:15:51.179 IN_51	Abu_Zenima.0-[M] , R(33.0) , P(-20.0)	
16:14		Abu_Zenima.0-[M] , R(33.0) , P(-10.0)
16:38		Abu_Zenima.0-[M] , R(33.0) , P(0.0)
17:01		Abu_Zenima.0-[M] , R(33.0) , P(10.0)
04:34		Arish.0-[M] , R(20.0) , P(-20.0)
15:29		Arish.0-[M] , R(42.0) , P(-20.0)
15:53		Arish.0-[M] , R(42.0) , P(-10.0)
16:16		Arish.0-[M] , R(42.0) , P(0.0)
Arish.0-[M]16-01-2015 07:16:40.367 IN_51		Arish.0-[M] , R(42.0) , P(10.0)
Arish.0-[M]16-01-2015 07:17:03.867 IN_51		Arish.0-[M] , R(42.0) , P(20.0)
Arish.0-[M]16-01-2015 10:04:58.461 IN_63		Arish.0-[M] , R(20.0) , P(-10.0)
Arish.0-[M]16-01-2015 10:05:21.961 IN_63	Arish.0-[M] , R(20.0) , P(0.0)	
Arish.0-[M]16-01-2015 10:05:45.461 IN_63		Arish.0-[M] , R(20.0) , P(10.0)
Arish.0-[M]16-01-2015 10:06:08.961 IN_63		Arish.0-[M] , R(20.0) , P(20.0)
BabMandab.0-[S]16-01-2015 11:25:57.862 SS_97		BabMandab.0-[S] , R(22.0) , P(10.0)
BabMandab.0-[S]16-01-2015 08:18:45.744 IN_63	BabMandab.0-[S] , R(19.0) , P(-20.0)	
BabMandab.0-[S]16-01-2015 07:21:14.502 IN_51		BabMandab.0-[S] , R(18.0) , P(-20.0)

Select This Image Obligatory
?
Selected
OK Cancel

Select This Image Obligatory
?
Selected
Locked:
☑ immovable during planning
OK Cancel

Latest best score: 0hard/0medium/6100soft
☑ Refresh screen during solving

Figure 3 All objectives' outputs (see online version for colours)



