IOP Conference Series: Materials Science and Engineering

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To cite this article: V B Derzhanskii *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **709** 022088

Substantiation of the trajectory planning algorithm for unmanned tracked vehicle

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Abstract. Mobility operation of an unmanned transport vehicle (UTV) when operating on rough terrain is a difficult task. The most difficult is the problem of the tracked UTV motion. Simplification of the controlled motion simulation, ambiguity of the track – terrain interaction parameters, the random nature of external impacts lead to fuzziness of the status parameters of the UTV as a controlled object. The article proposes a method for trajectory planning of the UTV motion, taking into account the nonholonomic nature of the track – terrain interaction. Within this objective, three aspects of the research stand out sharply. First, refinement of the tracked vehicle mathematical model. Secondly, the Voronoi diagram method is the basis of the algorithm for motion trajectory planning. Thirdly, the parameters of interaction with the external environment, in particular, the dependences of the coefficient of resistance to side slip, being obtained in real time, allow us to synthesize a correcting matrix that provides for increased motion stability. The effectiveness of the proposed approach is planned to be assessed by UTV controlled motion simulation and during experimental investigations.

1. Introduction

The solution of transportation problems in the absence of infrastructure is most efficient when using high-speed tracked vehicles. Long mileage, weather hazards raise the question of autonomous unmanned control systems applicability. The problem of creating an autonomous tracked vehicle control system is obfuscated by insufficient feedback of the existing mathematical model of motion. Nonholonomicity of track-terrain interaction, the parameters and physical and mechanical properties of which are of random character and do not allow for achieving high quality control of the tracked vehicle. Thus, the requirements for the algorithm of an unmanned vehicle should include constructing a trajectory using prescribed data and trajectory adjustment in accordance with the environment. The motion trajectory should take into account the current parameters of interaction both within the mechanical system and interaction with the ground contacting area. It is also necessary to provide a guaranteed allowance when avoiding obstacles to ensure safe motion.

The goal of the research is to create an autonomous unmanned control system. To achieve this goal, it is necessary to solve several basic tasks. The first task is to create an algorithm for constructing a motion trajectory. The second one is to refine the mathematical model of tracked vehicle motion. The third one is to obtain data on the parameters of track – terrain interaction. This paper analyzes the existing trajectory planning methods, identifies related problems and suggests the ways for solving them.

2. Analysis of the existing trajectory planning methods

Various methods are used to construct the trajectory. The analysis of the published works in this field allows us to distinguish two approaches: calculating the trajectory in a-priori-known static environment and traveling around the detected obstacles due to the information coming from the sensors. The best result is observed when combining these approaches [1].

Trajectory calculation in a static environment allows for planning a path that meets specified parameters, for example, the shortest path, a certain curvature, the shortest elapsed time, etc. The problem of defining the path between the starting and ending points is solved in different ways. The most frequently mentioned methods are the potential field method, the roadmap method, the genetic algorithm method, the use of the neural network, etcetera [1].

The methods based on one or another form of “machine learning” (the genetic method, neural network) consist in repeatedly traveling through a given situation with a random change in parameters or object behavior. The option that gives the best results becomes the basis for further mutations. The high potential of adaptability is an apparent advantage of these methods. However, high complexity of implementation and requirements for computational efforts complicates their practical application.

The method of potential fields is widely used [2]. A robot and obstacles are represented as positive charges, and the endpoint is negative. Despite the simplicity of the method implementation, it is necessary to solve the problems of a “local minimum trap” [1] and passing between two closely spaced obstacles.

Roadmap methods use a graph (Roadmap) round obstacles for a completely known map. At the same time, there are many ways how to construct a roadmap: visibility graph [3], cell decomposition [4], rapidly exploring random trees (RRT) [5, 6], and many others.

The following is an example of implementing construction of a trajectory based on the Voronoi diagram (graph) [7, 8]. This graph has a very important feature for navigation. It passes at the greatest distance from the nearest face. From the abovementioned data, it follows that the trajectory constructed on the basis of the Voronoi graph is the safest from the point of view of obstacle collision.

