Navigation of the autonomous vehicle reverse movement

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Abstract. The paper presents a mathematical formulation of the vehicle reverse motion along a multi-link polygonal trajectory consisting of rectilinear segments interconnected by nodal points. Relevance of the problem is caused by the need to solve a number of tasks: to save the vehicle in the event of a communication break by returning along the trajectory already passed, to avoid a turn on the ground in constrained obstacles or dangerous conditions, or a partial return stroke for the subsequent bypass of the obstacle and continuation of the forward movement. The method of navigation with direct movement assumes that the reverse path is elaborated by using landmarks. To measure landmarks on board, a block of cameras is placed on a vehicle controlled by the operator through the radio channel. Errors in estimating deviation from the nominal trajectory of motion are determined using the multidimensional correlation analysis apparatus based on the dynamics of a lateral deviation error and a vehicle speed error. The result of the experiment showed a relatively high accuracy in determining the state vector that provides the vehicle reverse motion relative to the reference trajectory with a practically acceptable error while returning to the start point.

1. Introduction

The development of systems for the vehicle automatic return based on the trajectories measured and stored in the onboard computer corresponds to the general trend of the development of autonomous and remotely operated vehicles. Among such may be planet-walkers, mobile robots, robotic combat vehicles, cars, etc. It is assumed that the data about landmarks are obtained by means of a stereo camera system on board the vehicle. The solution of the problem is connected with the use of adaptive control and intellectual information processing.

Relevance of the problem is caused by the need to solve a number of tasks: to save the vehicle in the event of a communication break by returning along the trajectory already passed, to avoid a turn on the ground in constrained obstacles or dangerous conditions (for example, while demining), or a partial return stroke for the subsequent bypass of the obstacle and the continuation of the forward movement.

Determination of vehicle trajectory parameters and a location of the vehicle from the navigation measurements, calculation of the trajectory corrections and elaboration of control system settings for the upcoming maneuvers constitute the essence of the navigational task, which is similar to the navigation of space vehicles [1]. The vision usage for navigating mobile systems has been studied, in particular, in [2-5]. The aim of the work is development of these studies in the direction of solving the problem of reverse motion optimizing by using the passed trajectory information.

2. Formulation of the problem

The task of automatic return of the vehicle on memorized landmarks provides two stages of vehicle movement:

- movement along the working area in an autonomous or remote control mode with saving trajectory parameters and a layout of the landmarks P, the length of the traversed path l, the angle φ of trajectory rotation and the rotation angle of the stereo block β;
- automatic return by reverse motion with the help of the stored point plans and newly obtained point plans for corrections of the trajectory.

It is assumed that the vehicle moves along a multilink polygonal trajectory consisting of rectilinear lengths l_k connected by nodal points $S_k, k = 1, 2, ..., N-1$. Such a trajectory requires a minimum number of parameters and the amount of memory to store in the on-board computer. At some nodal points, called reference points, landmark measurements are made (figure 1).
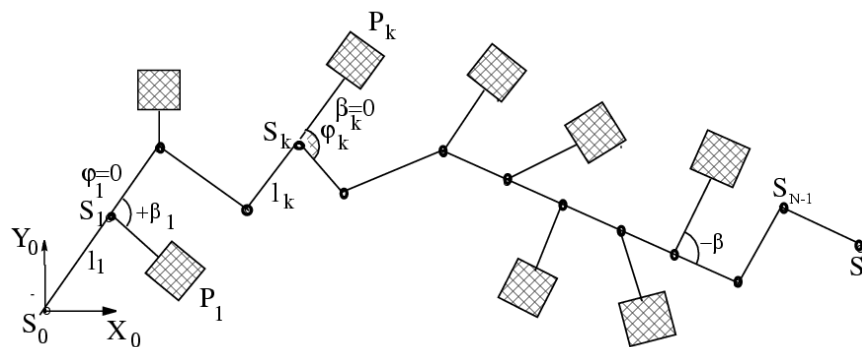

Figure 1. Diagram of binding the nominal trajectory to the plans of the neighborhoods P_k.

The vector of navigation measurements M_k in the k-th reference point can generally be written in the following form:

$$M_k = col(l_k, \varphi_k, \beta_k, P_k). \tag{1}$$

If the measurement is not made at the node then the measurement vector is incomplete and $M_k = col(l_k, \varphi_k, 0, 0)$. The trajectory passed and stored in the process of tele-controlled forward movement into the working area is nominal for automatic return of the vehicle.

