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Method for determining the trajectory of a sensor-controlled ground agricultural vehicle

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Abstract. The article describes a method for determining the unmanned ground agricultural vehicle trajectory, based on calculations of only the boundary values of restrictions, using root-finding and polynomial evaluation. The paper presents a mathematical description of the unmanned ground vehicle trajectory. This thesis also describes a mathematical model for generating the trajectory of movement unmanned ground vehicle; methods for determining the velocity of movement vehicle and the time optimal trajectory. The article presents the results of an experiment on generating the unmanned ground agricultural vehicle trajectory.

1. Introduction

At times of agricultural production intensification in consideration of the technical and technological trends in the production of industrial driverless vehicles, their number in agriculture increases every year. However, the solution of the problems of the trajectory synthesis, planning and implementation of the trajectory of movement is carried out by using un-manned ground-based agricultural vehicles in a complex environmental management system, an example of which is a rural area.

Currently, spline interpolation, which is the use of common polynomials and the determination of factors that ensure continuity at the junction points, is the usual method of constructing a trajectory [1]. The specific tasks, the amount of available data and the preliminary requirements of the researcher are determined by the choice of the order of the polynomials. Therefore, there are no universal rules for choosing the order of a polynomial, and it should be based on experiments and data analysis. For example, the process control appropriate to the first derivative, which correlates with the resulting parameter of the vehicle and its linear velocity, is carried out by the second-order polynomials.

It is known that ordinary polynomials can be used to calculate both the trajectory and the factors determining the necessary initial and final position. Therefore, in order to administrate the initial and final conditions, it is recommended to use a Bezier curve containing a suitable set of parameters [2]. Thus, the mathematical description of the Bezier curve is the basis for using the trajectory determination method presented in this article.

The method is based on the use of trajectory parameters and its initial and final velocity, which allow re-estimation within the actual tangential velocity and orientation of the moving vehicle in real time. The article also includes a description of a method for creating an optimal trajectory with a time gap based on a given set of points in compliance with the kinodynamic constraints of the vehicle (Bezier curves). Moreover, the set of points, based on which a trajectory is formed, can be intermediate points, post-processing the shortest way to the necessary target position.

2. Materials and methods

Customizable sensors must be used in modern robots. The authors of the article below considered the properties of an electromagnetic sensor [3]. At the same time, in order to improve the sensitivity and accuracy of the electromagnetic sensor, we need to configure it to the indicated resonant mode. It should also be noted that with a help of a program created in the DELPHI 7.0 programming language which works in all the versions of the WINDOWS operating system, it is possible to switch the sensor to the resonant mode swapping the required parameters.

The study identifies the main factors inducing vibration in electric motors. Moreover, we are researching the informative and spectral properties of vibration signals with a help of decentralization recognition causing increased vibration.

Researchers have been studying the use of stepper motors [5]. In their opinion, stepper motors increase the control accuracy of rotating mechanisms. However, in mentioned researches the engines were in a stationary position [3],[4],[5]. Here we consider a stepper motor set on a robot moving along a given trajectory. According to researchers [6], the amount of labor involved in identifying wheat diseases and spraying chemicals on a diseased plant will be significantly reduced through the use of a low-power and smaller-sized intelligently controlled search robot. The same researchers published updated data on the usefulness of using a low-power and smaller-sized search robot with intelligent control [7].

A trajectory controller described in [8] uses to move of an unmanned ground vehicle. Its unique feature is that the controller is supposed to use error dynamics to ascertain the input speeds of the robot, which will minimize its deviation from the specified trajectory. It should be noted the dynamic constraints of the vehicle must already be included in the trajectory. In addition, if the trajectory constantly requires speeds or acceleration exceeding the capabilities of the vehicle, then the technical device will move unrestrainedly.

Suppose that an unmanned ground vehicle must intersect a certain ordered set of points represented by $X = [X_0, X_1, \dots, X_n]$, where $n \in Z_+$ and $X_i \in R^2, \forall i \in [0, n]$ and X_0 is the starting position of the vehicle. The polynomial parts up to the third degree are the components of the trajectory, which is represented by a two-dimensional function of the time variable. We need the continuity up to the first derivative to provide that one of the reference velocity vector.

