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Integrated Navigation System for Unmanned Vehicle Convoy

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Abstract**:** ***This work discusses experimental results of integrated navigation system of unmanned vehicle convoy with manned master vehicle in road climatic environment of Russia. The developed navigation system is comprised of odometric system integrated with computer vision equipped with video cameras and radars. Navigation is supported by virtual sensors of parameters of center-of-mass motion, and motion path is adjusted by data of video camera and radar. The algorithms of wheel navigation system have been designed on the basis of concept of virtual data sensors. Virtual data sensors allow to solve navigation problem in minimum hardware configuration. As a consequence of the research, the operable integrated navigation system has been developed allowing detection of position of unmanned vehicles in convoy. The proposed engineering solutions have been confirmed by experimental results of navigation system for unmanned vehicle convoy with manned master vehicle in road climatic environment of Russia. The research novelty is in experimental verification of efficiency of algorithms and software of the developed integrated navigation system for unmanned vehicle convoy with manned master vehicle.***

Keywords**:** ***navigation, integration, mathematical models, virtual sensors, experimental results.***

I. INTRODUCTION

Automation of vehicles in the 21st century reaches the stage of unmanned vehicles. Leading Western companies carry out wide-scale R&D projects devoted to safe operation of these innovative vehicles.

The increased interest of manufacturers and consumers to advances in the field of unmanned vehicles is stipulated by possibilities of significant improvement of efficiency of passenger and cargo traffic.

The major factors determining economic attractiveness of unmanned vehicles are as follows [1]:

- decrease in labor cost of drivers due to reduced demand for workers in this field;
- decrease in road accidents due to elimination of human factor leading to collisions caused by driver errors;
- decreased consumption of fuel and lubricants due to optimization of control of engine, gearbox and brakes.

In terms of modern theory of control, the automated control of unmanned vehicle is reduced to dynamic stabilization of variables: longitudinal center-of-mass speeds, longitudinal and transversal accelerations, turn angle of steered wheels, wheel slipping, pressure and temperature of tires, distances to obstacles in traffic line, center-of-mass deviation from preset motion path and others.

The state variables are monitored by functional subsystem of computer vision [2] based on radars, lidars, video cameras, odometric, inertial and satellite navigation systems.

However, as demonstrated by experience, none of navigation systems based only on data processing of satellite systems [3], angular rates and accelerations in inertial systems [4], data on motion variables in odometric systems [5], can provide the required detection accuracy of object position under actual conditions of motion.

Integration of navigation systems based on various physical principles is comprised of combined data processing of several independent meters [6] making it possible to supplement measurements, to compensate and to filter errors.

A significant factor, which determines competitiveness of the proposed engineering approaches, is the cost of hardware applied in such integrated system. It is obvious, that among the variants of development of integrated system, the most preferable is the variant which provides execution of all functional requirements in minimum hardware configuration.

The work is aimed at analysis of experimental results of integrated navigation system of unmanned vehicle convoy with manned master vehicle in road climatic environment of Russia.

II. METHODS

A. General description

Substantially, the task is reduced to obtaining estimations of coordinates $\hat{L}_x, \hat{L}_y$ on plane close to actual coordinates L_x, L_y.

The degree of proximity of coordinates and their estimations is defined as the distance $\Delta r \geq 0$ between the points ($\hat{L}_x$, $\hat{L}_y$) and (L_x, L_y) equaling to $\Delta r(t) = \sqrt{[\hat{L}_x(t) - L_x(t)]^2 + [\hat{L}_y(t) - L_y(t)]^2}$.

In discrete time $t = t_k = k\Delta T$, we obtain the sequence $\Delta r(k)$ characterizing estimation adequacy of coordinates L_x and L_y.

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Quality of estimation by maximum error is $\Delta r_{max} = \max\,[\Delta r(1), \dots \Delta r(n)]$.

Estimations $\hat{L}_x(t)$ and $\hat{L}_y(t)$ can be obtained by various methods, for instance, using GPS or wheel navigation system. In this case, it is possible to select estimations $\hat{L}_x$ and $\hat{L}_y$ from the allowable set $(\hat{L}_{x\,sup}, \hat{L}_{y\,sup})$ formed by two sets, and the quality improvement of final estimations is formulated as follows:

$$\Delta r_{max} = \max\,[\Delta r(1), \dots \Delta r(n)] \to min$$

at $\left[\hat{L}_x(k), \hat{L}_y(k)\right] \in [\hat{L}_{x\,sup}(k), \hat{L}_{y\,sup}(k)]$.