The method of navigation with forward movement assumes that the route of movement is predetermined, and the path is refined provided that it passes near the landmarks. To measure landmarks on board the vehicle, a stereo block of cameras is placed on a vehicle controlled by the operator by means of the radio channel. The formation of point plans takes place in the following sequence.

1) During the stop, the operator searches for landmarks by turning the pointing device of the stereo unit on the angle β_k.

2) Stereo images are inserted into the on-board computer and their processing is performed.

3) A compressed representation of landmarks on the reference surface of motion is formed by projections of vertical lines in the form of point plans P_k in a coordinate system associated with the vehicle.

4) The parameters $(l_k, \varphi_k, \beta_k)$ and the resulting point plans P_k are saved for the automatic return of the vehicle.

5) The next section of the trajectory at each node S_k is set by the settings (φ_k, l_{k+1}), which are transmitted by the operator to the board.

The method for navigating an autonomous vehicle while moving to a work area requires parameters ($\tilde{l}_k, \tilde{\varphi}_k, \tilde{\beta}_k$), where $k = 1, .., N\text{-}1$. A pre-compiled orientation map stored in the on-board computer memory in the form of a sequence of point plans $\tilde{P}_k$ is used for navigation at reference points. Wherein:

- landmarks are captured in the field of view of cameras at the point S_k by turning the stereo block to an angle $\tilde{\beta}_k$;

- the trajectory correction is performed on the basis of the coordination results of the plans $\tilde{P}_k$ and the newly obtained point plans P_k that are stored for automatic return;

- measured values l_k, φ_k, β_k, and point plans P_k of landmarks are used for automatic return.

The principle of autonomous navigation in automatic reverse motion is based on the use of the operational machine relative map (MRM), automatically formed in the process of direct movement of the vehicle at the nodal and reference points. Such a card is represented in the memory of the on-board computer in the form of a stack. Each "sheet" of the MRM corresponding to the reference point k contains parameters (l_k, φ_k, β_k) along with a point plan P_k. If there are no reference points in the nodal points, then the corresponding "sheet" of the MRM is represented only by parameters φ_k, l_k. In the reverse motion, the MRM parameters are extracted from the stack computer memory in the reverse order, in accordance with the stop point number of the vehicle. In the MRM, the point plans are linked through the parameters of the trajectory and form a single information field.

The parameters φ_k, l_k of the trajectory are worked out by the control system with errors, so there is a deviation of the motion from the planned point S_{k-1} to the point S'_k at which the stereoscopic survey is performed and the point plan P'_k is obtained. As a result of the alignment of the plan P'_k with the plan P_k, the deviations from the trajectory ($\Delta\overline{r}_k, \Delta\varphi_k$), $\Delta\varphi_k = \varphi'_k - \varphi_k$ and the control parameters ($\hat{r}_k, \hat{\varphi}_k$) that ensure the vehicle motion to the point S_{k-1} are determined (figure 2).
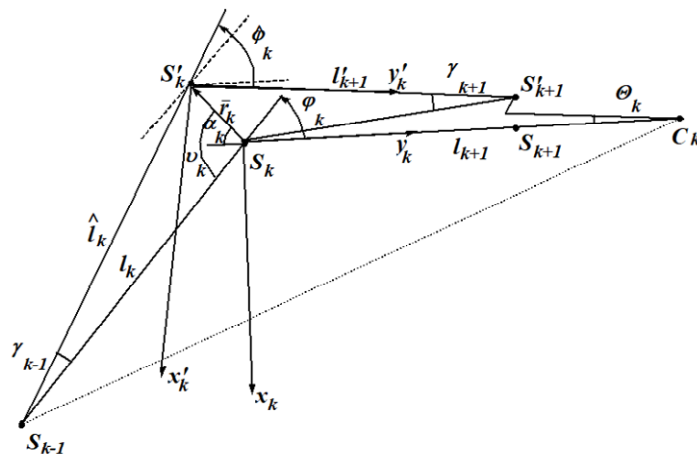

Figure 2. Diagram for determining path length $\hat{l}_k$ and heading angle $\hat{\varphi}_k$.

