The problem of the driverless vehicle specified path stability control

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Abstract. Currently the effort of many leading foreign companies is focused on creation of driverless transport for transportation of cargo and passengers. Among many practical problems arising while creating driverless vehicles, the problem of the specified path stability control occupies a central place. The purpose of this paper is formalization of the problem in question in terms of the quadratic functional of the control quality, the comparative analysis of the possible solutions and justification of the choice of the optimum technical solution. As square value of the integral of the deviation from the specified path is proposed as the quadratic functional of the control quality. For generation of the set of software and hardware solution variants the Zwicky "morphological box" method is used within the hardware and software environments. The heading control algorithms use the wheel steering angle data and the deviation from the lane centerline (specified path) calculated based on the navigation data and the data from the video system. Where the video system does not detect the road marking, the control is carried out based on the wheel navigation system data and where recognizable road marking exits – based on to the video system data. The analysis of the test results allows making the conclusion that the application of the combined navigation system algorithms that provide quasi-optimum solution of the problem while meeting the strict functional limits for the technical and economic indicators of the driverless vehicle control system under development is effective.

1. Introduction

Currently, the effort of many leading international automotive companies is focused on creation of driverless transport for transportation of cargo and passengers. Among many practical problems arising while creating driverless vehicles, the problems of the specified path stability control and collision prevention are in the center.

It is obvious that without their successful solution optimistic forecasts of practical application of driverless vehicles are meaningless.

The purpose of this research is formalization of the problem of the specified path stability control in terms of a quadratic functional of the control quality, the comparative analysis of the possible solutions and justification of the choice of the optimum technical solution.

2. Definition of the control task

As a quadratic functional of the control quality within a finite time interval $(t_1 \div t_2)$ is proposed the use of the following expression of $Q(t_2)$ is proposed :

$$Q(t_2) = \int_{t_1}^{t_2} C_0 [\Delta H(\tau)]^2 d\tau, \tag{1}$$

where $\Delta H(\tau)$ is the deviation from the specified path; $C_0 > 0$ is the scaling factor.

Given the fact that control action $U(t)$ is restricted in absolute value and its implementation is in the software and hardware environment$R = (R_H, R_S)^T$, which should satisfy a set of limitation for the technical and economic indicators $q_i(R)$, the problem of the optimum control is defined as:

$$Q(t_2) = \int_{t_1}^{t_2} C_0 [\Delta H(\tau)]^2 d\tau \to \min \tag{2}$$

with $U \in U_{adm}; R \in R_{adm}, q_i(R) \le q_{iadm}, i \le i \le r$, where U_{adm} and R_{adm} are the admissible sets of control actions and technical solutions.

The main technical and economic indicators $q_i(R)$ include the level of power consumption, the real environmental impacts, the failure resistance, the operating costs and the cost of the hardware and software kit.

For generating a set of variants of the hardware and software solutions the Zwicky "morphological box" method [1] in the hardware R_H and software R_S environment is used.

The minimization of the quadratic functional of the control quality when meeting the functional limitations (2) for the technical and economic indicators of the control system should be accomplished through the limited control action on the steered wheels which changes the vehicle's heading.

The best solution of the problem as defined will be a control algorithm of the heading regulator providing deviation from the specified path which is close to zero implemented in the software and hardware environment that meets the system of constraints for the technical and economic indicators.

3. The results of solving the problem of the specified path stability control

The control task is subdivided into two independent tasks: construction of the specified path and the driving path stability control.

To solving the first problem one can use: path planning on an electronic terrain map [2] and path recording based on the data of the satellite, inertial and odometric (wheel) navigation systems.

For solving the second task once can also the above presented navigation systems to determine the positioning and the orientation of driverless vehicle [3], as well as video systems allowing determination of the vehicle's positioning on the lane in relation to the visible marking.

The output data of the navigation systems based on different principles, both for specified path planning and the path stability control are the evaluations of the heading $\widehat{\Psi}_m(t)$ and the object's position $\hat{L}_y(t)$ and $\hat{L}_x(t)$ in the Cartesian coordinate system.

The evaluations $\widehat{\Psi}_m(t)$, $\hat{L}_y(t)$ and $\hat{L}_x(t)$ together with the true values contain the measurement noise of certain physical nature in the form of influence of real external factors.

4. Comparative analysis of possible technical solutions

For solving the problem of the driverless vehicle path stability control the control system can include various navigation systems. The positioning determination accuracy is influenced by various factors.