Optimal reservation is reduced to selection of stations from allowable set on the basis of predefined toggling rule. The considered task is characterized by the fact that actual coordinates $L_x(t)$ and $L_y(t)$ are unknown, and $\Delta r(k)$ is not defined.

Solution of the navigation task by means of odometric (wheel) system is based on the set of differential equations of vehicle motion in Cartesian coordinates:

$$\begin{cases} \dot{\Psi}_m = \omega_m + \Delta\omega_m; \\ \dot{L}_x = V_m sin\Psi_m; \\ \dot{L}_y = V_m cos\Psi_m \end{cases} \qquad (1)$$

where Ψ_m is the course angle limited by the range (0÷2π); ω_m is the angular rate in turning; $\Delta\omega_m$ is the additional constituent of center-of-mass angular rate upon drifts or slips of front or rear axle; V_m is the longitudinal center-of-mass rate.

Taking into consideration the Euler equation for angular and linear rates: $\omega_m = V_m \cdot R_m^{-1}$, and the turn radius R_m as a function of vehicle base b and turn angle of steered wheels Ψ_c: $R_m = b \cdot \Psi_c^{-1}$,we have the following solution of Eq. (1):

$$\begin{cases} \Psi_m(t) = b^{-1} \cdot \int_{t_0}^{t} V_m(\tau) \cdot \Psi_c(\tau)d\tau + \int_{t_0}^{t} \Delta\omega_m(\tau)d\tau + \Psi_m(t_0); \\ L_x(t) = \int_{t_0}^{t} V_m(\tau)sin\Psi_m(\tau)d\tau + L_x(t_0); \\ L_y(t) = \int_{t_0}^{t} V_m(\tau)cos\Psi_m(\tau)d\tau + L_y(t_0) \end{cases} \qquad (2)$$

where $\Psi_m(t_0), L_x(t_0)$ and $L_y(t_0)$ are the initial values of course angle and Cartesian coordinates L_x and L_y at the time t_0.

Equations (2) of navigation task in discrete time should be solved on the basis of input data of longitudinal rate V_m, turn angle of steered wheels Ψ_c and additional constituent of angular rate $\Delta\omega_m$.

Trivial solution of the task on obtaining these data is in equipment of a vehicle with respective physical data sensors together with their conversion and filtration [7, 8]. Estimations of the mentioned variables could contain significant errors, which decreases significantly the solution accuracy of navigation task and impairs nearly all consumer properties of the control system.

Nontrivial solution of this problem is in the use of virtual data sensors based on mathematical models and algorithms of indirect measurements [9], which makes it possible to minimize the additional hardware and to improve nearly all consumer properties of the system.

B. Algorithm

Mathematical model of wheel rotation rate in turnings has been used as the mathematical model for development of virtual sensors of motion variables:

$$\begin{cases} V_1 = V_m + 0.5a_1 b^{-1} V_m \Psi_c + \Delta V_{S1} + 0.5a_1 \Delta\omega_m; \\ V_2 = V_m - 0.5a_1 b^{-1} V_m \Psi_c + \Delta V_{S2} - 0.5a_1 \Delta\omega_m; \\ V_3 = V_m + 0.5a_2 b^{-1} V_m \Psi_c + \Delta V_{S3} + 0.5a_2 \Delta\omega_m; \\ V_4 = V_m - 0.5a_2 b^{-1} V_m \Psi_c + \Delta V_{S4} - 0.5a_2 \Delta\omega_m \end{cases}$$

(3)

where V_1, V_2, V_3, V_4 are the linear rates of vehicle wheel rotation corresponding to the front left (V_1), the front right (V_2), the rear left (V_3) and the rear right (V_4) wheels; $\Delta V_{Si}, 1 \le i \le 4$ are the longitudinal slipping speeds of respective wheels; a_1 and a_2 are the gauges of front and rear wheels, respectively.

