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Space mission analysis

EFFICIENCY ENHANCEMENT OF SITUATIONAL ANALYSIS FOR SPACE MISSION DESIGN USING REORDERED HEURISTICS

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Abstract

Situational analysis deals with verifying conditions of a geometric or physical nature during satellites' movement in their orbits. This analysis is applied to determine time intervals, optimal for the execution of specific satellite operations. Situational problems are solved at various stages of the preparation and operational phases of the satellite missions. The most interesting cases are when a situational problem contains multiple conditions. Each situational problem is solved by sequential verifications of the involved conditions. Verifications can be terminated when an unfulfilled condition is detected (Horner's rule) to improve the efficiency of the analysis. Calculations are repeated for subsequent time steps. Solving such a situational problem may be time-consuming when multi-variant and multi-satellite simulations are performed. A heuristic approach is proposed for the efficiency enhancement of situational analysis for problems including multiple conditions. This approach is based on the reordering of conditions checks. The approach is algorithmized and incorporated into the situational analysis solver that was previously developed. The efficiency of the proposed heuristics is evaluated based on examples with different numbers of situational conditions. This approach shows better efficiency than applying Horner's rule.

Key words: situational analysis, reordered heuristics, space mission analysis and design

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Introduction. The rapid advancement of space technology has led to a significant increase in spacecraft population orbiting the Earth. Furthermore, satellites become increasingly smaller. Multi-satellite missions are designed and implemented in various scientific and applied fields [1].

Limitations are imposed on the preparation time, cost, and reliability of operational use when designing and preparing space missions, regardless of the number and type of satellites. Computer programs are used at different stages from the preparation to the realization of space missions. Various aspects of space missions are simulated to meet the ever-increasing requirements. It is important to note that in addition to well-known programs designed for commercial distribution (STK, FreeFlyer, ASTOS) or open source program GMAT, some organizations develop their own programs to meet specific needs. Some of these own programs extend beyond satellite dynamics simulations [2, 3]. Wertz and Larson [4] suggest using programs tested in numerous missions created and supported by specialized companies. Nonetheless, they highlight that developing one's own programs allows for a deeper understanding of the underlying problems. Chagas et al. [5] emphasize the importance of applying a comprehensive set of modelling and simulation toolkits to develop complex space missions. Applying multi-physics environments is crucial to tame the complex problems in space mission design [6].

The situational analysis deals with the determination of time intervals optimal for the implementation of certain satellite operations (performing measurements with various sensors, communication with ground stations; and special or general satellite operations). The fulfillment of specific conditions is verified for separate moments throughout the simulation time in the frame of this analysis. This analysis examines the conditions associated with the environment in which satellites function. We assume that the corresponding orbital event occurs when one or a combination of several conditions is met. Situational analysis along with orbital analysis, satellite operations planning, and various engineering/mechatronic-oriented analyses play a critical role in optimizing satellite missions. Applying this analysis is crucial at different stages of the preparation and execution of space missions.

At the Space Research and Technology Institute, BAS, work is being done on creating and improving the Parallel Situational Analysis Solver (PSAS) [7] and its application in space physics [8]. A reordered heuristics applicable to solving situational problems with several conditions is proposed in the present work.

Related work. Determining the optimal time intervals for observation and measurement is crucial at the initial stage of space mission preparation. Performing a situational analysis is indispensable for assessing the feasibility and realism of any mission. At the next stages, parameters related to various satellite subsystems and instruments can be optimized. These time intervals are used as input resources when planning and scheduling payload operations at the operation stage of a satellite mission [9].

The ability to make observations and measurements depends on the platform's location in orbit and various other conditions that either allow or prohibit them. These conditions are related to the visibility of the observed objects (or to the placement of measuring instruments in appropriate spatial zones) and to potential sources of interference or obstructions caused by other objects or phenomena.