For instance satellite navigation systems (SNS) do not cope with the navigation task under the conditions of limited radio visibility (in tunnels, densely built-up areas, in areas with tall trees, etc.), as well as under the conditions of the electromagnetic noise.

The inertial navigation systems (INS) with their operating principle based on integration of accelerations and angular velocities along the orthogonal axes are characterized by error accumulation as the route length increases and the influence of road surface irregularities and off-road conditions.

The wheel navigation system (WNS) with the operating principle based on integration of the center of mass velocity V_m and the wheel steering angle FiC is also characterized by the integration error accumulation and influence of the road surface irregularities and off-road conditions on the navigation performance.

The road marking detection video system (LDW) is designed to detect deviations of the vehicle's centerline from the middle of the lane. The application of this system is limited by the lane lighting conditions, precipitation and recognizable marking.

Table 1 summarizes the results of the qualitative comparative analysis of the impact of the real environmental factors on the performance of the above navigation systems. The "-" sign marks the negative impact on the navigation system performance, and the "+» sign marks no negative influence.

Table 1. Qualitative assessment of impact of real factors on performance of navigation systems.

Exposures	Navigation system			
	SNS	INS	WNS	LDW
Limited radio visibility	——	+	+	+
Electromagnetic noises	——	+	+	+
Rough surface, off-road	+	——	——	+
Lighting level, precipitation	+	+	+	——
Long travel distance	+	—	——	+
Road marking availability	+	+	+	——
Turns with radii <20 m	+	+	+	——
Reversing	+	+	—	——

The analysis of the environmental impacts on the performance of the navigation systems shows that none of the systems in question copes with the task under the urban traffic conditions.

It appears that for obtaining an acceptable result a combination of two or more navigation systems with different operation principle is necessary. From the point of view of the additional equipment cost, the combined WNS + LDW system has significant advantage compared to other options. For driving on local paths of limited length with smooth surfaces without reversing to use of the WNS only is enough. Under more difficult driving conditions a combined SNS + WNS + VMD navigation system with higher cost could be used.

5. Differential equation system for the center of mass motion

For solution of the navigation task for the driverless vehicle in the Cartesian coordinate system the following system of equations is used:

$$\begin{cases} \dot{L}_y = V_m cos\Psi_m; \\ \dot{L}_x = V_m sin\Psi_m; \\ \dot{\Psi}_m = \omega_m + \Delta\omega_m, \end{cases} \tag{3}$$

where V_m is the longitudinal velocity of the center of mass (m·s^{-1}), Ψ_m is the heading angle (rad), ω_m is the angular speed of the center of mass while turning (rad·s^{-1}), $\Delta\omega_m$ is additional component of the angular speed of the center of mass during wheel slippage and drift (rad·s^{-1}).

The solution of the system of equations (3) for the center of mass motion using the Euler formula for $\omega_m = V_m R_m^{-1}$ and $R_m = bFiC^{-1}$, where R_m is the turn radius, b is the vehicle's wheelbase, will have the following form:

$$\begin{cases} L_y(t) = \int_{t_0}^{t} V_m(\tau)cos\Psi_m(\tau)d\tau + L_y(t_0); \\ L_x(t) = \int_{t_0}^{t} V_m(\tau)sin\Psi_m(\tau)d\tau + L_x(t_0); \\ \Psi_m(t) = b^{-1}\int_{t_0}^{t} V_m(\tau)FiC(\tau)d\tau + \int_{t_0}^{t}\Delta\omega_m(\tau)d\tau + \Psi_m(t_0), \end{cases} \quad (4)$$

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

For solving the system (4) high precision measurements of V_m, FiC and $\Delta\omega_m$ performed either by dedicated or virtual information sensors [4] would be necessary. The last technical solution option is the preferred one, as it improves almost all technical and economic indicators, including the cost and the operating expenses.

6. The path stability control system

For solving the problem of the driverless vehicle specified path stability control a double-loop computer control system was developed that uses the data of the wheel navigation system and the road marking detection video system. The first control loop must ensure maintaining of the specified heading, while the second – the reduction of the deviation from the specified path when driving on by parallel courses.