The central problem is determination of the benchmark plans for calculating the navigation parameters ($\overline{r}_k, \Theta_k$) shown in Figure 2, and the control parameters ($\hat{l}_k, \hat{\varphi}_k$) to continue motion to the next node. Diagram of the reverse movement trajectory is shown in figure 3.
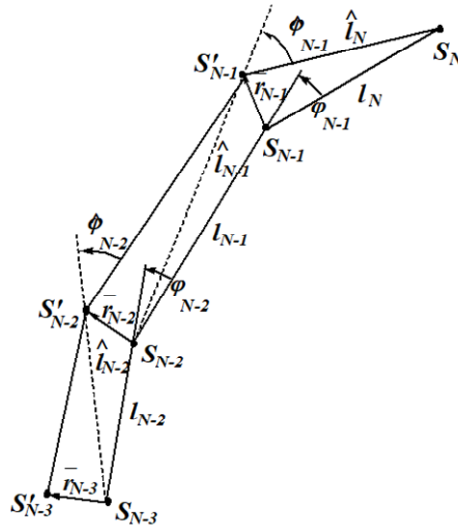
Figure 3. Diagram of the reverse movement trajectory.

Mathematical statement of navigation and control tasks with automatic return is the same for remote control and autonomous movement. The definition of the parameters l_k, φ_k, β_k and P_k has the random nature, therefore the nominal trajectory is probabilistic, as well as the return path.

The motion model in the vicinity of the stored trajectory is based on the representation of the disturbed motion relative to the planned trajectory by a system of linear differential equations. It is assumed that the vehicle moves rectilinearly between the nodal points at a constant speed. The main error component is caused by the constantly increasing lateral deviation due to an error in the course, which leads to deviations from the target point $\delta x_k \approx V \cdot T_{k+1} \cdot \delta \varphi_k$, where T_{k+1} is duration of the movement from point S_{k+1} to point S_k. Both quantities δl and $\delta \varphi$ are random and determine the deviation from the point, which is assumed to be subordinate to the two-dimensional normal distribution law.

Errors in estimating deviations from the nominal trajectory of motion are determined using the multidimensional correlation analysis apparatus based on the dynamics of the error variation of the lateral deviation ρ_1 and the vehicle speed ρ_2 of deviation from the nominal trajectory. The quantities ρ_1 and ρ_2 are components of the state vector $\overline{\rho}$. Differential equations of perturbed motion in matrix form are as follows:

$$\frac{d\overline{\rho}}{dt} = A\overline{\rho}, \qquad \overline{\rho} = \begin{vmatrix} \rho_1 \\ \rho_2 \end{vmatrix}, \qquad A = \begin{vmatrix} 0 & 1 \\ 0 & 0 \end{vmatrix}, \qquad (2)$$

where A is the matrix of a linear differential equations system,

$$\rho_1 = \delta x_k, \qquad \rho_2 = d\rho_1/dt = V \cdot \delta \varphi_k, \qquad (3)$$

under the initial conditions: $\rho_1(0) \in (0, \delta r)$, $\rho_2(0) \in (0, V \cdot \delta \theta)$ with a correlation matrix of initial deviations

$$\Sigma_\rho = \begin{vmatrix} \sigma_1^2 & K_{12} \\ K_{21} & \sigma_2^2 \end{vmatrix}, \qquad K_{12} = K_{21} = K\sigma_1\sigma_2, \qquad (4)$$

where σ_1 and σ_2 are the variance of the errors in the determination of ρ_1 and ρ_2; K is the correlation coefficient.

The state of the system $\overline{\rho}(T)$ at the final instant of time T is found by means of a transition matrix $\Phi(T,t), t \in (0,T)$, which is determined from the solution of the conjugated system [6]. With the help of this transition matrix, the state vector of the system is determined at the final instant of time T according to the state at the current time:

$$\overline{\rho}(T) = \Phi(T,t)\overline{\rho}(t); \rho_1(T) = \Phi_1(T,0)\overline{\rho}(0), \tag{5}$$

where $\Phi_1(T,0)$ is the first row of the transition matrix.

The maximum possible deviation from the node S_k due to a position error δr and an error in the implementation of the rotation angle $\delta\varphi$ is obtained by substituting the value $T = \hat{T}$ of the predicted motion time from point S_{k+1} to point S_k and the maximum possible deviations in the components of the state vector $\overline{\rho}(0)$ at the initial moment:

$$\rho_1(\hat{T}_i) = \begin{vmatrix} 1 & \hat{T} \end{vmatrix} \begin{Vmatrix} \delta r \\ 3V\sigma_\varphi \end{Vmatrix} = \delta r + 3V\hat{T}\sigma_\varphi. \tag{6}$$

The predicted value of the variance of deviation from the calculated trajectory at the instant $\hat{T}$ relatively the initial instant $(t = 0)$ is:

$$\sigma_x^2 = \Phi_1(\hat{T},0)\Sigma_\rho\Phi_1^*(\hat{T},0), \tag{7}$$

where $(*)$ is the transpose, K is the correlation coefficient, which determines the orientation of the dispersion ellipse [6].