Forecasting the optimal time intervals for observations in the frame of astrophysical missions necessitates the assessment of various factors, some of them related to the positions of the Sun, Moon, and satellite platform [10–12]. Additionally, physical factors such as the satellite's position relative to the South Atlantic Anomaly and polar cusps must also be considered [13, 14]. The presence of high levels of radiation background in certain segments of the orbits above these areas is a significant issue, as it can lead to electrical discharges, scientific instrument damage, and background enhancement in images obtained by optical instruments with SSD detectors. Constraints related to passing through radiation belt passages regarding XMM-Newton and Chandra missions are applied [15]. Thus, an analysis of geometrical and physical factors is essential when selecting the appropriate observation intervals, especially when dealing with sensitive scientific instruments and image acquisition systems.

The use of optical sensors in space to track space debris raises a number of interesting and pressing challenges. Scott and Thorsteinson [16] consider different constraints regarding NEOSSat Space-Based space situational awareness mission representing microsatellite space telescope designed to track resident space objects and perform asteroid astronomy. Orbital conditions related to constraints related to the satellite platform and its orientation relative to the Sun and the Earth, the observation objects and the mutual position of the platform and the observed objects (resident space objects) are considered in detail. Further constraints are applied to the telescope's field of view – avoiding the galactic centre and containing background stars. Du et al. [17, 18] presented results from computer simulations to evaluate the performance of multi-satellite space debris cataloguing missions.

The visibility of objects and areas of the Earth's surface depends on the parameters of the Earth's orbit and its rotation in remote sensing missions. For observations in the visible spectral range, the objects must be illuminated by the Sun. Observations of the unilluminated part of the earth's surface are carried out in the infrared spectral range, as the satellite may be in the umbra [19].

Concept of situation analysis. As pointed out above, situational analysis is applied to the space mission analysis at the initial stages of their preparation. During the operation stage, this analysis provides the planning and scheduling of satellite operations with appropriate time intervals for their execution. Each situational problem SP is composed of one or a conjunction of several situational conditions sc_i of different types:

$$SP = sc_1 \wedge sc_2 \wedge \ldots \wedge sc_n = \bigwedge_{i=1}^{n} sc_i. \tag{1}$$

Applying Horner's rule we can write
(2)

$$SP = (\ldots(\ldots(sc_1 \wedge sc_2) \wedge \ldots) \wedge sc_m \ldots \wedge sc_{n-1}) \wedge sc_n = \bigwedge_{i=1}^{m} sc_i, \quad (m \leq n),$$

where m is the index of the first unfulfilled condition among ordered n conditions of the situational problem. While the algorithmic complexity of representation Eq. (1) is $O(n)$, that of Eq. (2) is $O(m)$ $(m \leq n)$. The conditions themselves are predicate functions accepting values of ***true*** or ***false***. They can be generally represented as:

$$sc_i = sc_i\left(\{\overrightarrow{R}\}, \{\alpha\}, \{\beta\}, t\right),$$

where $\{\overrightarrow{R}\}$ is a set of radius vectors of satellites, $\{\alpha\}$ is a set of parameters of the mathematical model describing the situational condition, and $\{\beta\}$ is a set of specific constraints. The sets of parameters $\{\alpha\}$ and constraints $\{\beta\}$ are specific for each situational condition. In some cases they are explicitly entered when composing the situational task (conditions 3 in Table 1). In other cases they are defined by models. This is the case of conditions 1 and 2 in Table 1. The radius vectors of the Sun and Moon are parameters of the geometric models of the corresponding situational conditions, which are calculated based on models of their movements. In this formulation, solving a situational problem represents a verification of the feasibility of a logical function at appropriate (or equidistant) moments.

Enhancement of situational analysis efficiency. ***Basics.*** Improving the effectiveness of situational analysis is important for the following reasons:

- A large number of situational problems must be solved; the large number of problems is a result from the number of satellites, scientific instruments, objects to study, and scientific tasks to solve;
- Solving problems with several situational conditions each requires more calculations;
- Multiple solving while varying different parameters (orbital parameters, parameters of satellite subsystems) in order to optimize them;
- Running computer simulations over a long time horizon.