The computational portion of the system includes three computers integrated into a hybrid telemetry information and control commands exchange network. The first computer provides initial processing of the information from the wheel speed sensors and its conversion into driving parameters of movement and electronic switches for the switching of electric power steering motor. The second computer performs the navigation task, generates the commands for the electric power steering and serves as the system's control panel. The network interface between the first and second computer implemented using the Bluetooth protocol and the Bluetooth RFCOMM (Radio Frequency Communication) stack. The third computer performs the task of processing of images from the TV camera for detecting the road marking, determining the lane center and the deviation of vehicle's centerline from the lane centre. The telemetry data between the third and first computer is transmitted over the serial interface.

The equivalent schematic diagram of a double-loop path stability control system is shown in figure 1.
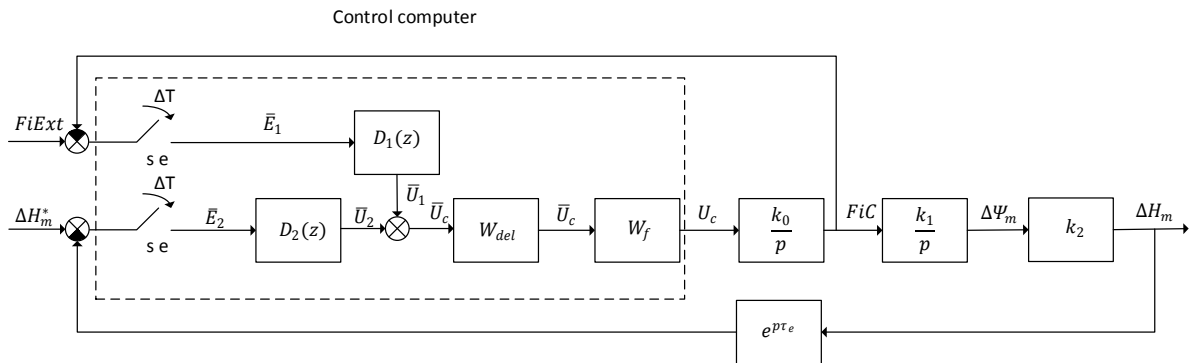

Figure 1. The equivalent schematic diagram of a double-loop computer path stability control system.

7. The single-step wheel steering angle regulator

The first control loop includes the electric motor of the power steering connected to computer-controlled reversible electronic switches. The regulator program is implemented on the navigation computer that receives information on the driving parameters, speed and wheel steering angle from the first computer, generates and sends the control commands to the first computer connected to the electronic switches with the PWM signal.

The computer portion of the system includes a pulse element that performs the quantization of the signals in time with the period of ΔT, the transfer function of the regulator $D_1(z) = k_P$, the delay element

$W_{del}(p) = e^{-p\Delta T}$ for the time of data exchange with the navigation computer and a clamper with the transfer function $W_f(p)$. The continuous part of the system in the form of the reversible power steering motor is represented by the integrating element $W_m = k_0 p^{-1}$ with a gain k_0 that relates the output signal of the steering angle FiC to the input in the form of the control voltage U_c.

The finite-difference equation of the motor in discrete time can be presented as follows:

$$FiC(k) = FiC(k-1) + \Delta T k_0 U_c(k-1); \tag{5}$$

In case a proportional regulator is used with the gain of k_p with the delay step of ΔT the following equation results:

$$U_1(k-1) = k_p[FiExt(k-2) - FiC(k-2)]; \tag{6}$$

The equation of the dynamics of $FiC(k)$ given (5) and (6) reduces to the form:

$$FiC(k) = FiC(k-1) - \Delta T k_p k_0 FiC(k-2) + \Delta T k_p k_0 FiExt(k-2); \tag{7}$$

Considering that during the pause time interval of pause the switches transfer the motor to the dynamic braking mode and $FiC(k-1) \approx FiC(k-2)$ and if $k_p = (k_0 \Delta T)^{-1}$, then $FiC(k) = FiExt(k-2)$.

To compensate the delay the setting value $FiExt$ recorded for the specified path shifts two steps forward with a linear approximation of the intermediate values and in that case $FiC(k) \approx FiExt(k)$ and the effect of the delay is completely compensated.

8. Path deviation control

The specified path stability control is performed on sections that are nearly straight $|FiExt| \leq \Psi_{lim}$ also by controlling the reversible electric power steering motor over to the second loop (Figure 1).

