The study of intelligent transport systems management of convoy of unmanned vehicles with a lead vehicle with the purpose of increase of efficiency of cargo transportation

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Abstract. This material describes the development of an intelligent transport system for controlling the movement of a column of unmanned vehicles with a leading pilot vehicle in order to increase the efficiency and safety of freight and passenger transportation in remote regions of the North of Russia, as well as in the Arctic and Antarctic. The obtained scientific results allow us to move on to the creation of new types of freight and passenger vehicles that can move unmanned modes over long distances, but at the same time, the possibility of direct human intervention remains. The introduction of this type of vehicles will improve the efficiency of freight and passenger transportation, reduce fuel consumption by predicting the traffic situation and increase the safety of transportation on public roads. The materials describe the circuit diagram of the components of the slave and leading intelligent vehicle, give mathematical models of some control systems and describe the tests that confirmed the operability of this type of vehicle. Tests have shown the adequacy of mathematical models and the complete autonomy of driven vehicles that follow the lead.

1. Introduction

The development of unmanned freight vehicles (UFV) among the world's leading automakers is considered one of the most promising areas. The leaders in this area, actively competing among themselves, are the American companies Waymo (a division of Google Corporation, Figure 1) and Otto (a division of Uber Technologies, Figure 1) formed in 2016. Other leading UFV developers are Volvo Trucks (Sweden) and Daimler (Germany).

A characteristic feature of the developments carried out by the aforementioned companies is the re-equipment of the production car in the UFV while maintaining the ability to control it with a driver, in connection with which the UFV retains the driver's cab and the controls of the base chassis [1-2].

It should be noted that the Otto division was organized with the aim of developing equipment and software for adapting operated trucks to autonomous control, and, for example, the well-known UFV Oshkosh TerraMax model, introduced in 2004, is an example of the application of the universal technology of unmanned control TerraMax UGV on standard tactical army car. Automakers such as Daimler and Volvo are developing in their UFV prototypes (Figure 1) automatic control technologies that have been tested on production vehicles as Advanced Driver Assistance Systems (ADAS). In November 2017, the world's leading manufacturer of electric vehicles Tesla Inc (USA) introduced a prototype of the electric cargo vehicle Tesla Semi (Figure 1) with a carrying capacity of 36 tons,
equipped with an autopilot system. Tesla Semi is an original chassis with a single driver's cab, equipped with a traction battery pack and four electric motors, each of which drives one of the wheels of the rear bogie. Traction batteries provide a range of 500 miles (804 km). The autopilot system includes a standard set of functions for driver assistance systems (ADAS), including lane keeping, and also provides the ability to change lanes. Thus, the presented prototype is not fully UFV, however, according to the development company, by 2020 it is expected to mass production of a fully autonomous freight electric vehicle [3].

Figure 1. Top: Waymo Track, Otto, Volvo Trucks; Button: Daimler, Oshkosh TerraMax, Tesla Semi.

It is believed that the use of UFV in the column is the most effective, in which it is expected to achieve the following results:

- improving road safety, since the negative impact of the human factor, which according to statistics is the cause of almost 80% of road accidents, is minimized;
- achieving savings of up to 20% of fuel;
- increase in transportation productivity by 1.3–1.4 times;
- ensuring comfortable working conditions for drivers in driven trucks;
- minimization of harmful effects on the environment;
- reducing the need to maintain a large staff of professional drivers with high pay;
- the ability to integrate unmanned transport systems into the technological process of enterprises, primarily large transport and logistics centers, ports, etc., ensuring their continuous round-the-clock operation.