Enhancing the efficiency of situational analysis by reordered heuristics. Heuristics are ways of solving problems based on practical or intuitive assumptions about optimality. Unlike methods, they are not associated with rigorous evidence. Here, a heuristic to enhance the efficiency of solving multi-conditions situational problems by reordering them is proposed – reordered heuristics.

Instead of the direct problem SP, to verify Eq. (1) or Eq. (2), let us consider the opposite problem [20]:

$$\overline{SP} = \overline{sc(t)_1 \wedge sc\,(t)_2 \wedge \ldots \wedge sc(t)_n} = \left(\overline{\bigwedge_{i=1}^{n} sc(t)_i}\right). \tag{3}$$

According to (1) or (2), we look for time intervals when all conditions are met. In the opposite task (3), we look for time intervals when at least one of the conditions is not fulfilled. Applying de Morgan's law, we can represent the opposite problem Eq. (3) as follows:

$$\overline{SP} = \overline{sc(t)_1} \vee \overline{sc\,(t)_2} \vee \ldots \vee \overline{sc\,(t)_k} \vee \ldots \vee \overline{sc\,(t)_n}.$$

To solve the opposite problem $\overline{SP}$, it is enough that only one of the conditions $\overline{sc\,(t)_k}$ is fulfilled. After finding the $k^{\text{-}th}$ condition $(\overline{sc\,(t)_k} = true)$ sufficient to solve the problem, one can proceed with verifications in the next steps by applying the following heuristic:

$$\overline{SP} = \overline{sc(t+\Delta t)_k} \vee \overline{sc(t+\Delta t)_1} \vee \ldots \vee \overline{sc(t+\Delta t)_{k-1}} \vee \overline{sc(t+\Delta t)_{k+1}} \vee \ldots \\ \ldots \vee \overline{sc(t+\Delta t)_n} \tag{4}$$

The meaning of reordering the conditions is related to the fact that the situational conditions themselves are slowly changing functions with respect to the time step with which the simulation model is discretized. In fact, moving the $k^{\text{-}th}$ unfulfilled condition in the first place causes verifications to interrupt already on the very first condition for a large number of time steps.

Examples of applications. ***Situational problem compilation.*** Let us consider a situational problem composed of several types of conditions (Table 1):

Table 1

Example of situational problem

Numerical identifier	Titles of the types of situational conditions that are used below
1	The satellite is in the Earth's shadow
2	The Moon is under the horizon
3	The satellite passes over a circular area of Earth's surface with geographic coordinates of its centre (φ, λ) and angular radius δ.

Such situational problems arise in remote sensing missions. The situational conditions mentioned in Table 1 are included in the situational problem editor and the situational solver.

Evaluation of the efficiency depending on the order of the conditions. A numerical experiment is conducted to evaluate the efficiency of the proposed heuristic. Both experiments simulated the motion of a satellite in an orbit with the following parameters: semi-major axis a=7 000 000 m, eccentricity e=.001, and inclination i of 5°. It is verified whether the satellite passes above a circular area on the surface of the Earth with geographical coordinates of the centre at $(0^\circ, 0^\circ)$, and an angular radius of $\delta = 10^\circ$. Additionally, it is verified whether the satellite is in the shadow of the Earth, and if the Moon is below the horizon. The integration of the equations of motion of the satellite and the checks of the conditions are performed within a time horizon of thirty days with a step $dt = 10$ s.

Table 2 contains results regarding the number of verified conditions when solving the situational problem based on a static ordering of the conditions applying Horner's rule (2) and when applying reordered heuristics.

Table 2

Number of condition verifications performed the situational problem

Variants of the conditions ordering	Verified conditions with Horner's rule	Verified conditions with heuristics	Efficiency [%]
1-2-3	277 635	263 919	4.94
1-3-2	277 588	263 916	4.92
2-1-3	358 035	263 918	26.29
2-3-1	389 388	263 919	32.22
3-1-2	358 320	263 915	26.35
3-2-1	389 720	263 920	32.28

Figure 1 shows a timing diagram of the situational conditions for the considered time horizon. The three situational conditions are fulfilled simultaneously in the following time intervals: (31 200, 31 410), (37 340, 37 670), (43 580, 43 920), (49 840, 50 170), (56 100, 56 410), and (62 360, 62 430).