The equivalent schematic diagram of the computer path stability control system includes three additional elements: the heading change integrator $\Delta\Psi_m$, the proportional deviation change ΔH_m element and the element for extrapolation of its values with the coefficients $k_1 = b^{-1}V_m$; $k_2 = V_m\Delta T$ and τ_e, respectively. The continuous portion of the initial system contains two integrators connected in series and potentially may be prone to persistent oscillations. For giving to the system exponential stability a differential regulator with $D_2(z) = k_c k_{main}^{-1}(1 - z^{-1})\Delta T^{-1}$ is used:

$$U_2(k) = [U(k) - U(k-1)]\Delta T^{-1}, \tag{8}$$

where $U(k) = k_c k_{main}^{-1}(k)E(k)$; $k_{main} = b^{-1}V_m(k)\Delta T k_0$; $E(k) = \Delta H_m^*(k) - \Delta\widehat{H}_m(k)$; k_c is the factor to be set.

The assessment of the current deviation from the specified path ΔH_m is made based on the data from the WNS and LDW from condition:

$$\Delta\widehat{H}_m(k) = \begin{cases} \Delta H_{TV}, \text{if } |\Delta H_{TV}| \leq E_1 \text{ и } |\Delta H_N| \leq E_2 \text{ and } |FiExt| \leq E_3; \\ \Delta H_N \text{ otherwise,} \end{cases} \tag{9}$$

where ΔH_{TV} is deviation from specified path according to LDW (m); ΔH_N is the deviation from specified path according to the WNS (m); E_1, E_2 and E_3 are the parameters subject to setting.

The compensation of the delay introduced by the data exchange programs is achieved by extrapolating of the deviations from the lane center by defining distance at which the middle of the lane is evaluated:

$$\Delta L_d = \begin{cases} \Delta L(V_m), \text{если } \Delta L(V_m) > \Delta L_{min}; \\ \Delta L_{min}, \text{если } \Delta L(V_m) \leq \Delta L_{min}, \end{cases} \tag{10}$$

where $\Delta L(V_m) = V_m\tau_e - \Delta L_n$ (m); ΔL_n is the distance from front bumper to the center of mass (m); ΔL_{min} is the minimal range of the marking detection (m).

The deviation ΔH_N is defined as the height of the navigation triangle constructed on two nearest points of the specified path and the current position point determined from the WNS.

9. Experimental results

The research tests of the specified path stability control system were carried out at the sites of FSUE NAMI and Dmitrov proving ground.

The tests were carried out on the electric Lada Kalina vehicle. The control system set-up included the following:

- standard wheel speed sensors of the ABS system;
- standard electric power steering;
- oCam-5CR0-U video camera installed inside the car on the windscreen;
- ODROID-XU4 microcomputer ;
- primary information processing and control unit;
- a tablet computer performing the functions of the WNS and the control panel;
- autonomous control system power supply.

Figure 2 shows the frame of the video recording of the test drive on the circuit that includes a straight section with recognizable marking, a left 180 degree turn without marking and a straight section with marking that returns to the starting point. The deviation from the center of the lane ΔH_{TV} is defined as the variation of coordinates of the vehicle's longitudinal axis and the center of the lane.
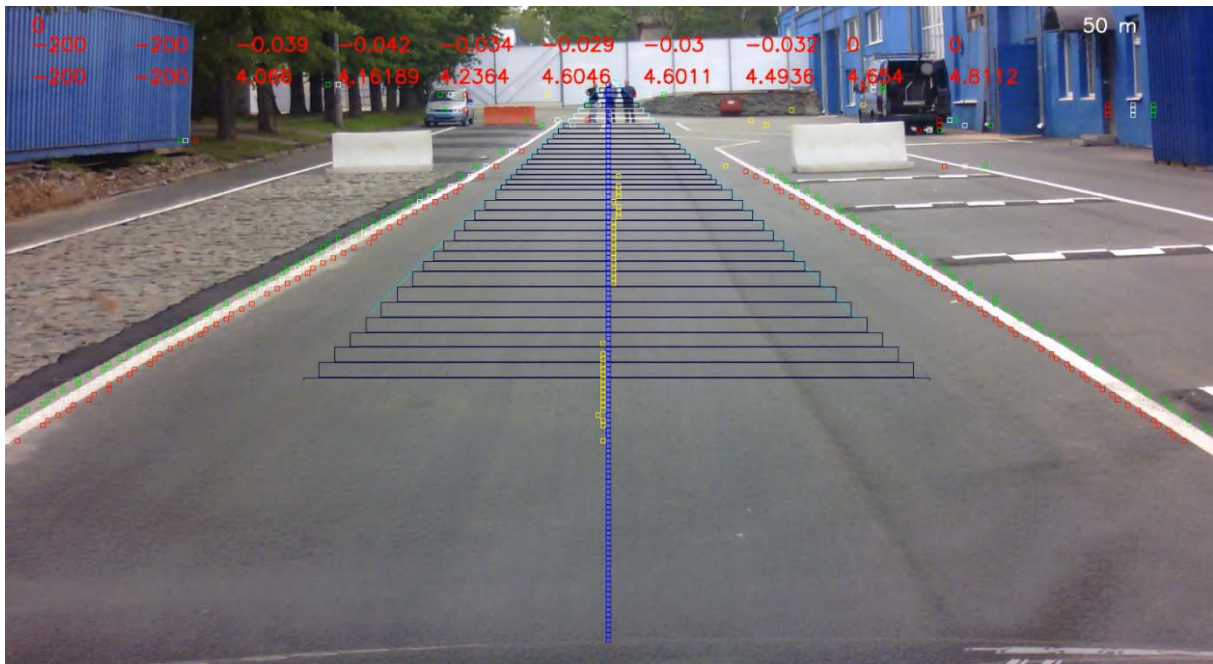

