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11 Opportunitation planning for agile satellite using modified $\frac{11}{12}$ Onboard mission planning for agile satellite using modified ¹³ mixed-integer linear programming and the state of the state o 14

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23 Article his paper investigates a new Agile Earth Observation Satellite (AEOS) mission planning algorithm. This ₈₉
Passius 21 November 2017 24 Received in revised form 22 October 2017 which takes the minimum slew angle and highest priority criterion. The key point of the paper lies 25 Accepted 5 November 2017
and that the planning process is treated as a Dynamical Combinatorial Optimization (DCO) problem due 26 Available online xxxx
to the time-varying constraint and the requirement of the problem. The design of the new algorithm is $\frac{27}{\text{Kewuncts}}$ also to meet the real-time requirement of onboard mission planning. The mathematical formulation of $\frac{93}{\text{Kewuncts}}$ ²⁸ Agile satellite **1948** the problem is modified to satisfy the demand of the LP solver, and a newly developed dynamic database ⁹⁴ 29 Onboard mission planning **the constantly changing satellite-target** relative position with limited observation 95 30 96 windows. The new mission planning model is solved by the LP method to test its reliability. Another 31 Linear programming **Solution with Generic Algorithm (GA)** is also given to check the result. The calculation time of these two 32 32 32 38 methods is compared to show that the LP approach has a better compatibility with the onboard mission planning requirement. The property of the prop new developed algorithm is based on Modified Mixed-Integer Linear Programming (MILP) approach, planning requirement.

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1. Introduction

⁴⁴ 110
List servation mode is totally different from those of the traditional in the field of earth observation satellites, the development of

cle operation mode [\[7\].](#page--1-0) The newly demonstrated CASPER system is able to realize the mission planning process for EO-1 satel-

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38 **1. Introduction lite considering the time-varying condition, which is one of the** 39 105 most convincing examples of the onboard planning technology be-⁴⁰ The Agile Earth Observation Satellite (AEOS) is considered as ing used in real satellite mission [8]. Whereas, CASPER's planning ¹⁰⁶ ⁴¹ the most promising representative of the next-generation earth service only stops at the general activity level, the detailed satel-⁴² observation platform [\[1\].](#page--1-0) The Attitude and Orbit Control System lite dynamic model and optimal control criterion are not consid- 43 (AOCS) of AEOS is significantly improved recent years, and the ob-
 $_{\text{ered.}}$ ing used in real satellite mission [\[8\].](#page--1-0) Whereas, CASPER's planning service only stops at the general activity level, the detailed satellite dynamic model and optimal control criterion are not considered.

⁴⁵ earth observation spacecraft. To this reason, the new mission anal-
the onboard mission planning system is hindered by the limited ⁴⁶ ysis, planning and operation system must be developed to meet on hoard computing capability. The traditional earth observation ⁴⁷ the more complex mission requirements [\[2–4\].](#page--1-0) ⁴⁸ 114
The idea of mission management for aircraft and spacecraft is directions. The onboard instruments can take images only when ⁴⁹ a long discussed topic, and many important works in this region the attitude of satellite is stable. To these reasons the researches ⁵⁰ have been reported. Lin addressed the issue of space station over-
in the field of satellite mission planning are mainly forwed on 51 all mission planning by use of decomposition approach $[5]$. Wang 11 the constellation configuration and multi-satellite cooperation Fx -⁵² presented the robust gain scheduled control and optimal trajectory angles of such works can be found as the framework of opera- $\frac{53}{2}$ planning for an autonomous space rendezvous system subject to $\frac{53}{2}$ tion strategy of space constellation proposed by Chan [0] and the $\frac{54}{2}$ input saturation [\[6\].](#page--1-0) However, the onboard mission planning and $\frac{101}{2}$ coftware architecture design presented by Yu to improve the con- 55 self-management technology is not widely adopted yet. The most self-management addition at the self-management technology is not widely adopted yet. The most stallation authenomeus formation fluing capability [10] Wi 56 scientific observation missions still rely on the ground space cy-
scientific observation missions still rely on the ground space cy-
continuous development of AOCS technology more at 57 secondary manufactured and the secondary of the continuous development of AOCS technology, more and more at-
57 selection more at- $\frac{124}{124}$ is able to religion his process for EQ 1 satelly tention has been paid to the attitude control of complex structures $\frac{124}{124}$ $\frac{1}{59}$ is able to realize the mission planning process for EO 1 satel a with higher accuracy and higher angular velocity. An example of $\frac{125}{125}$ 60 126 such works can be given as the flexible structure control strategy 61 $\overline{\text{4}}$ Corresponding author and the set of the set of the set of the addressed by Cao [\[11,12\].](#page--1-0) In the field of earth observation satellites, the development of the onboard mission planning system is hindered by the limited onboard computing capability. The traditional earth observation satellites only have the capability of slewing along the certain fixed directions. The onboard instruments can take images only when the attitude of satellite is stable. To these reasons, the researches in the field of satellite mission planning are mainly focused on the constellation configuration and multi-satellite cooperation. Examples of such works can be found as the framework of operation strategy of space constellation proposed by Chen [\[9\],](#page--1-0) and the software architecture design presented by Xu to improve the constellation autonomous formation flying capability [\[10\].](#page--1-0) With the

