

A Method for Analyzing the Complexity and Safety of the Movement of Controlled Objects along Specified Routes

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Abstract: This paper presents a comprehensive study on the analysis of the complexity and safety of the movement of controlled objects along specified predefined routes. The focus is on a method for evaluating route complexity, which entails encoding routes into a finite number of non-overlapping segments and applying recurrent forms to compute the spectra of dynamic parameters. This technique allows for an assessment of the difficulty level of a particular object's route.

The methodology enables the identification of potential obstacles and safety hazards associated with the movement along such routes. An instance of this technique illustrated in this study through a practical example, which includes the movement of a rover on Mars. This instance demonstrates the efficacy of the proposed technique in a real-world scenario, highlighting its potential applicability in both terrestrial and extra-terrestrial navigation. The study emphasizes the significance of route complexity analysis for enhancing the reliability and security of controlled objects, which is essential for the advancement of technologies in space exploration and other areas.

Keywords: Complex systems, assessment of the complexity of the route of movement for mobile objects, controlled objects, the reliability and safety of mobile objects.

1. INTRODUCTION

The advancement of robotics has reached a qualitatively new level [15]. Robots now operate in practically all spheres of human life, including space exploration [22]. Companies and researchers reduce the cost of shipping cargo beyond Earth every year [1], develop more sophisticated spacecraft engines [13], and conduct experiments with diverse fuel types [18]. These efforts create opportunities to further lower costs and streamline rover delivery to space objects.

Furthermore, the evolution of rovers has been a gradual process, spanning from the initial designs in 1963 [14] to the present-day models [3]. The advancement in navigation methods [17] and the development of innovative propulsion systems [7] are two notable examples of this evolution. To date, there have been seven successful missions involving rovers on the surface of the Moon [6] and six such missions to Mars [5].

One of the principal challenges facing autonomous robots is their ability to navigate effectively on unfamiliar and complex surfaces [9]. Planetary vehicles designed to explore the Moon and Mars must be capable of functioning effectively in harsh conditions, including rough terrain, rocks, dust, and temperature changes [10, 11, 12]. This necessitates the development of robust and resilient mobility systems to ensure the stable operation of rovers even in extreme conditions. Additionally, remote control and autonomous operation technologies play a crucial role in such missions, enabling rovers to fulfill their tasks without constant interference from operators on Earth [19].

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The approach outlined in the paper represents a significant area of research that is becoming increasingly crucial in the context of contemporary technological development, particularly in the domain of space exploration.

Route complexity analysis plays a crucial role in designing object movement on Earth [20] and other celestial bodies [2]. This method estimates route complexity by defining the route code, recurrence forms [4, 21], and dynamic spectra of parameters, which hold particular importance during critical phases like aircraft landing [16]. Recent advances in navigation and autonomous system control, including the use of SLAM (Simultaneous Localization and Mapping) techniques, further enhance route complexity analysis [8].

This paper analyzes and implements a methodology for assessing the complexity and safety of an object's movement along given routes. This assessment is crucial when traveling on complex and poorly explored surfaces. The methodology encodes routes as a finite number of non-overlapping segments and applies recurrence forms to compute dynamic spectra. This approach quantifies the level of complexity of a particular route for a controlled object.

Furthermore, the work presents a practical illustration of the developed methodology's application to rover movement on Mars. This example demonstrates the efficacy of the proposed method and its prospective real-world applications.

Therefore, the present study addresses route planning and is of fundamental importance for improving the safety of guided object motion in various environments.

2. GOALS AND OBJECTIVES

This work aims to develop and apply a method to compare the complexity of specified routes. The method represents the route as a finite number of non-overlapping segments and analyzes movement properties on these segments. The spectrum of dynamic characteristics of the sequence provides a formal apparatus for analyzing route complexity.

Research tasks:

1. Application of route encoding methodology.
2. Application of recurrent forms.
3. Assessment of route complexity based on computed parameters.
4. Comparison of the complexity of different routes and selection of the most optimal one.
5. Analysis of the obtained results.

3. PROBLEM STATEMENT

The problem consists of several steps:

1. Define routes in space.
2. For each route, according to a given alphabet, record the sequence $\bar{\xi}$ of codes of the segments in order of the object's movement direction.
3. According to these sequences $\bar{\xi}$ and recurrent forms, introduce a functional Ω of dynamic parameters for each route to obtain numerical values characterizing the structure of the sequence $\bar{\xi}$ elements, rule changes, and sequence $\bar{\xi}$ parts where the control action selection rule applies. Ω functions are criteria for evaluating and comparing various pre-defined routes for controlled object movement.

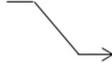
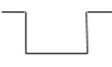
4. SOLUTION METHODS

Solution methods consist of a few steps:

1. Build several routes from point A to point B.
2. Encode the entire route by dividing it into segments corresponding to selected standard sections.