2. Prerequisites and means to solve the problem.

The specific climatic conditions of most of the territory of Russia [4], the state of the road infrastructure, as well as the current legislation, do not allow us to expect the appearance of UFV on public roads in the near future. About 70% of the territory of the Russian Federation belongs to the regions of the Far North, and more than 20% is located beyond the Arctic Circle [5]. Areas of the Far North, including the Arctic shelf, are rich in minerals, the development of which is not sufficiently effective, including due to the poor development of the transport system. Road transport is most common in the absence or limited ability to use a network of railways, airfields, waterways. The increase in road transport requires a wider use of all-terrain vehicles and is a prerequisite for the development of the northern regions. Given these factors, it can be assumed that for Russia, the development of off-road unmanned vehicles should also be the main direction in the field of UFV. It is in the regions of the Far North that the commissioning of unmanned ground transportation systems (primarily transport columns) should provide increased efficiency and safety of all-season cargo transportation between settlements, strongholds of enterprises of the fuel and energy complex, etc. The road climatic conditions of the Arctic zone of the Russian Federation are characterized by the following features [6-7]:
• abnormally low temperatures (up to -60 °C), which complicate the starting of engines and limit the normal functioning of the technical means of autopilots;
• severe off-road driving conditions that allow the vehicle to be used only in winter conditions;
• reference-free terrain, which impedes visual determination of the location of the pilot vehicle along the route;
• snow drifts that do not allow recognition of road markings and impede the functioning of vision devices;
• constancy of limited visibility in polar night conditions;
• unpredictable influence of the geomagnetic situation and the state of the troposphere and ionosphere of the Earth at polar latitudes on the conditions for uninterrupted reception of satellite navigation signals.

3. Description of the column of unmanned vehicles
Convoy of unmanned freight vehicles (CUFV) (with a leading manned vehicle) can have any configuration in accordance with its purpose and may include a different number of unmanned links, which, in turn, can be different types of cargo vehicles (Figure 2).

![Figure 2. Diagram of a column of unmanned trucks with a leading vehicle.](image)

The motion control system of the leading manned vehicle CUFV receives information about the location and trajectory of movement of the CUFV from wheel speed sensors, the GPS navigation module CH-5707 and strapdown inertial navigation system. Input data from the listed devices are processed in the microprocessor unit MCS. After that, the navigation problem is solved, the current vector of control actions on the UFV is determined, and road signs are identified according to the data of the navigation system[8]. The received data is transmitted to the command and navigation terminal for deciding on the management of the column.

Using the communication module, the command terminal conducts a constant exchange of telemetry information with UFV, the next in the column and generates directive commands for UFV.

Special software for the vehicle control system has been developed for UFV:
• stabilization of UFV on the trajectory set by the leading pilot vehicle;
• stabilization of speed and distance UFV in the column;
• automatic braking of the UFV in the convoy before obstacles;
• control of directional stability and prevention of capsizing of UFV in a column;
• monitoring tire pressure in the UFV column;
• emergency stop UFV in the convoy.

Auxiliary algorithms do the job of logging the system, exchanging data between the blocks that make up the system, and its functional units.

In all vehicles, algorithms for working with GPS / GLONASS receivers and strapdown inertial navigation system modules are implemented. The MCS of the slave CUFV receives information from the following telemetry sources:
• from the host UFV;
• from wheel speed sensors;
• from the navigation module satellite navigation system;
• from means of technical vision and video processing unit.

According to the results of the work, the following MCS algorithms were developed:
• stabilization of UFV on the trajectory set by the leading pilot vehicle;
• stabilization of speed and distance UFV in the column;
• automatic braking of the UFV in the column before the obstacle;
• control of directional stability and prevention of capsizing of UFV in a column;
• monitoring tire pressure in the UFV column;
• emergency stop UFV in the convoy.

Auxiliary algorithms do the job of logging the system, exchanging data between the blocks that make up the system, and its functional units. So, according to data from navigation systems and processed video information, the UFV stabilization algorithm on the trajectory works. According to data from technical vision and wheel speed sensors, algorithms for stabilizing the speed and distances of UFV, automatic braking in front of an obstacle, and emergency stop in the column work [9].

4. Description of unmanned vehicle convoy control algorithms

Various mathematical models and algorithms have been developed for the control and interaction of the links of an intelligent convoy of freight vehicles:

• a mathematical model of the longitudinal motion of the center of mass of the driven UFV;
• mathematical model of brake deceleration;
• a mathematical model for controlling the course of the followers of the UFV;
• intelligent MCS control algorithm;
• traction control algorithm;
• brake control algorithm;
• course management algorithm;
• an algorithm for the interaction of vehicles in a convoy.