62 62 62 E-mail address: lishuang@nuaa.edu.cn (S. Li). Computational optimizational optimization is one of the major research topics 128 63 ¹ Department of Astronautics Engineering. **Example 2018** 129 **in the artificial intelligence and computer science. The GA based 129**

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¹ combinatorial optimization algorithm was presented by Yeniay to Table 1 2 solve the optimization problem with various constraints [\[13\].](#page--1-0) The Related parameters of mission scenario. ³ advanced optimizer is also adopted in the field of aerospace con-**characters and a series are also assume** to the series of 69 ⁴ trol. For example, Komfeld proposed a GA based algorithm for the $\frac{1}{100}$ Standard observation sequence interval $\frac{70}{100}$ s ⁵ optimal attitude planning [\[14\].](#page--1-0) However, the computing capability onboard mission planning interval 5 min before the beginning of 71 6 and the strict real-time constraint of the onboard mission plan- 6 and $^{\circ}$. The observation sequence $^{\circ}$ $^{\circ}$ $^{\circ}$ $^{\circ}$ 7 7 ning are rarely considered in the studies mentioned above. Melton $^{\circ}$ boservation pointing constraint $^{\circ}$ anti-sun pointing $^{\circ}$ 73 $\frac{8}{100}$ presented a Maximum-Likelihood method in order to achieve the $\frac{9}{100}$ Standard slew angular velocity $\frac{1}{100}$ ⁹ optimal attitude control, which proved that the calculation time **of the controller of the control** of the control of the calculation time **of the controller of the controller of the control** of the calculation time **o** ¹⁰ can be reduced dramatically with the modified formulation and $\frac{76}{100}$ ¹¹ new developed computing algorithms from the attitude control deceleration processes at the beginning and end of slew maneuver ⁷⁷ ¹² perspective [\[15\].](#page--1-0) The results from the work of Melton prove the are neglected. $\sqrt{2}$ ¹³ feasibility of reducing the calculation time cost to meet the real-
¹³ feasibility of reducing the alculation time cost to meet the real-
In order to conduct the earth observation, the AEOS ¹⁴ time requirement. At the same time, this paper also presents the satellite needs to slew frequently in engineering practice. To prop- 80 ¹⁵ similar idea with the Linear Programming (LP) solver. The LP tech- erly describe and define the movement and the attitude of the 81 ¹⁶ nology was firstly introduced by Orourke to solve the general opti-