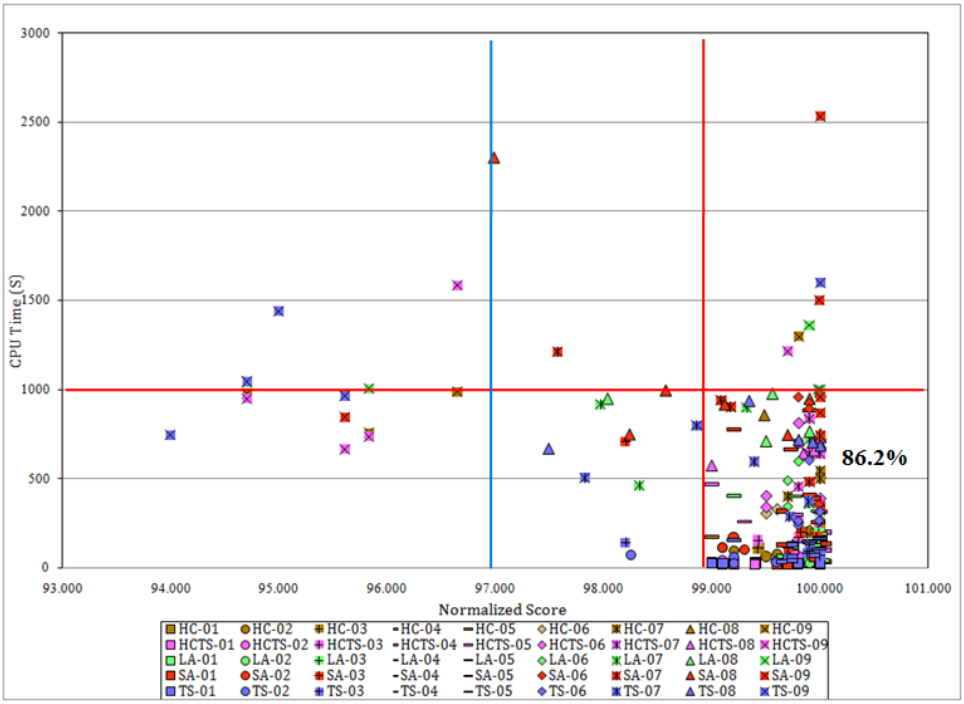
	Gain	*Image Quality*	*Waiting Time*	*Execution Time*	*Area*
Satellites	Selected	Selected	Selected	Selected	Selected
IN_51	Tehran.1-[S] , R(33.0) , P(-25.0)	Tehran.1-[S] , R(33.0) , P(-25.0)	Tehran.1-[S] , R(33.0) , P(-25.0)	Tehran.1-[S] , R(33.0) , P(-25.0)	Tehran.1-[S] , R(33.0) , P(-25.0)
	Tehran.1-[S] , R(33.0) , P(25.0)	Tehran.1-[S] , R(33.0) , P(25.0)	Tehran.1-[S] , R(33.0) , P(25.0)	Tehran.1-[S] , R(33.0) , P(25.0)	Tehran.1-[S] , R(33.0) , P(25.0)
	Misratah.1-[M] , R(-33.0) , P(-19.0)	Cairo.1-[S] , R(30.0) , P(-25.0)	Misratah.1-[M] , R(-33.0) , P(7.0)	Misratah.1-[M] , R(-33.0) , P(-25.0)	Misratah.1-[M] , R(-33.0) , P(25.0)
	Darnah.1-[M] , R(2.0) , P(-20.0)	Cairo.1-[S] , R(30.0) , P(25.0)	Cairo.1-[S] , R(30.0) , P(-25.0)	Darnah.1-[M] , R(2.0) , P(-25.0)	Cairo.1-[S] , R(30.0) , P(-25.0)
	Cairo.1-[S] , R(30.0) , P(-25.0)	NahdaDam.0-[S] , R(-38.0) , P(-25.0)	Cairo.1-[S] , R(30.0) , P(25.0)	Cairo.1-[S] , R(30.0) , P(-25.0)	Cairo.1-[S] , R(30.0) , P(25.0)
	Cairo.1-[S] , R(30.0) , P(25.0)	NahdaDam.0-[S] , R(-38.0) , P(25.0)	Arish.0-[M] , R(42.0) , P(-2.0)	Cairo.1-[S] , R(30.0) , P(25.0)	Arish.0-[M] , R(42.0) , P(-7.0)
	NahdaDam.0-[S] , R(-38.0) , P(-25.0)	BabMandab.0-[S] , R(18.0) , P(-25.0)	NahdaDam.0-[S] , R(-38.0) , P(-25.0)	Arish.0-[M] , R(42.0) , P(-7.0)	NahdaDam.0-[S] , R(-38.0) , P(-25.0)
	NahdaDam.0-[S] , R(-38.0) , P(25.0)	BabMandab.0-[S] , R(18.0) , P(25.0)	NahdaDam.0-[S] , R(-38.0) , P(25.0)	NahdaDam.0-[S] , R(-38.0) , P(-25.0)	NahdaDam.0-[S] , R(-38.0) , P(25.0)
	BabMandab.0-[S] , R(18.0) , P(-25.0)	Taiz.0-[S] , R(30.0) , P(-25.0)	BabMandab.0-[S] , R(18.0) , P(-25.0)	NahdaDam.0-[S] , R(-38.0) , P(25.0)	BabMandab.0-[S] , R(18.0) , P(-25.0)
	BabMandab.0-[S] , R(18.0) , P(25.0)	Taiz.0-[S] , R(30.0) , P(25.0)	BabMandab.0-[S] , R(18.0) , P(25.0)	BabMandab.0-[S] , R(18.0) , P(-25.0)	BabMandab.0-[S] , R(18.0) , P(25.0)
IN_63	Taiz.0-[S] , R(30.0) , P(-25.0)	Cairo.2-[S] , R(27.0) , P(-25.0)	Sanaa.0-[S] , R(26.0) , P(-25.0)	BabMandab.0-[S] , R(18.0) , P(25.0)	Taiz.0-[S] , R(30.0) , P(-25.0)