The practical use of these mathematical models involves the identification of their parameters using experimental data and data on the technical characteristics of vehicles. Settings for control algorithms should also be determined by the results of test tests of the control system in various operating modes. Mathematical models of the longitudinal motion of the center of mass, an algorithm for controlling brake mechanisms, as well as an algorithm for the interaction of intelligent vehicles moving in a column are described earlier [10]. Below are models of deceleration retardation, course control models driven by the UFV course control algorithm.

4.1. Description of the mathematical model of brake deceleration

In the mathematical model, the brake deceleration equation is described as:

\[
a_T(U_3) = \begin{cases} 
    m_0^{-1} \sum_{i=1}^{4} k_{3i} U_3, & \text{если } 0 \leq U_3 \leq U_{3\text{rp}}, \\
    m_0^{-1} \sum_{i=1}^{4} k_{3i} U_{3\text{rp}}, & \text{если } U_3 > U_{3\text{rp}},
\end{cases}
\]

where

\[k_{3i} = 10^5 S_{Ti} R_{Ti} k_{sti} R_{di}^{-1} P_{\text{max}}\]  - brake gain of the i-th wheel;

\[S_{Ti} = \text{total area of brake cylinders of the i-th wheel, } m^2;\]

\[R_{Ti} = \text{radius of the brake disc (drum) of the i-th wheel, } m;\]

\[R_{di} = \text{dynamic radius of the i-th wheel, } m;\]

\[k_{sti} = \text{coefficient of sliding friction of the i-th brake disc (drum);}\]

\[P_{\text{max}} = \text{maximum pressure in the hydraulic system, bar;}\]

\[m_0 = \text{vechicle mass, kg;}\]

\[U_{3\text{rp}} = \text{the boundary value of the control action on the brake system.}\]

The adopted numbering of the wheels corresponds to the remoteness of the wheel from the driver’s seat in the car with a left-side steering wheel layout. So, the front left wheel \(i = 1\), the front right \(i = 2\), the rear left \(i = 3\) and the rear right \(i = 4\).

Brake force \(F_{Ti}, 1 \leq i \leq 4\) in the contact spot, limited by the sliding friction force \(F_{Tst}\), are defined as \(F_{Ti} = k_{3i} U_3\).

The boundary values of the control actions \(U_{3\text{rp}}\) are determined from the conditions of equal braking forces \(F_{Ti}\) and the maximum values of the sliding friction forces \(F_{Tst}\) taking into account the redistribution of weight on the wheels of the front and rear axles during braking and on the wheels of the left and right sides when cornering for a car with a track gauge \(a\) and wheel base \(b\):

\[\]
\[ \begin{align*}
F_{Ti} &= k_{3i}U_{3rp_i}; \\
F_{TSi} &= F_{Ni}k_{Si}^*;
\end{align*} \]

At \( \alpha_T = 0 \):

\[ F_{Ni} = m_i \cdot g + 0.5C_T b^{-1} \sum_{i=1}^{4} R_{di} k_{3i}U_{3rp_i} + 0.5C_{ci} m_o b^{-1} a^{-1} h_m V_m^2 \Psi_c, \]

where \( C_T = \begin{cases} \{1, if 1 \leq i \leq 2; \\ -1, if 3 \leq i \leq 4; \end{cases} \)

\( C_{ci} = \begin{cases} 1, if i = 1, 3; \\ -1, if i = 2, 4; \end{cases} \)

\( m_i \) – mass attributable to i-th wheel;

\( \Psi_c \) – steering angle;

\( k_{Si}^* \) – the maximum value of the sliding friction coefficient of the i-th wheel.