Figure 2. Frame of video recording of the straight section with recognizable marking.

In figure 3 shows time diagrams of the parameters of the driving on the straight section with the recognizable marking.

The analysis of experimental results confirms the exponential convergence of the deviation from centre of lane when using the differential regulator algorithm with the deviation extrapolation.
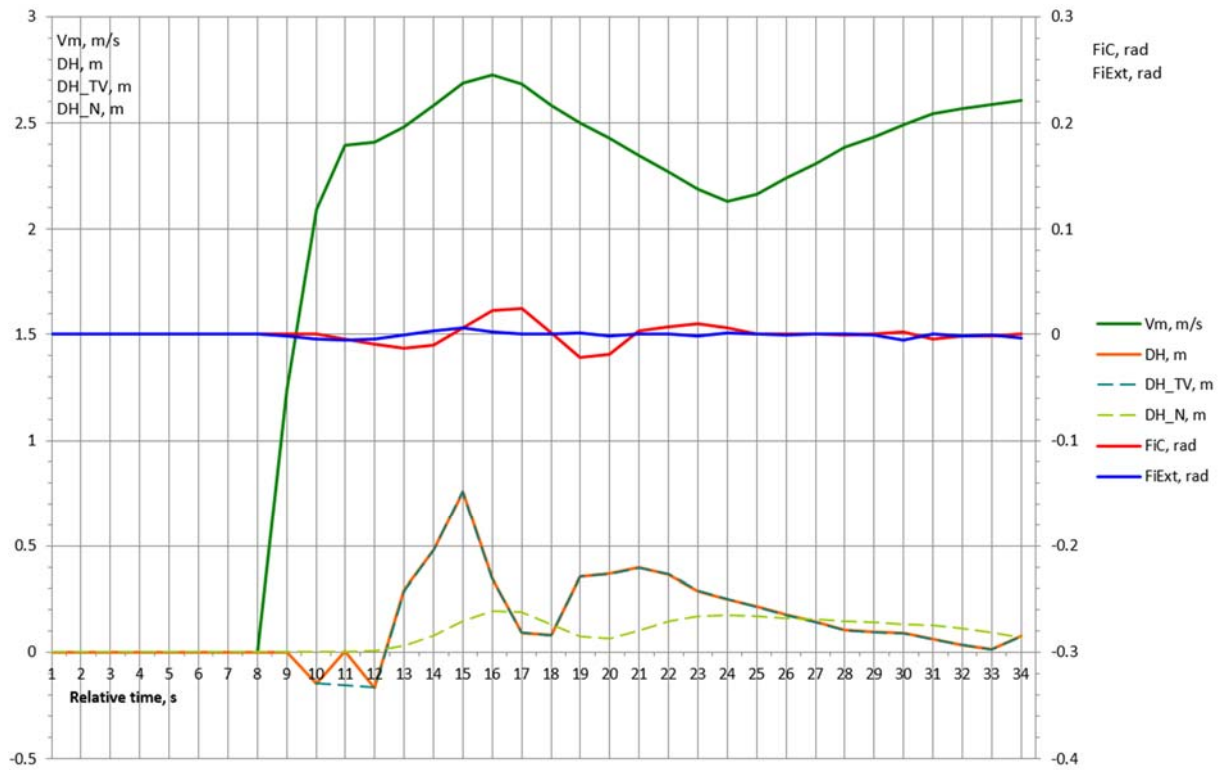
Figure 3. Time diagrams of the motion parameters on the straight section with recognizable marking.