For route encoding, we use the alphabet from Table 4.1 [5].

Table 4.1. Alphabet for coding obstacles on the route

Surface type	Form and Introduced Code			
	form	codes	form	codes
Rock, roller		b_1, z_1		b_2, z_2
		b_3, z_3		b_4, z_4
Stepped obstacle		c_5, z_5		c_6, z_6
		c_7, z_7		c_8, z_8
Ditch		v_9, z_9		v_{10}, z_{10}
		v_{11}, z_{11}		v_{12}, z_{12}
Hill		g_{13}, z_{13}		g_{14}, z_{14}
Crater without rollers		k_{15}, z_{15}		k_{16}, z_{16}
Crater with rollers		k_{17}, z_{17}		k_{18}, z_{18}
Section without obstacles		e_{19}, z_{19}		e_{20}, z_{20}

3. For each route, record a sequence $\bar{\xi}$ of segment codes in order that represents the direction of the object's movement.
4. According to these sequences $\bar{\xi}$ and recurrent forms, a spectrum Ω of dynamic parameters is introduced for each route to obtain numerical values characterizing the structure of element arrangement in the sequence $\bar{\xi}$, rule changes, and sequence $\bar{\xi}$ parts where the control action selection rule applies.
5. As rules P_1, P_2, \dots, P_c for building the spectrum Ω , recurrent forms F_1, F_2, \dots, F_c defining the element arrangement in parts of the sequence $\bar{\xi}$ are used.
6. Two spectra are defined in our case:
 - a. For the sequence $\bar{\xi} \in U^*$, the smallest order of the recurrent form defining the sequence $\bar{\xi}$ is denoted as $m_0(\bar{\xi})$ — spectrum $\Omega_0(\bar{\xi})$.
 - b. For any sequence $\bar{\xi} \in U^*$ and $m \in N^+$, where $1 \leq m \leq m_0(\bar{\xi})$ the longest initial segment of the sequence $\bar{\xi}$ defined by a recurrent form of order m is denoted as $d^m(\bar{\xi})$ — spectrum $\Omega_1(\bar{\xi})$.
7. Using these notations, the spectrum $\Omega(\bar{\xi})$ is defined as follows: $\Omega(\bar{\xi}) = \langle \Omega_0(\bar{\xi}), \Omega_1(\bar{\xi}) \rangle$, where:

$$\Omega_0(\bar{\xi}) = \langle m_0(\bar{\xi}) \rangle,$$

$$\Omega_1(\bar{\xi}) = \langle d^1(\bar{\xi}), d^2(\bar{\xi}), \dots, d^\alpha(\bar{\xi}) \rangle.$$
8. After determining the spectra for each sequence, identify the best route among the previously defined ones as the most reliable and safe. Consider the obtained spectrum

for the sequence $\bar{\xi}$ as a numerical structure that represents the sequence complexity through the sequence $\bar{\xi}$ structure and the rule used to describe the sequence by recurrent forms, i.e., the process of controlling movement along the route.

5. MAIN RESULTS

Routes were drawn up on the surface of Mars.

Two routes from the start point to the finish point that bypass a crater on the surface of Mars. In Figure 5.1, the first route is marked with a red line, and the second with a blue line.

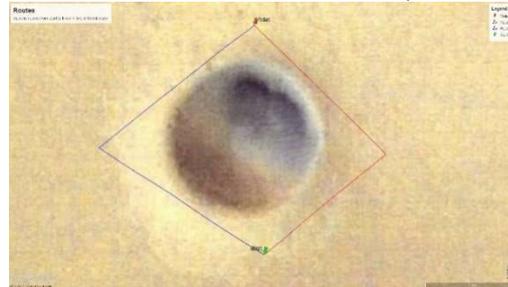


Fig. 5.1. Routes

We will encode routes depending on the terrain. We will get two marked routes with heights as seen in Figure 5.2 and Figure 5.3.