The boundary value of the total brake control \( U_{3rp} \) is defined as the minimum of 4 and 1:

\[ U_{3rp} = \min\{U_{3rp1}, U_{3rp2}, U_{3rp3}, U_{3rp4}, 1\}, \]

where

\[ U_{3rp_i} = \left[ m_i g + 0.5C_{ci} m_o b^{-1} a^{-1} h_m V_m^2 \Psi_c \right] k_{Si}^* \cdot \left[ k_{3i} - 0.5C_T b^{-1} k_{Si}^* \sum_{i=1}^{4} R_{di} k_{3i} \right]^{-1}. \] (2)

In a correctly designed brake system \( U_{3rp1} = U_{3rp3} \) at

\[ a_T = a_{T_{\text{max}}} \approx k_5 \cdot g \] and the ratio of \( a = k_{33} \cdot k_{31}^{-1} \) equally:

\[ a = \left[ m_3 \cdot m_o^{-1} g - 0.5b^{-1} \cdot R_d a_T \right] \cdot \left[ m_1 \cdot m_o^{-1} g + 0.5b^{-1} \cdot R_d a_T \right]^{-1}. \]

In this case \( \sum_{i=1}^{4} k_{3i} = 2k_{31}(1 + \alpha) \) and coefficient brake booster \( k_{32} = k_{32} \) and \( k_{33} = k_{34} \) defined as:

\[ \begin{align*}
&k_{31} = 0.5(1 + \alpha)^{-1} a_{T_{\text{max}}} m_o; \\
&k_{33} = \alpha \cdot k_{31}, \text{where}
\end{align*} \]

\( a_{T_{\text{max}}} = 0.5 \cdot V_m^2 \cdot \Delta L_3^{-1}; \)

\( \Delta L_3 \) – stopping distance determined from experimental data of braking from speed \( V_m \).

Maximum brake deceleration value \( a_{T_{\text{max}}} \) determined from the equation:

\[ a_{T_{\text{max}}} = m_o^{-1} \sum_{i=1}^{4} k_{3i}U_{3rp_i}. \]

4.2 Description of the mathematical model of the slave course control UFV

To solve the problem of controlling the course of the driven UFV, according to the data received from the wheel speed sensors, calculation of the heading angle estimate \( \Psi_m \), is required, this value in general form is obtained from the formula:

\[ \Psi_m = \omega_m + \Delta \omega_m \cdot \] (3)

Where \( \omega_m \) – angular frequency of rotation of the center of mass at the bend, rad/sec;

\( \Delta \omega_m \) – additional component of the angular frequency of rotation of the center of mass during drifts and drifts of wheels, rad/sec;

Formula (3) is a mathematical model of the dynamics of the heading angle.

The angular frequency of rotation of the center of mass at the bend is identified by a virtual sensor of the parameters of the center of mass as:

\[ \omega_m = V_m R_m^{-1} = b^{-1} h_m \Psi_c, \]

Where \( R_m \) – bend radius, \( b \) – car wheelbase, \( V_m \) – longitudinal velocity of the center of mass, m/sec;

\( \Psi_c \) – steering angle.

Equation solution we write in the form:

\[ \Psi_m(t) = b^{-1} \int_{t_0}^{t} V_m(\tau) \Psi_c(\tau) d\tau + \int_{t_0}^{t} \Delta \omega_m(\tau) d\tau + \Psi_m(t_0). \] (4)
This solution describes the dynamics of the course angle behavior as a function of the speed and angle of rotation of the steered wheels.

4.3 Development of a course management algorithm.

The mathematical model of the dynamics of the heading angle is described by formula 4. For the formation of the heading control algorithm, we write the formula (4) in a discrete form:

$$\Psi_m(k) = \Psi_m(k-1) + b^{-1} \int_{t_{k-1}}^{t_k} V_m(\tau) \Psi_C(\tau) d\tau + \int_{t_{k-1}}^{t_k} \Delta \omega_m(\tau) d\tau$$

To control the steering trapezoid of the car, we consider a computer control scheme for the angle of rotation of the steered wheels $\Psi_m$ (Figure 3):

![Figure 3 – The scheme of computer control of the angle of rotation of the steered wheels.](image)

The input parameter in the system $\Psi_m$ is set based on the solution of the navigation problem performed by the high-precision navigation system and the estimation of the location error on a given motion path.

The control circuit contains an electric motor for the power steering connected to the reversible electronic keys controlled by a computer. The controller program is implemented on a navigation computer, which receives information about the parameters of movement, speed and angle of rotation of the steered wheels, generates and transfers control actions to the electronic keys with a PWM signal.