Figure 4 shows the time diagrams of motion parameters at the turn with no visible marking.
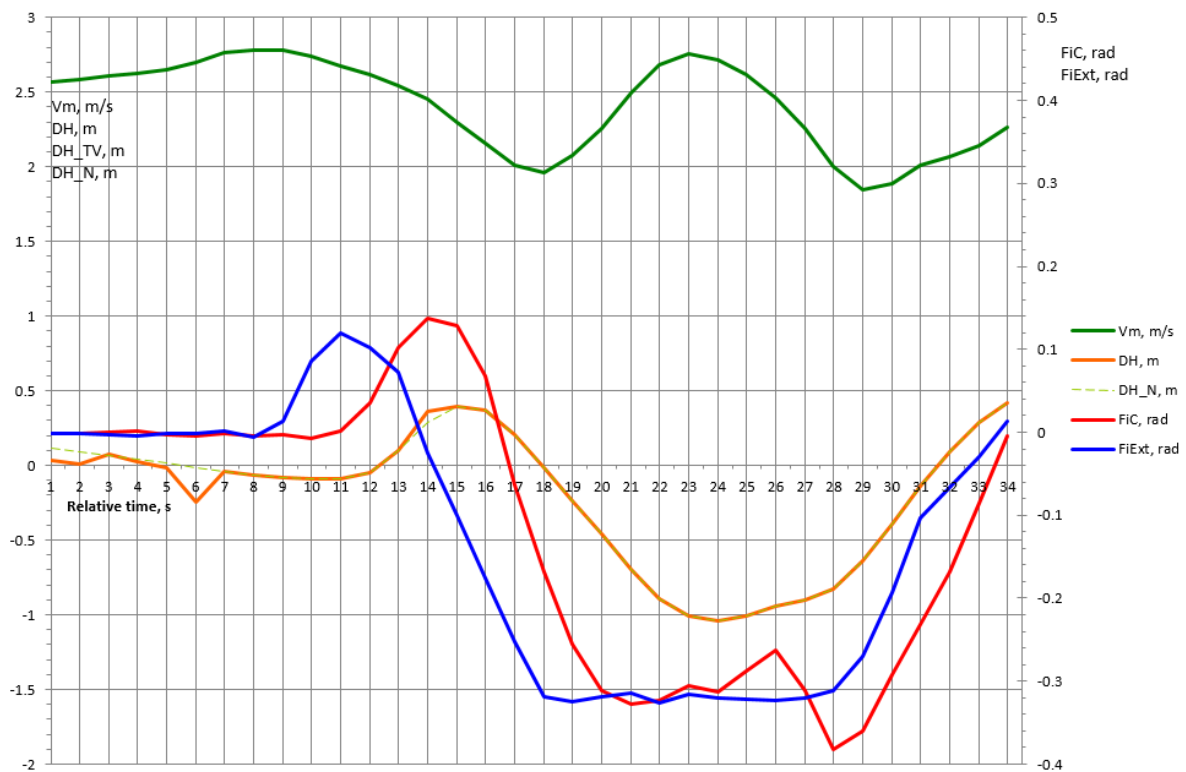

Figure 4. Time diagrams of the motion parameters at the turn with no visible marking.

The analysis of the results confirms the feasibility of the algorithm of the single-step regulator of the wheel steering angle with compensation of delay introduced by the software.

Conclusions
The analysis of the results of undertaken research of the problem of the driverless vehicle specified path stability control allows drawing the following conclusions:
- The formalized definition of the stability control problem in terms of minimization of a quadratic functional of the quality of control with consideration for the functional limitations for technical and economic indicators is adequate for the purposes of creating competitive systems;
- A comparative qualitative analysis of the navigation systems for actual operating conditions leads to conclusion that combining them is necessary;
- For circuits of limited length with sections with of recognizable the combination of the WNS and LDW gives the technical solution with the minimal configuration of additional technical means and with the optimum level of technical and economic indicators;
- The double-loop computer control system with a single step heading regulator and the virtual sensors of the center of mass velocity, the wheel steering and wheels and the additional angular speed during wheel slippage and drift and a differential deviation stabilizer that has been developed ensures compensation of the delays introduced by the software and the exponential stability with their finite step ΔT;
- The results of test driving do not contradict to the theoretical research and allow considering the achieved solution of the problem as effective.

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