If the solution of direct task of V_i detection by known terms in the right part of Eq. (3) is trivial, then the reverse task of detection of terms in the right side by known V_i is ill-posed problem. Solution of the considered problem is given in [7]. Thus, in particular, the estimations of longitudinal center-of-mass speed $\hat{V}_m(k)$ and turn angle of steered wheels $\hat{\Psi}_c(k)$ in discrete time are:

$$\begin{cases} \hat{V}_m(k) = V_m(k) + 0.5\left[\Delta V_{Si}(k) + \Delta V_{Sj}(k)\right]; \\ \hat{\Psi}_c(k) = \Psi_c(k) + a^{-1} b V_m^{-1}(k)\left[\Delta V_{Si}(k) - \Delta V_{Sj}(k)\right] + b V_m^{-1}(k)\Delta \end{cases}$$

(4)

where $|\Delta V_{Si}(k) + \Delta V_{Sj}(k)| = \min\,[|\Delta V_{S1}(k) +$ *ΔVS2k, ΔVS3k+ΔVS4k, ΔVS1k+ΔVS4k, ΔVS2k+ΔVS3k].*

In the case of right and left wheel pairs with zero longitudinal slippage, $\hat{V}_m(k) = V_m(k)$ and $\hat{\Psi}_c(k) = \Psi_c(k) + bV_m^{-1}(k)\Delta\omega_m(k)$. Estimation of turn angle of steered wheel $\hat{\Psi}_c(k)$ does not contain the term depending on longitudinal wheel slipping, provided that $\Delta V_{Si}(k) = \Delta V_{Sj}(k) \neq 0$.

The use of estimations $\hat{V}_m$ and $\hat{\Psi}_c$ for solution of Eqs. (2) of the navigation task concerning determination of course angle $\hat{\Psi}_m$ in discrete time is characterized by the following property:

$$\hat{\Psi}_m(k) = b^{-1} \int_{t_0}^{t} \hat{V}_m(\tau)\hat{\Psi}_c(\tau)d\tau + \hat{\Psi}_m(t_0) =$$

$$b^{-1} \int_{t_0}^{t} \hat{V}_m(\tau)\hat{\Psi}_c(\tau)d\tau + b^{-1} \int_{t_0}^{t} \Delta\omega_m(\tau)d\tau + \Psi_m(t_0). \quad (5)$$

Therefore, the use of estimated turn angle of steered wheels containing additional angular rate $\Delta\omega_m$ as a measurement error, makes it possible to obtain the solution similar to accurate one.

Initial data in the considered problem are the estimations of linear rates of wheel rotation $\hat{V}_i = V_i + \zeta_i$, with additive constituent of measurement noises ζ_i.

Linear rate of wheel rotation V_i and their estimations $\hat{V}_i$ are determined by Euler equations for linear and angular rates:

$$\begin{cases} V_i = \omega_i R_{ci} \\ \hat{V}_i = \hat{\omega}_i \hat{R}_{ci} \end{cases} \qquad (6)$$

where $R_{ci} = R_{ci}(0) + k_1 P_i + k_1 k_v V_i^2$; $\hat{R}_{ci} = \hat{R}_{ci}(0) + k_1 \hat{P}_i + k_1 k_v \hat{V}_i^2$; $\hat{\omega}_i = \omega_i + \Delta\omega_i$.

Free wheel radiuses R_{ci} and their estimations $\hat{R}_{ci}$ depend on their initial values $R_{ci}(0)$ and $\hat{R}_{ci}(0)$ at zero excess pressures P_i and $\hat{P}_i$ as well as on own linear rates of rotation V_i and their estimations $\hat{V}_i$. The coefficients k_1 and k_v take into account linear tire expansion under the action of pressure and centrifugal force. Estimations of angular rates are $\hat{\omega}_i$ and measurement noise is $\Delta\omega_i$.

Under condition of high accurate measurement of rotation frequencies, $\hat{\omega}_i \to \omega_i$ and $\Delta\omega_i \to 0$. In this case the additive constituent of measurement noise ζ_i is:

$$\zeta_i = \omega_i\{[\hat{R}_{ci}(0) - R_{ci}(0)] + k_1[\hat{P}_i - P_i] + k_1 k_v(\hat{V}_i^2 - V_i^2)\} \tag{7}$$

The main role in generation of ζ_i is played by difference in estimations of initial free radiuses $\hat{R}_{ci}(0)$ and their actual values $R_{ci}(0)$. This circumstance determines the importance of their accurate identification for improvement of solution efficiency of navigation task.