The motion of an unmanned transport vehicle in a natural dynamic and/or unknown environment is accompanied by appearance of accidental obstacles on a pre-computed trajectory. To ensure safe motion, it is necessary to make adjustments. In many cases, for this purpose, the algorithms of the Bug’s family are used [1, 9]. In addition, there are modifications of various methods, for example, of the potential field, of the Voronoi graph, etc. [10, 11].

3. Formation of the trajectory planning algorithm

The Voronoi graph will be used as the basis for a trajectory, the advantages of this method are described above. Fig. 1 shows the construction of the trajectory. First (Fig. 1a), the graph (blue lines) is constructed, around obstacles (purple polygons). The start and end points are marked with “o” and “+” respectively. In the future, the shortest trajectory based on the lines of the graph is calculated. The resulting trajectory is shown in Fig. 1 b) and highlighted in gray.

It is important not to lose the fact that real vehicle motion, in contrast to a material point, is conducted with restrictions due to the conditions of interaction both inside the mechanical system and with the ground contact area. Therefore, this trajectory fails to provide optimal energy-efficient motion and the shortest travel time.

The next step in constructing a trajectory is to analyze the trajectory from the point of view of a tracked vehicle mathematical model. The shortest trajectory is not always able to provide motion optimal speed, and, consequently, the shortest travel time. Minimum turning radius limit depending on the current traveling speed in certain conditions can lead to a collision with an obstacle being steered around and, in order to ensure motion safety, it will be necessary to reduce the speed. The speed of a real vehicle can also be limited by the following factors: by ensuring vehicle maneuverability, running smoothness when driving over rough surface, energy performance while varying the coefficients of resistance to motion and turning, as well as providing traction and adhesion properties (limiting track undercarriage longitudinal slide, determined by the value of the adhesion coefficient) From the above,

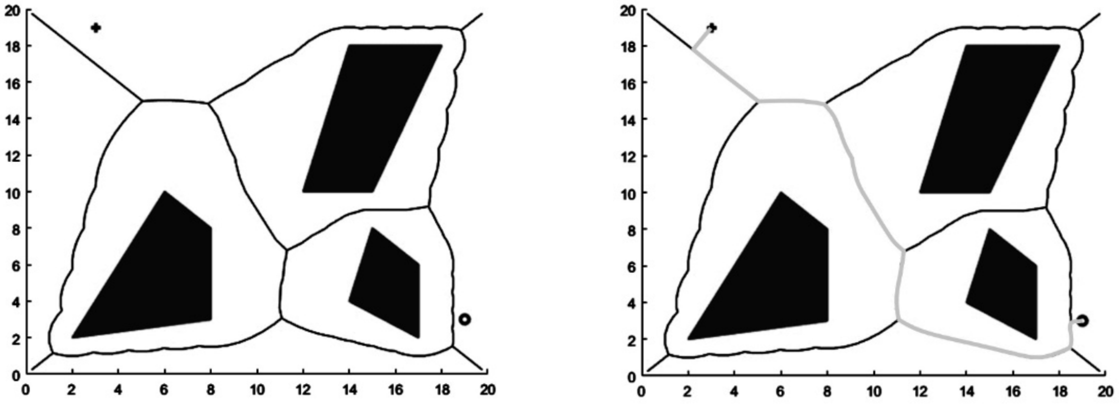

Figure 1. construction of a Voronoi graph for a 20x20 zone with obstacles (a) and finding the shortest trajectory from the start point “o” to the end point “+” (b).

it follows that the trajectory should be adjusted depending on the value of the physical and mechanical properties of the contact surface, the parameters of interaction with the track undercarriage, measured in real time mode.