⁸² ¹⁷ mization problem (not specified to be in aerospace area) [\[16\].](#page--1-0) The **183** ¹⁸ concept of LP continues to develop and becomes more efficient, ¹ The earth-centered earth-fixed coordinate system o_f - $X_fY_fZ_f$: ⁸⁴ ¹⁹ and recent research shows that this approach can be combined This coordinate system is to define the orientation of satellite ⁸⁵ ²⁰ with neural network and reinforcement training approaches to re- and the positions of all the ground targets. The satellite's ori- 86 ²¹ alize more complex and effective optimization [\[17\].](#page--1-0) The use of **the entation is presented in the quaternion form**, while the ground 87 ²² LP approach in satellite trajectory and attitude planning has also targets are presented in a two-dimensional coordinate system: 88 ²³ long been carried out. Coverstone-Carroll adopted the traditional $\mathbf{p}_{ti} = [\lambda_i \; \varphi_i]$ with λ_i and φ_i denoting the target's longitude and ⁸⁹ ²⁴ LP method to realize an activity planning for a space robot consid-**Antial potatitude**, respectively. For simplicity, the coordinate system is 90 ²⁵ ering the robot's orbit dynamics and its orientation cost criterion **named as the earth fixed coordinate thereafter**. 26 [18]. Richards proposed a mixed integer optimizer for satellite's 2) The satellite body coordinate system $o_b - X_b Y_b Z_b$: This coor-²⁷ traiectory planning with avoidance constraints [19]. Zhang devel- dinate system is defined to calculate the pointing direction of $\frac{93}{2}$ ²⁸ oped a modified LP algorithm for space rendezvous mission plan-
the instrument in the inertial space. The center of the coor-
 94 ²⁹ ning, in which the problem of rendezvous and docking maneuver dinate locates at the center of mass of the satellite: The *z* ⁹⁵ 30 planning was solved by dynamical activity distribution approach direction is defined by the bore sight of the instrument. The 96 ³¹ [20] ² ⁹⁷ *y* direction is defined by the rotational axis of spacecraft's solong been carried out. Coverstone-Carroll adopted the traditional LP method to realize an activity planning for a space robot consid-[\[18\].](#page--1-0) Richards proposed a mixed integer optimizer for satellite's trajectory planning with avoidance constraints [\[19\].](#page--1-0) Zhang developed a modified LP algorithm for space rendezvous mission planning, in which the problem of rendezvous and docking maneuver planning was solved by dynamical activity distribution approach [\[20\].](#page--1-0)

33 research topic [21]. Lemaitre proposed a mission selecting and 3) The earth J2000 inertial coordination system $o_j - X_j Y_j Z_j$. The ³⁴ scheduling algorithm using image processing and area target re-
definition of this coordination system is traditional. It can be 35 grouping approach, which mainly focused on the ground area tar-
used to calculate the orbit of satellite. From the orbit informa-³⁶ get analysis and the Field of View (FOV) scanning direction plan- tion, one can determine the observation window of all targets. ¹⁰² 37 ning of onboard instrument [22]. Based on the discussion above. The coordinate system is named as the earth inertial coordi- $\frac{38}{104}$ it is clear that more improvements can be made in this research and the for simplicity. ³⁹ area. The aim of this paper is to propose a new onboard mission 4) The orbit coordinate system $o_0 - X_0Y_0Z_0$: This coordinate sys-⁴⁰ planning method for agile satellite using modified mixed-integer tem is used to describe the position of satellite in orbit. The ¹⁰⁶ 41 linear programming. The rest of this paper is organized as follows. 2 axis is collinear to the satellite position vector in the earth 107 42 Section 2 describes the detailed formulation of the onboard mis-
[2000 coordinate system. The *x* axis is perpendicular to *z* axis ⁴³ sion planning problem of agile satellites. In Section 3, the new and points to the satellite's velocity direction and the y axis 109 44 model is solved by the LP method to test its reliability, and the completes the right-hand rule. 45 111 solution obtained by Generic Algorithm (GA) is also given to con-⁴⁶ duct comparative analysis. And finally a conclusion is drawn in [Fig. 1](#page--1-0) shows the relative position between the earth, the satel-47 113 lite and the ground targets. It also demonstrates all the coordinate The mission planning for agile satellite is a relatively new research topic [\[21\].](#page--1-0) Lemaitre proposed a mission selecting and scheduling algorithm using image processing and area target regrouping approach, which mainly focused on the ground area target analysis and the Field of View (FOV) scanning direction planning of onboard instrument [\[22\].](#page--1-0) Based on the discussion above, area. The aim of this paper is to propose a new onboard mission planning method for agile satellite using modified mixed-integer linear programming. The rest of this paper is organized as follows. Section 2 describes the detailed formulation of the onboard mission planning problem of agile satellites. In Section [3,](#page--1-0) the new duct comparative analysis. And finally a conclusion is drawn in Section [4.](#page--1-0)