Obviously, both the velocity and the time interval must be specified for each point, as well as for constructing a spline interpolation of polynomials of the third degree [9]. For this reason, in this part we take into account the following parameters: tangential velocity vectors $V_i \in R^2$ and time points, nodes, $t_i \in R_+, t_i > t_{i-1}$. The initial time ($t_i = 0$) coincides with the moment of time t_0, while the initial velocity vector of the robot ($V_n = 0$) is represented by the velocity V_0.

Thus, in order to link these points, it is necessary to implement the trajectory function $T(t) = [x_r(t), y_r(t)\ ]^T$, with $t \in [t_0, t_n]$, as $T(t_\iota) = X_i$ and $T^{(1)}(t_\iota) = V_i$. By representing the polynomial segments as $T_j(t) = \left[x_{rj}(t), y_{rj}(t)\ \right]^T$, with $j \in [0, m], m = n - 1$, the total trajectory results in

$$T(t) = \begin{cases} T_0(t), t_0 \le t \le t_1, \\ \quad \dots \\ T_j(t), t_j \le t \le t_{j+1}, \\ \quad \dots \\ T_m(t), t_m \le t \le t_n. \end{cases}$$

It is within our competence to conduct a primary assessment of the appropriate duration dt_j for each segment by interacting with the polynomial origin of the segments, taking into account the dynamic limitations of an unmanned ground vehicle. Then, in order to reduce the duration, we designate the task of enhancing constraints for each segment. However, extracting the necessary supplementary information from the trajectory is unavoidable for the implementation of this method. We need to get the initial linear velocity and orientation of the vehicle, which are respectively $v_r(t) = \sqrt{\dot{x}^2(t) + y^2(t)}$ and $\theta_r(t) = arctan_2(\dot{y}(t), \dot{x}(t))$. Taking the derivative of the last formula it is possible to determine the reference angular velocity as follows $\omega_{r(t)} = \theta_r(t) = \frac{\dot{x}_r(t)\ddot{y}_r(t) - \dot{y}_r(t)\ddot{x}_r(t)}{\dot{x}_r^2(t) + \dot{y}_r^2(t)}$. Also, it is necessary to mention the initial linear acceleration $a(t) = \dot{v}(t)$ and the angular acceleration $\alpha(t) = \dot{\omega}(t)$. Moreover, we need $\dot{a}(t)$ and $\dot{\alpha}(t)$, the linear and angular jerk, respectively. Thus, it is necessary to define the remaining Bezier curve derivatives. The cubic Bezier corresponds to the form $B(\lambda) = (1-\lambda)^3 P_0 + 3 \cdot (1-\lambda)^2 \cdot \lambda P_1 + 3 \cdot (1-\lambda) \cdot \lambda^2 P_2 + \lambda^3 P_3$, where $P_i \in R, l \in \{0, 1, 2, 3\}$ are control points and $.\lambda \in [0,1]$ is the curve parameter. The polynomial form is

$$B(\lambda) = \begin{bmatrix} P_3 - 3P_2 + 3P_1 - P_0 \\ 3 \cdot (P_2 - 2P_1 + P_0) \\ 3 \cdot (P_1 - P_0) \\ P_0 \end{bmatrix} \cdot \begin{bmatrix} \lambda^3 \\ \lambda^2 \\ \lambda \\ 1 \end{bmatrix}.$$

From the polynomial form, it is necessary to take its first, second, third and fours derivatives [10].

To define each segment of trajectory lettered T_j, we should know the initial and determine the final velocity lettered V_{j+1}. We can define the initial velocity as $V_0 = 0$ and we substitute it by $V_0 = \alpha_a T_s \angle \Theta_0$, to explicitly indicate the initial direction, while providing an acceptable velocity value. Determining the desired direction Θ_{j+1} is the first step in choosing the velocity. This direction should be directed to the next point X_{j+2}. The trajectory of an unmanned ground vehicle should not change its normal path significantly, even in case of inevitable abrupt aberrations of its orientation. The second step is to define the normal path vector $r_j = X_{j+1} - X_j$ (see figure 1) and choose $\Theta_{j+1} = \angle(r_j + r_{j+1})$. Similarly, we have $\Theta_{m+1} = \angle r_m + d\theta_{m,s}$, which becomes $\Theta_n = 2\angle r_m + \Theta_m$.

The third step is to choose the maximum allowed velocity as $v_{a,j} = min\left(v_{max}, min\left(\frac{\alpha_a \|r_j\|}{v_{max}}, \frac{\alpha_d \|r_{j+1}\|}{v_{max}}\right)\right)$.