When designing a trajectory, a mathematical model of vehicle motion is required. Known models require adjustment that take into account additional constraints determined by the algorithm of autonomous control system functioning. In this regard, the paper describes the model, the novelty of which lies in the fact that the elastic-inertial properties of the steering control system (elastic-inertial properties of the “Engine-Transmission- Track Undercarriage” system) are taken into account. This allows for simulating the quality of transients more accurately. In addition, in the mathematical model, it is assumed that the moment of resistance is formed by the forces of lateral skid of the track undercarriage elements. At the same time, the function of the resistance coefficient to the lateral skid of slip angle is nonlinear. The mathematical model is presented as a system of differential equations (1).

The first two equations of the system describe the translational movement of the vehicle in the longitudinal (x) and lateral (y) directions. The third equation determines the rotational motion of the vehicle about the vertical axis (z), taking into account the centrifugal effect. The fourth equation determines the oscillatory process in the control drive in the Engine – Transmission –Vehicle system.

In these coordinates, the plane-parallel motion of the vehicle is determined by the following system of differential equations:

$$\begin{cases} \dot{V}_x = \delta_x^{-1} \mathrm{g}(f_d - f_C) - V_y \omega_y \\ m\dot{V}_y = mV_x\omega_z + \sum C_{y_i}\theta_i \\ \dot{\omega}_z J_z = -mV_x\omega_z(\chi - l_{c.m.}) + \sum_i C_i \cdot \theta_i(\chi - l_i) - C_{tor}(\varphi_m - \varphi_e) + M(f) \\ \dot{\omega}_e J_e = -C_{tor}(\varphi_e - \varphi_m) - b_{dis}(\omega_z - \omega_e) + M(f) \\ f_C = f_{gr} + i + f_p \\ \chi = f(V_x, \omega_z, \mu) \\ \theta_i = f(\omega_z, V_x, \chi) \\ C_{y_i} = f(\mu, \omega_z) \end{cases} \qquad (1)$$

where m is the vehicle mass; $\mathrm{V_x}$, $\mathrm{V_y}$, $\mathrm{\dot{V}_x}, \mathrm{\dot{V}_y}$ are longitudinal and transverse speeds and accelerations, respectively; $\omega_e, \dot{\omega}_e$ are an angular velocity and engine acceleration, respectively, reduced to the Z axis; g is gravitational acceleration; f_d is a dynamic factor; f_C is the coefficient of resistance to motion; C_{y_i} is the coefficient of resistance to side slip of the i-th pair of road wheels; χ is longitudinal displacement of the turning pole; θ_i is the slip of the axis of the i-th pair of road wheels; l_i is the distance from the axis of the rear pair of road wheels to the axis of the i-th pair of road wheels; $l_{c.m.}$ is the distance from the axis of the rear road wheels to the center of masses; J_z is the moment of inertia of the vehicle; J_e is the moment of inertia of the engine, reduced to the Z axis; φ_m, ω_Z is the angle and angular velocity of the vehicle; φ_e, ω_e is angle and angular velocity of the engine reduced to the Z axis; $\mathrm{b_{dis}}$ is dissipation coefficient; $\mathrm{C_{tor}}$ is the reduced stiffness of the control system.

The nonholonomic nature of the track – terrain interaction is of particular importance. To formalize the process of track slip, methods of computational-experimental determination are developed and coefficients of leading track longitudinal sliding and lagging track skidding are introduced into the mathematical model; transverse displacement of tracks rotation poles, as well as the magnitude of the adhesion coefficients of the lagging and leading tracks, limiting the implementation of tractive forces. One of the major parameters is the coefficient of resistance to the side slip, which, in turn, is a function of the slip angle of the track undercarriage elements [12].