	Taiz.0-[S] , R(30.0) , P(25.0)	Cairo.2-[S] , R(27.0) , P(25.0)	Sanaa.0-[S] , R(26.0) , P(25.0)	Taiz.0-[S] , R(30.0) , P(-25.0)	Taiz.0-[S] , R(30.0) , P(25.0)
	Cairo.2-[S] , R(27.0) , P(-25.0)	Arish.0-[M] , R(20.0) , P(-17.0)	Cairo.2-[S] , R(27.0) , P(-25.0)	Taiz.0-[S] , R(30.0) , P(25.0)	Cairo.2-[S] , R(27.0) , P(-25.0)
	Cairo.2-[S] , R(27.0) , P(25.0)	Bat_Yam.0-[M] , R(20.0) , P(22.0)	Cairo.2-[S] , R(27.0) , P(25.0)	Cairo.2-[S] , R(27.0) , P(-25.0)	Cairo.2-[S] , R(27.0) , P(25.0)
	Arish.0-[M] , R(20.0) , P(-19.0)	Tehran.2-[S] , R(-32.0) , P(-25.0)	Tehran.2-[S] , R(-32.0) , P(-25.0)	Cairo.2-[S] , R(27.0) , P(25.0)	Tehran.2-[S] , R(-32.0) , P(-25.0)
	Tehran.2-[S] , R(-32.0) , P(-25.0)	Tehran.2-[S] , R(-32.0) , P(25.0)	Tehran.2-[S] , R(-32.0) , P(25.0)	Bat_Yam.0-[M] , R(20.0) , P(-23.0)	Tehran.2-[S] , R(-32.0) , P(25.0)
	Tehran.2-[S] , R(-32.0) , P(25.0)	Misratah.2-[M] , R(-6.0) , P(3.0)	Misratah.2-[M] , R(-6.0) , P(19.0)	Tehran.2-[S] , R(-32.0) , P(-25.0)	Misratah.2-[M] , R(-6.0) , P(25.0)
	Misratah.2-[M] , R(-6.0) , P(-22.0)	Darnah.1-[M] , R(-35.0) , P(-3.0)	Darnah.1-[M] , R(-35.0) , P(16.0)	Tehran.2-[S] , R(-32.0) , P(25.0)	Darnah.1-[M] , R(-35.0) , P(25.0)
SS_97	Sanaa.0-[S] , R(9.0) , P(-25.0)	Sanaa.0-[S] , R(9.0) , P(-25.0)	Taiz.0-[S] , R(12.0) , P(-25.0)	Misratah.2-[M] , R(-6.0) , P(-25.0)	Sanaa.0-[S] , R(9.0) , P(-25.0)
	Sanaa.0-[S] , R(9.0) , P(25.0)	Sanaa.0-[S] , R(9.0) , P(25.0)	Taiz.0-[S] , R(12.0) , P(25.0)	Sanaa.0-[S] , R(9.0) , P(-25.0)	Sanaa.0-[S] , R(9.0) , P(25.0)
	Bat_Yam.0-[M] , R(42.0) , P(5.0)	Haifa.0-[S] , R(40.0) , P(-25.0)	Bat_Yam.0-[M] , R(42.0) , P(8.0)	Sanaa.0-[S] , R(9.0) , P(25.0)	Bat_Yam.0-[M] , R(42.0) , P(7.0)
	Haifa.0-[S] , R(40.0) , P(-25.0)	Haifa.0-[S] , R(40.0) , P(25.0)	Haifa.0-[S] , R(40.0) , P(-25.0)	Haifa.0-[S] , R(40.0) , P(-25.0)	Haifa.0-[S] , R(40.0) , P(-25.0)
	Haifa.0-[S] , R(40.0) , P(25.0)	Darnah.2-[M] , R(-40.0) , P(-2.0)	Haifa.0-[S] , R(40.0) , P(25.0)	Haifa.0-[S] , R(40.0) , P(25.0)	Haifa.0-[S] , R(40.0) , P(25.0)
	Darnah.2-[M] , R(-40.0) , P(-18.0)	Misratah.1-[M] , R(14.0) , P(20.0)	Darnah.2-[M] , R(-40.0) , P(-18.0)	Darnah.2-[M] , R(-40.0) , P(-25.0)	Darnah.2-[M] , R(-40.0) , P(-25.0)