2. Formulation of the problem

52 118 *2.1. Coordinate system definition*

56 122 titude of 500 km. This kind of orbit enables the satellite to have 57 is global earth coverage and relative low altitude to obtain clear im- $\begin{array}{c|c} \mathcal{X}^t_{\text{c}at} & \mathcal{X}^t_{\text{c}at} \end{array}$ 58 ages [\[23,24\].](#page--1-0) The detailed mission scenario and related parameters $\mathbf{r}_{\text{cat}}^1 = |v_{\text{cat}}^1|$ (2) 124 59 in this paper are set in Table 1. $\begin{vmatrix} 1 & 1 & 1 \end{vmatrix}$ 125

60 126 The standard observation interval defined in Table 1 is obtained 64 mission planning level, the simplified dynamic model of satellite is $\begin{bmatrix} \mathcal{L}^2 \zeta_{\text{at}} \end{bmatrix}$ $\begin{bmatrix} \mathcal{L}^2 \zeta_{\text{sat}} \end{bmatrix}$ 65 adopted. It is also assumed that the satellite is able to slew with the same state of the satellite is able to slew with the satellite is able to slew with the satellite is also assumed that the satellite is able to sle ⁶⁶ a constant angular velocity in any direction. The acceleration and $\mathbf{r}'_{rel} = \mathbf{d}_{tf} - \mathbf{r}'_{sat}$ (4) ¹³²

Table 1

deceleration processes at the beginning and end of slew maneuver are neglected.

In order to conduct the earth observation mission, the AEOS satellite needs to slew frequently in engineering practice. To properly describe and define the movement and the attitude of the satellite, the following coordinate systems are defined:

- 1) The earth-centered earth-fixed coordinate system $o_f X_f Y_f Z_f$: This coordinate system is to define the orientation of satellite and the positions of all the ground targets. The satellite's orientation is presented in the quaternion form, while the ground targets are presented in a two-dimensional coordinate system: named as the earth fixed coordinate thereafter.
- ³² The mission planning for agile satellite is a relatively new lar panel and the *x* direction completes the right hand rule. ⁹⁸
	- nate for simplicity.
	- completes the right-hand rule.

48 114 148 11 Systems and the concept of scanning path of the satellite's instru-49 **115 115 115 115 115 115 115 115 115 115 115 116 11**

50 116 With the definition of the coordinate systems, the following rel- $\frac{51}{100}$ ative positions can be easily obtained: $\frac{117}{100}$

The earth observation satellites usually operate on the sun-
\nsyanchonized orbit with the inclination of 97 degree and the al-
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\mathbf{d}_{tf} = \begin{bmatrix} x_{tf} \\ y_{tf} \\ z_{tf} \end{bmatrix} = r_e \cdot \begin{bmatrix} \cos(\varphi_i) \cdot \cos(\lambda_i) \\ \sin(\varphi_i) \cdot \cos(\lambda_i) \\ \sin(\lambda_i) \end{bmatrix}
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$$
\mathbf{r}_{sat}^{i} = \begin{bmatrix} x_{sat}^{i} \\ y_{sat}^{i} \\ z_{sat}^{i} \end{bmatrix}
$$
 (2)

$$
\begin{array}{c}\n\text{For a standard observation interval defined in table 1 is obtained} \\
\text{for a standard observation interval defined in table 1 is obtained} \\
\text{for a standard position of the first line, and the first line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\n\text{For a standard position, the second line is given by the formula:\n\[\
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\mathbf{r}_{rel}^f = \mathbf{d}_{tf} - \mathbf{r}_{sat}^f \tag{4}
$$

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