Moreover, in this experiment, the conditions are more than those in the second, and given the applied reordered heuristic the probability of fulfilling more conditions in one time step is smaller than that with fewer conditions. Therefore, the number of checks performed decreases with an increase in the number of conditions when applying this heuristic!

Effectiveness of the proposed heuristics. Let us note that terminating the verifications upon failure of the next checked condition in (2) increases the efficiency of solving the situational problem compared to initially solving all predicate functions sc_i and computing the situational problem as $SP = \overset{n}{\underset{1}{\wedge}} sc_i$. Let us note that when solving situational problems, applying Horner's rule as $SP = \overset{k}{\underset{1}{\wedge}} sc_i$, $k < n$, instead of checking all conditions as $SP = \overset{n}{\underset{1}{\wedge}} sc_i$ improves the efficiency in obtaining the final result. Applying (1) within a thirty-day simulation interval with a 10-sec step will lead to 777 600 and 1 036 800 checks for each of

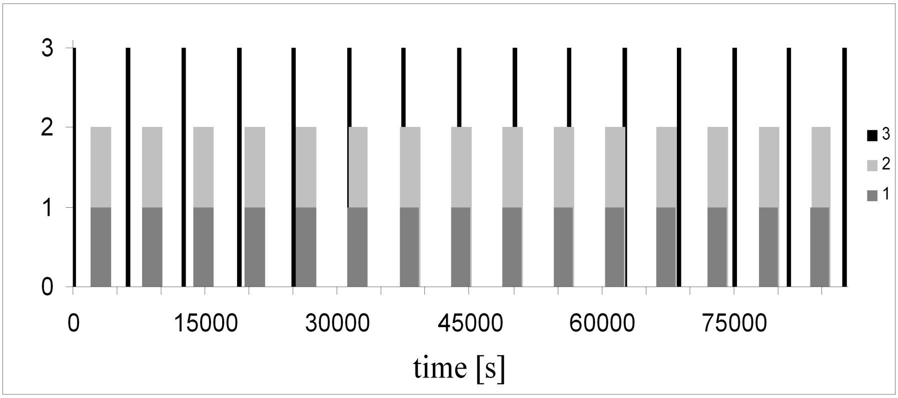

Fig. 1. Time diagrams of situational conditions is shown; 1 – the satellite is in the Earth shadow, 2 – the satellite is in the shadow of the Moon, and 3 – the satellite passes over a circular region

the first two situational problems, respectively.

Table 2 shows the performance when applying these two approaches – Eq. (2) and Eq. (4), evaluated for different initial orderings of conditions in the two situational problems. It can be seen that the initial order of conditions affects the efficiency when applying Horner's rule. Applying the proposed heuristic results in an almost complete equalization of the number of checks.

Discussion. Solving a situational problem involving several conditions, for an extended interval of simulation time, is not based on an exact algorithm even when applying Horner's rule. The number of verified conditions for different moments of time t varies. Thus, the algorithmic complexity changes depending on the checked conditions – $O(m(t))$. Only for the time interval when all conditions are fulfilled the complexity is $O(n(t))$. Applying conditions reordering, the algorithmic complexity is O(1) for long segments along the time axis!

When applying Horner's rule, the number of checks is sensitive to the order of situational conditions and the orbital parameters of the satellite. The value of the orbital parameters of the satellites, as well as the position of the Sun and the Moon, determine the geometric configuration with which the situational conditions are associated. The reordered heuristic minimizes this and other irregularities. Further numerical experiments show that with an increase in the number of conditions in situational problems, the number of checks decreases.

Conclusion and outlook. The proposed approach for efficiency enhancement of the situational analysis was implemented within the framework of the developed PSAS. The latest version of the situational solver is designed for use in a multiphysics environment for space mission simulations. The application of this approach turns the solver into a powerful analysis tool, increasing the efficiency of simulations.

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