The effect of noises in estimations of course angle and position coordinates results in accumulation of errors leading to deviation of predicted path from actual one. In order to compensate errors, the developed integrated navigation system provides adjustment of coordinates of slave vehicles of convoy on the basis of data from video camera and radar at straight road segments. The coordinates of slave vehicle L_{y2} and L_{x2} are re-evaluated by the coordinates of master vehicle L_{y1} and L_{x1} as follows:

$$\begin{cases} L_{y2} = L_{y1} - (Dl + L_c)cos\Psi_{m1}; \\ L_{x2} = L_{x1} - (Dl + L_c)sin\Psi_{m1} \end{cases} \tag{8}$$

where Dl is the estimated distance between bumpers of master and slave vehicles according to radar; L_c is the vehicle length.

The coordinates of slave vehicle are adjusted when the axis of slave vehicle deviates from the center of rear part of master vehicle not more than by 0.5 m.

III. RESULTS

The integrated navigation system was tested at Dmitrov test track (NAMI) in various climatic environment, daytime and precipitations in the form of rain and snow. The navigation system, comprised of on-board computer, radar and video camera, video data processing unit, data input display, was installed on Lada Kalina and Lada Vesta.

Figure 1 illustrates Lada Vesta vehicle with a Continental ARS408 at the place of license plate and a Basler video camera installed behind rearview window.

Fig. 1. Lada Vesta equipped with Continental ARS408 radar and Basler video camera.

Figure 2 illustrates unmanned Lada Vesta vehicle convoy with manned master vehicle at starting position of Dmitrov test track. The test motion path of the convoy motion was comprised of circular route with two straight segments and two turnings by 180° with total distance of about 285 m.

Fig. 2. Unmanned Lada Vesta vehicle convoy with manned master vehicle at starting position of Dmitrov test track.

Figure 3 illustrates coordinated turning of convoy comprised of three Lada Vesta vehicles at the speed of about 5 m·s-1.

Fig. 3. Coordinated turning of convoy comprised of three Lada Vesta vehicles.

Figure 4 illustrates data input display of master manned vehicle showing motion path. Coordinates of center-of-mass position are displayed as sequence of points forming closed path where the start point coincides with the end point.

Fig. 4. Data input display of master manned vehicle showing motion path.

Figure 5 illustrates video image of data processing from camera installed in the slave vehicle following the master vehicle. The vertical lines restrict sizes of the master vehicle and the middle line determines the center of its rear part. The distance between longitudinal axis of the slave vehicle and the center line of the master vehicle determines displacement of their axes required for automatic route control.

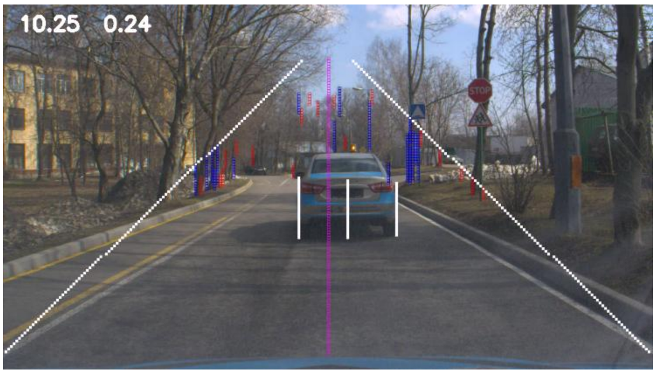

Fig. 5. Data processing from video camera installed in the slave vehicle following the master vehicle.

The size determined by software is converted into the distance to rear portion and is used for route control of slave vehicle. In the considered example, the displacement is 0.24 m, and the distance is 10.25 m.

Figure 6 illustrates test motion path of three Lada Vesta vehicles with master manned vehicle at the NAMI premises. The length of the closed route with common point of start and finish is 1,490 m. Red dots in the figure denote motion path of the master vehicle; the green dots denote motion path of the first slave vehicle; and the black dots denote the motion path of the second slave vehicle.

In the turns, the motion of slave vehicles repeats the route of master vehicle due to the transferred turning angles of steered wheels as a function of covered path. At straight road segments, the vehicles move by fixed routes with adjustments by data from video camera and radar. In the case of minor displacement of axes of slave and master vehicles, the coordinates are adjusted in the navigation system of slave vehicles, thus eliminating the accumulated errors of coordinates and route angle. Requirements to accuracy of solution of navigation task could be reduced whereas they remain sufficiently strict for master vehicle.