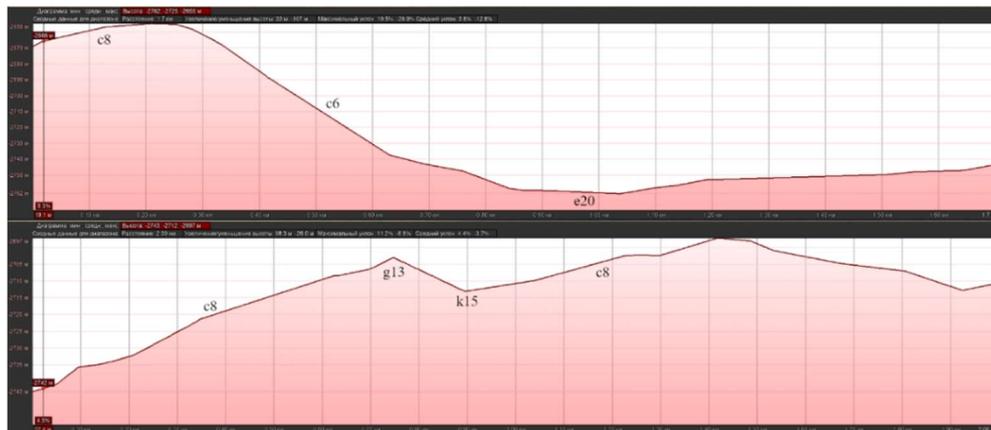


Fig. 5.2. Route №1

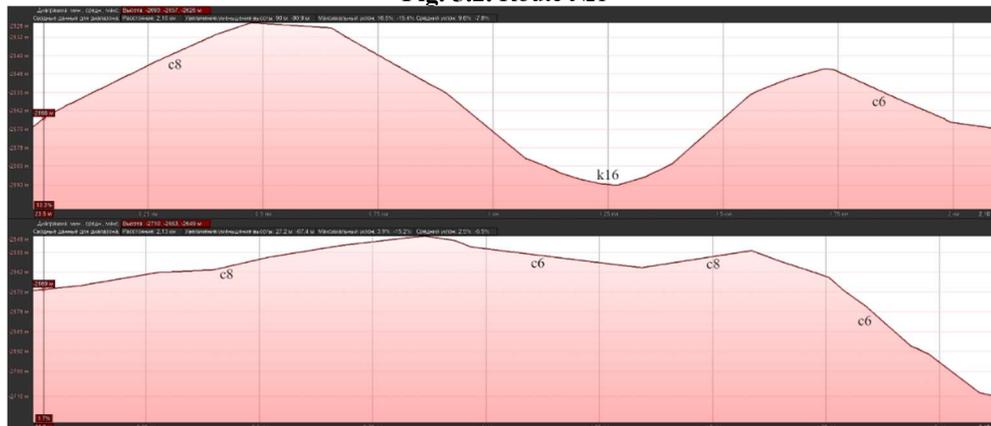


Fig. 5.3. Route №2

The next step is to record sequences $\bar{\xi}_1$ and $\bar{\xi}_2$ which represent the direction of the object's movement on two different routes. These sequences will help us to assess the difficulty and safety of the routes. The following routes codes were obtained:

$$\bar{\xi}_1 = c_8 c_6 e_{20} c_8 g_{13} k_{15} c_8;$$

$$\bar{\xi}_2 = c_8 k_{16} c_6 c_8 c_6 c_8 c_6.$$

Calculate the spectra using sequences $\bar{\xi}_1$ and $\bar{\xi}_2$:

For the 1st route:

$$\begin{aligned}\Omega_0(\alpha_1^{(1)}) &= 2 \\ \Omega_1(\alpha_1^{(1)}) &= \langle 4,7 \rangle\end{aligned}$$

For the 2nd route:

$$\begin{aligned}\Omega_0(\alpha_1^{(2)}) &= 2 \\ \Omega_1(\alpha_1^{(2)}) &= \langle 4,7 \rangle\end{aligned}$$

In the result, we can say that based on the zero criteria and the first criteria, the routes are equal in their complexity and safety. That leads us to the conclusion that in this case the choice of routes is equal whether we choose the first or the second route, despite their seeming to be different.

6. DISCUSSION

The methodology outlined in this study offers significant potential for enhancing the complexity and safety analysis of controlled object movement. By leveraging route encoding and recurrent forms, the approach provides a quantitative framework for assessing route difficulty. This is particularly advantageous in scenarios where precision and safety are paramount, such as space exploration and automated navigation systems.

One of the key strengths of this method is its flexibility and applicability to various environments. The case study involving Mars rover movement underscores the method's effectiveness in extra-terrestrial settings. However, the principles and techniques can be readily adapted for terrestrial applications, such as autonomous vehicle navigation in urban or off-road environments.

7. CONCLUSION

In conclusion, the proposed methodology for analyzing the complexity and safety of controlled object movement along specified routes offers a robust framework for evaluating route difficulty. By encoding routes into non-overlapping segments and employing recurrent forms to compute dynamic parameter spectra, this method enables a detailed assessment of potential obstacles and hazards. The application of this methodology to the movement of rovers on Mars demonstrates its practical utility and effectiveness in real-world scenarios, displaying its potential for terrestrial and extra-terrestrial navigation.

The analysis of route complexity and the identification of the most reliable and safe routes are crucial for advancing technologies in space exploration and other domains. The ability to quantitatively compare different routes and select the optimal one based on computed parameters enhances the reliability and safety of controlled objects. This research contributes significantly to the field of route planning, ensuring the safe and efficient movement of controlled objects in diverse and challenging environments.

Future work could explore further refinements of the encoding and computational techniques, as well as the application of this methodology to a broader range of scenarios and object types. The integration of this approach with advanced control systems and autonomous navigation technologies holds promise for continued advancements in the safety and efficiency of route planning for moving objects.

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