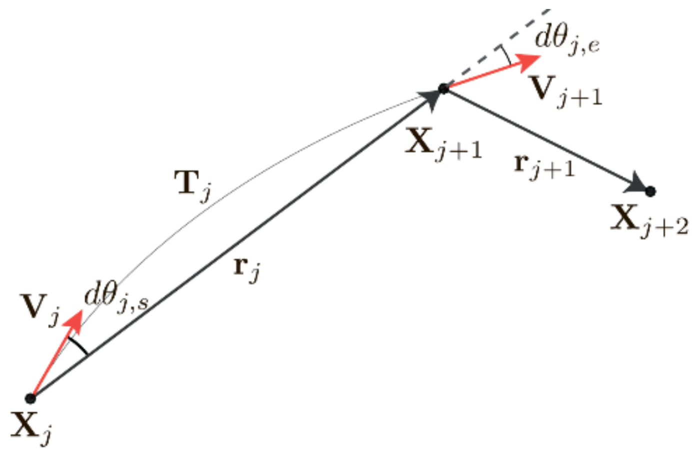

Figure 1. Velocity selection $t_i \in R_+, t_i > t_{i-1}$.

The next point that needs to be considered is the definition of a factor that can limit velocity due to orientation aberrations$f_j = \left(1 - \xi \sin^2 d\theta_{j,\varepsilon}\right) \cdot \cos^2 d\theta_{j,s}$, with $d\theta_{j,s} = \Theta_j - \angle r_j$ and $d\theta_{j,e} = \angle r_j - \Theta_{j+1}$. A heuristic constant, closely related to the maximum permissible acceleration and angular velocity of an unmanned ground vehicle, is equal to $\xi \in (0, 1)$ simultaneously with the deviation of the angles of velocity change from the normal trajectory.

The final next is to choose the velocity vehicle as $V_{j+1} = f_j \cdot v_{a,j} \angle \Theta_{j+1}$.

For selecting durations, it is necessary to benefit from the polynomial nature of the trajectory segments and generate information about the trajectory in the form of rational polynomials. The reference linear velocity is $v(t) = \sqrt{\dot{x}_r^2(t) + \dot{y}_r^2(t)} = \sqrt{v_r(t)}$.

The initial angular velocity is $\omega(t) = \frac{\dot{x}_r(t)\cdot\ddot{y}_r(t) - \dot{y}_r(t)\cdot\ddot{x}_r(t)}{v^2(t)} = \frac{\omega_r(t)}{v^2(t)}$. We can form the tangential and angular acceleration as follows $a(t) = \dot{v}(t) = \frac{a_r(t)}{v(t)}, \alpha(t) = \dot{\omega}(t) = \frac{a_r(t)}{v^4(t)}$.

The above equations are valid both for the entire trajectory and for each individual segment. Now we can formulate the boundaries of the velocity and acceleration of the segment relative to the parameter under consideration. dt_j. Limiting values are not presented in this article due to requirements for the volume of scientific paper. Finally, it is possible to define the minimum value satisfying the dynamic constants by solving the optimization problem with a help of the above value as an initial condition.

3. Results and discussion

For experiment, we deploy the physical model of an unmanned ground agricultural vehicle, presented in figure 2. In this experiment, we are based on the research related to the encoder-based vehicle measurements to determine its location and orientation. The results of the experiment are depicted in Table 1.

Table 1. Point-Sets of the experimental study.

X	$x[m]$	$y[m]$	X	$x[m]$	$y[m]$
1	0.30	0.20	7	2.93	0.00
2	1.19	2.10	8	3.16	-0.63
3	1.69	0.00	9	3.38	0.00
4	2.07	-1.45	10	3.58	0.31
5	2.39	0.00	11	3.77	0.00
6	2.67	1.00	12	4.00	0.00

Figure 2. The physical model.

It is accepted that the initial orientation of the vehicle is $\Theta_0 = 0\, rad$ and its initial tangential velocity is $0\ \frac{m}{s}$. The sampling interval is equal to $T_s \approx 100\, ms$ and the active restrictions are $v(t) \in [0, 0.35]\ \frac{m}{s}, a(t) \in [-0.1, 0.1]\ \frac{m}{s^2}, \omega(t) \in [-30, 30]\ \frac{deg}{s}\ and\ \alpha(t) \in [-50, 20]\ \frac{deg}{s^2}$. Additionally, after trial and error, the path controller parameters were equal to $g = 30$ and the path heuristic parameter were equal to $\xi = 0.6$. Figure 3 indicates the resulting reference trajectory (along with the measured one). Besides, the position error given by $e = \sqrt{\left(x_{r,k} - x_k\right)^2 + \left(y_{r,k} - y_k\right)^2}$ is shown in figure 4.