Output plans for the same input data using five objectives appear in Figure 3. It is clear that changing the objective, changes the output plan. The selected images, and their number, assigned to each satellite differ with different objectives. Each satellite selections appear in a specific colour for clarification.

6 Tests and results analysis

The system is tested for nine case studies differ in problem size (means the planning horizon, number of satellites, and number of targets). The first case study consists of a single-track planning horizon, single satellite and 25 targets, while the ninth case study consists of a single month planning horizon, three satellites and 2,500 targets. Figure 4 illustrates the system's performance in all the nine case studies using the five search algorithms by depicting the relation between the normalised score (objective function's output after normalisation) and the CPU time for each combination whose a specific coloured symbol in the legend.

Figure 4 System performance when solving nine different size case studies (see online version for colours)



The shown figure depicts that whatever the objective function is and the search algorithm used in solving is, a percentage of 86.2% of the results for all the nine case studies have a normalised score value greater than 99 and smaller than 1,000 seconds CPU time. This is a comparable good result.

However, all the other combinations do not list a normalised score value less than 97 except for the ninth case study as the most complicated one. If we exclude the ninth case study from our statistics, the percentage becomes 94.2%. The minimum value for the whole results didn't go below 94 normalised score.

Since there are not acknowledged benchmark test problems in satellite scheduling research area, as Yao et al. (2010), we compared our results with other references' ones from the CPU time point of view. The comparison's cases differ according to the number of satellites in the constellation and the number of targets used in the tests. Although using different machine's specifications, the comparison introduces the comparative advantage of the proposed system. Table 6 is dedicated for depicting the comparison's results.

Table 6 Comparison with other systems

#	*# of Sat's*	*The reference results*			*Proposed system results*	
		Ref.	*# of targets*	*CPU time (seconds)*	*# of targets*	*CPU time (seconds)*
1	1	Wang et al. (2010)	30	153.2	25	32
2	3	Wang et al. (2015)	100	486.12	180	442
3	1	Wang et al. (2010)	500	3,538	900	1,209
4	3	Yao et al. (2010)	1,300	477.89	563	1,209

7 Conclusions and future work

The previous discussed topics introduce a MPS system having the following characteristics:

1 realistic (satisfies the practical life operations needs by introducing different objectives)

2 dynamic (has quick response to users' actions)

3) scalable (works with problem sizes with comparatively very good performance)

4 modular (constraints, objectives and algorithms are independent configurable modules)

5 user interactive (enables selecting/deselecting of specific images during the plan creation)

6 robust (is a strong and successful system and not likely to fail).

Finally, the proposed MPS system can be used with multi-target type, multi-satellite, multi-user, multi-planning horizon, multi-constellation type, multi-payload type, multi-imaging mode, multi-constraint, multi-objective, multi-search algorithms and determines specific values for pitch angles in the output plan.

A future work can be concentrated on the following issues:

1 increase the granularity of the satellite's roll angle during imaging operation to create a more accurate plan

2 include more constraints in the system such as the onboard available energy to deal with a more complicated problem

3 use different satellite's agility models

4 insert the download operations with the imaging operations in the same output plan.

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