Measurement of the coefficient of resistance to the side slip is determined by the magnitude of the yawing affecting the road wheel support arm. In this case, determination of the slip angles of the track undercarriage elements is the most difficult and not a fully solved problem. One of the most well-known methods for determining slip angles is the use of optical sensors [13, 14], in which the analysis of the motion of the contact area characteristic points, marked in the digital image, is performed. The abovementioned method has already found its application in the automotive industry, work is underway to expand the possibilities of its application at low speeds on rough surface, i.e. for off-road vehicles [15, 16]. Another approach is to use GPS coordinates [17, 18]. This eliminates the influence of external factors such as dust, dirt, precipitation, frost and fog. Thus, when studying the tracked vehicle behavior characteristics on various types of soil, a method has been implemented for determining the slip angles of elements of the track undercarriage configuration with respect to transverse and longitudinal speeds [19].

During the tests, the coordinates of two separated GPS receivers were determined. The analysis of the obtained data allowed us to find the real slip angle at each separate moment of time. Later, the dependence was found of the coefficients of resistance to side slip on the slip angles of the track undercarriage configuration elements. Figure 2 a) shows the results of experimental determination of the coefficient of resistance to side slip on angles for two types of soil for a tracked vehicle: 1 - turfed soil; 2 - sandy ground. Figure 2 b) shows approximate dependencies for different soils with variation of the resistance coefficient to turning from 0.1 to 0.8.

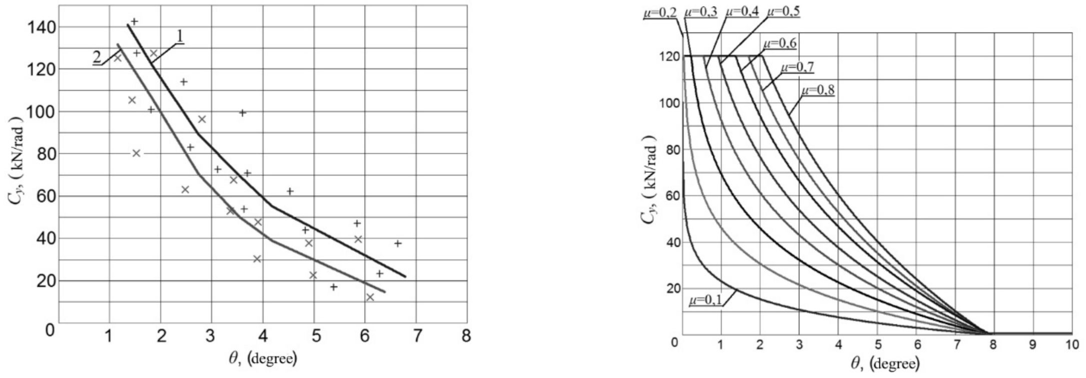

Figure 2. Dependence of coefficients of resistance to side slip on slip angles of elements of the track undercarriage configuration a) experimental dependences b) approximated dependencies

These dependences allow us to propose a reliable method for determining the type of soil over which the vehicle travels. Thus, it becomes possible to adjust the control input and eigen parameters of the transport vehicle in accordance with the current measured physical and mechanical properties of the contact area.

4. Findings

1) Based on the analysis of the known methods of trajectory planning of an autonomous transport vehicle in an area with obstacles, it has been established that one of the effective algorithms is to construct a trajectory based on the Voronoi diagram.

2) It has been established that the motion trajectory should take into account the current parameters of interaction both within the mechanical system and interaction with its contact area. It is also necessary to provide for a guaranteed clearance when avoiding obstacles to ensure motion safety.

3) The motion trajectory being constructed should be adjusted in accordance with the updated mathematical model of the control object, which differs from the known ones by the fact that the elastic-inertial properties of the control system, the torque of resistance is formed by the lateral skidding efforts of the track undercarriage elements. This function is non-linear, which is determined by the nonholonomicity of the track – terrain interaction.

4) Refinement of the trajectory being constructed should provide motion without side slip, machine maneuverability, smoothness when driving over rough surface, energy efficiency with variations in the coefficients of resistance to motion and turning.

5) A calculation and experimental determination method has been developed to determine the coefficient of resistance to side slip of the elements of the track undercarriage configuration as a function of the slip angle.

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