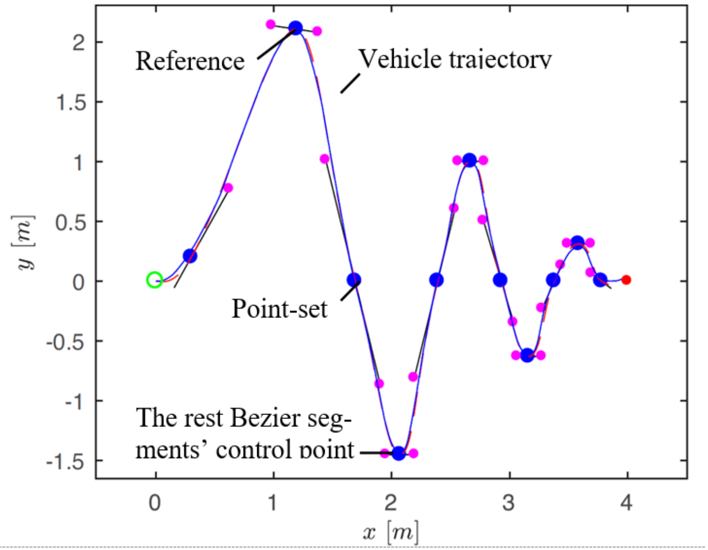

Figure 3. The resulting reference trajectory.

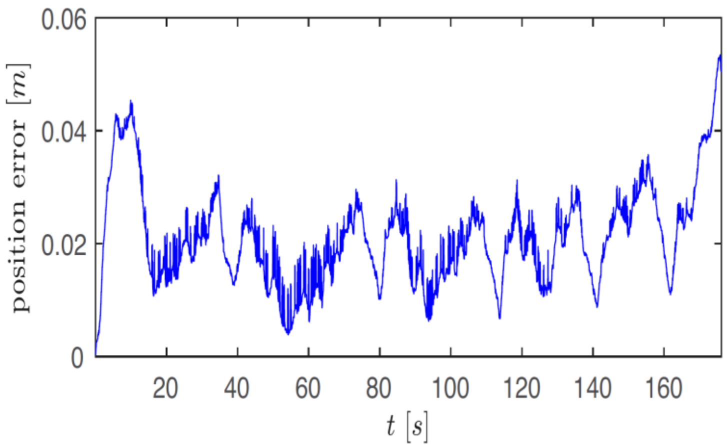

Figure 4. Vehicle position deviation.

The unmanned ground vehicle cannot exceed the constraints

$$\begin{cases} v_{min} \le v(t) \le v_{max}, \\ |\omega(t)| \le \omega_{max}, \\ |a(t)| \le \begin{cases} a_a, for\ v(t)a(t) \ge 0 \\ a_d, for\ v(t)a(t) < 0, \end{cases} \\ |\alpha(t)| \le \begin{cases} \alpha_a, for\ \omega(t)\alpha(t) \ge 0 \\ \alpha_d, for\ \omega(t)\alpha(t) < 0, \end{cases} \end{cases}$$

where $v_{min} \in R_-^*$, $v_{max} \in R_+^*$ and $\omega_{max} \in R_+^*$ are the boundaries of the linear and angular velocity, $a(t), \alpha(t) \in R$ are the linear and angular acceleration, that is why, one of its bounding values will be used instead. Nevertheless, the vehicle smoothly adheres to the reference trajectory owing to observe the position error. For point-set in Figure 2 the maximum deviation is 5.34 cm. The mean deviation is at 2.12 cm.

4. Conclusion

Proposed method of the trajectory determination is the basis for the process of unmanned ground agricultural vehicle trajectory determination. An ordered set of points is connected with a help of the segments based on the spline interpolation (Bezier curves). Polynomials participate in the estimation of constraints based on the nonlinear optimization to reduce the duration of the trajectory segments. Successful tracking of the constructed trajectory has been confirmed by experimental studies.

Controlling unmanned ground vehicle research based on the proposed method is a more direct approach since it does not require preliminary calculation of any trajectory.

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