The purpose of the correction is to limit the deviation r_0 from the starting point S_0, but at the same time the current deviations r_k from the nominal trajectory, controlled at the reference points, also should not exceed the permissible value: $r_k \le R_d$, where $k = 1, 2, ..., N-1$, and R_d is the maximum permissible deviation. This condition, in addition to safety considerations while returning, involves taking camera pictures from closely spaced points to the nominal trajectory and minimizing the differences in the plan of landmarks P_k' from the plan P_k. The beam width of the possible return paths is determined at the node points relative to the nominal trajectory by scattering ellipses R_k, $k = N-1, ..., 0$.

3. Experimental results

As an experimental example, an interval control was tested, the necessary condition of which is the movement of the vehicle from each current node S_k to the next node S_{k-1} and the control parameters are selected from the approximation conditions near this point.

The hardware included an on-board computer, and the passed distance was measured by the rotation of the driving wheels. Rotation of the vehicle was performed by rotating left and right wheels in opposite directions. The software consisted of a set of programs for automatic analysis of stereo images, the formation and coordination of point plans, calculation of the guidance parameters ($\hat{r}_k, \hat{\varphi}_k$) in the vicinity of the k-th reference point. A variant of the vehicle motion trajectory in the room along 6 reference points and 4 points of rotation and the trajectory of reverse motion to the initial point are shown in figure 4.
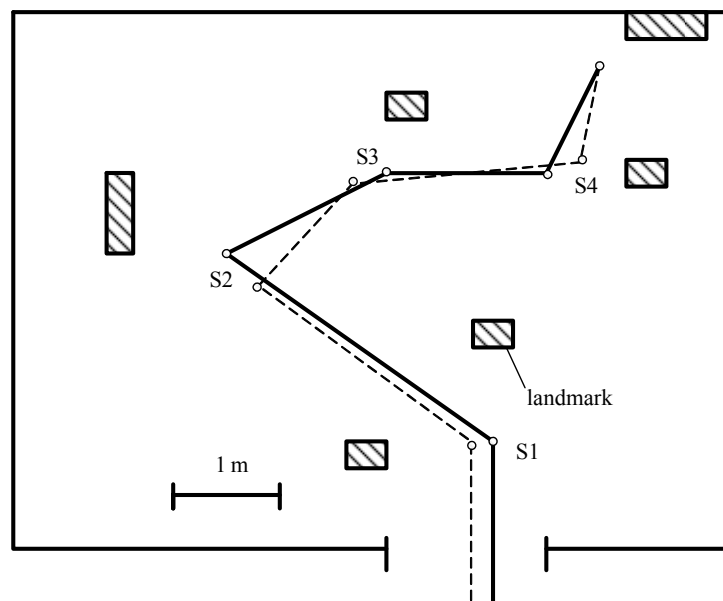
Figure 4. Plan of the room and the trajectory of motion
(solid line - direct movement, dashed line - reverse movement).

The result of the experiment showed sufficient accuracy of determining the state vector $(r_{N-k}, \Delta \hat{l}_{N-k}, \hat{\varphi}_{N-k})$ according to the results of the point plans matching, providing reverse movement relative to the reference trajectory with an acceptable error about 0.2 m at the start point.

4. Conclusion
A mathematical formulation of the vehicle reverse motion along a multi-link polygonal trajectory consisting of rectilinear segments interconnected by nodal points is determined. The method of navigation with direct movement assumes that the route of movement is measured, and the reverse path is corrected by using landmarks. To measure landmarks on board, a block of cameras is placed on a vehicle controlled by the operator through the radio channel.

Errors in deviation estimating from the nominal trajectory of motion are determined using the multidimensional correlation analysis apparatus based on the dynamics of the lateral deviation error and the vehicle speed error.

The principle of autonomous navigation in automatic reverse motion is based on the use of an operational machine relative map automatically formed during the forward movement of the vehicle at the node and reference points. The vehicle motion model in the vicinity of the stored trajectory is based on the representation of the disturbed motion relative to the planned trajectory by a system of linear differential equations. It is assumed that the robot moves rectilinearly at a constant speed between the nodal points.

The result of the experiment showed a relatively high accuracy in determining the state vector that provides a reverse motion relative to the reference trajectory with a practically acceptable error while vehicle returning to the start point.

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