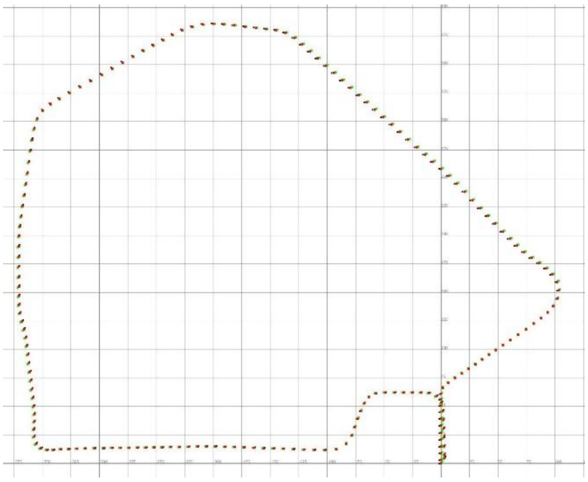

Fig. 6. Test motion path of three Lada Vesta vehicles with master manned vehicle at the NAMI premises

The function of recognition of fixed road markings by data of odometric navigation system was also tested at the NAMI premises. Figure 7 illustrates an image of video record of recognition of road markings during snowfall. The road markings are shown in the data display in their valid zone with consideration for their priority concerning vehicle position. The closest markings 1.23 and 2.5 are located at the distance of 2 m from the front guard, they occupy positions 1 and 2 in the first displayed string. The markings 1.1 and 5.20 are located at the distance of 11 m, they are displayed at positions 3 and 4 in the first displayed string. The marking 2.1 located at the distance of 49 m is displayed at position 5 in the first displayed string. The first five markings are distinctly visible from driver position and are located in the road in the same sequence as in the display. The markings 3.27 and 5.19.1 at the distance of 72 and 82 m are not visible from the driver position in such weather environment, they are displayed in the second string of valid road markings. Similarly, the road markings are recognized reliably when they are hindered for visual recognition by high truck bodies, buses, tree and bush branches.

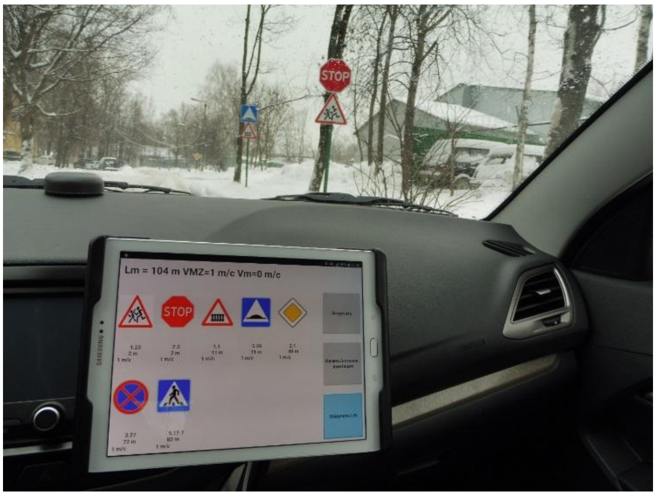

Fig. 7. Recognition of road markings during snowfall

IV. DISCUSSION

The obtained experimental results of integrated navigation system of unmanned vehicle convoy with manned master vehicle in road climatic environment of Russia confirm validity of the proposed engineering solutions.

Adjustment of coordinates of slave vehicles using the data from radar and video camera at straight road segments makes it possible to compensate accumulated errors of coordinate detection by the data of wheel navigation system. In turns, when the front vehicle disappears from the field of view of radar and camera, the route is controlled by turning angle of steered wheels of the master vehicle. The experimental results have demonstrated that application of video images is restricted by bright illumination and rainfall with operating windshield wipers. Under such conditions, the data on displacement of axes of slave and master vehicles can be supplied by their radars.

Recognition of road markings by data of the navigation system is highly reliable and does not depend on day time, weather conditions, radio visibility and obstacles hindering their visual detection [10, 11, 12]. Fixed road markings are added once to route database, and in the case of temporary road markings, it is required to update database.

V. CONCLUSION

The following conclusions can be derived on the basis of the experimental results:

– the wheel navigation system with virtual sensors of center-of-mass speed and turning angle of steered wheels makes it possible to support navigation in various road climatic conditions and does not require for additional hardware;

– the error sources of the wheeled navigation system are the errors of identification of free wheel radiuses, their minimization requires for adjustment of their estimations;

– for unmanned vehicle convoy with manned master vehicle, it is possible to adjust estimations of coordinates of master vehicles by the data from video camera and radar in automated mode at straight road segments;

– the highest reliability of recognition of road markings using the wheel navigation system is determined by independence of dead reckoning on various factors hindering visual recognition.

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