The computer part of the system contains a pulse element (IE), performing quantization of signals in time with a period $\Delta T$, the transfer function of the controller $D(z) = k_c k_{full}^{-1} (1 - z^{-1}) \Delta T^{-1}$, delay element $W(p) = e^{-p\Delta T}$ for the time of data exchange with the navigation computer, latch with transfer function $W_\lambda (p)$. The continuous part of the system in the form of a reversible electric power steering motor appears to be an integrating link. $W_\lambda = k_0 b^{-1}$ is the gain factor $k_0$, connects the output signal in the form of an angle of rotation $\Psi_C$ with the input signal in the form of a control voltage $U_y$.

The finite-difference equation of the engine in discrete time:

$$\Psi_C(k) = \Psi_C(k-1) + \Delta T k_0 U_y(k-1);$$

(5)

The equivalent circuit of a computerized course control system includes an additional link: an integrator of course change $W_u$, with a coefficient $W_u(p) = b^{-1} V_m/p$. The original system in the continuous part contains two integrators in series and can potentially be prone to undamped oscillations. To give the system an exponential stability, a differential controller with

$$D(z) = k_c k_{full}^{-1} (1 - z^{-1}) \Delta T^{-1};$$

$$U_\lambda (k) = [U(k) - U(k-1)] \Delta T^{-1},$$

(6)

where $U(k) = k_c k_{full}^{-1}(k) E(k);$ $k_{full} = b^{-1} V_m(k) \Delta T k_0;$ $E(k) = \Psi_m \Delta \omega_m (k) - \Delta \Psi_m (k);$ $k_c$ – custom coefficient.

5. Tests convoy of unmanned vehicles.

Tests of the intellectual convoy of freight vehicles took place in August 2019 at the NITSIAMT FSUE "NAMI" automobile training ground using the following unique scientific facilities: "Scientific-research complex of road structures for testing and fine-tuning of automotive equipment
During the research tests, a check was carried out for compliance with the functions of the control system to the basic requirements of the technical specifications in terms of special functions:

- trajectory construction by a leading pilot vehicle;
- stabilization of UFV on the trajectory set by the leading vehicle;
- stabilization of speed and distance of UFV in the column;
- automatic braking of unmanned vehicles in a convoy in front of an obstacle;
- control of directional stability and prevention of capsizing of UFV in a column;
- recognition of road signs by the leading pilot vehicle;
- tire pressure monitoring in the UFV column;
- emergency stop UFV in the column.

![Figure 4 – Convoy of unmanned trucks during the test](image)

The construction of the trajectory by the leading pilot vehicle of the UFV column in the column transport control system is carried out according to the integrated navigation system (satellite and wheel) and, in the presence of road markings, according to the data from the video camera. Figure 5 shows the image of the arrival map with the constructed path of the leading pilot vehicle according to the integrated navigation system. Analysis of the arrival map shown in Figure 5 allows us to conclude that when constructing the trajectory by the leading pilot vehicle, the error in constructing the trajectory was less than 0.5 m at a vehicle speed of 30 km/h. The total length of the route was 673 meters. Start and finish points fell.

Tests of the function of stabilizing the speed and distance of the UFV in the convoy were carried out on a straight section of the dynamometer road of the Dmitrov auto test site at a speed of 7 km/h. The distance between the slave UFV and the lead pilot vehicle was measured using a long-range radar mounted in front of the slave UFV. Figure 6 shows the timing diagrams of the test of the stabilization function of the speed and the UFV distances in the column.

Analysis of time charts shows that when driving in the mode of stabilization of speed and distances, the distance between cars during the movement was on average 11-14 meters, and the error of stabilization of speed did not exceed 1 km/h. The distance after joint braking was 2.4 meters.
Figure 5 – Test Result: test map of the driving vehicle with indication of deviations from the specified route.

Figure 6 – Timing diagrams of the test of the stabilization function of the speed and distance of unmanned vehicles in the column.
6. Conclusion
The analysis of the results of research tests of the prototype column transport control system of the cars of the leading pilot and driven UFV allows us to conclude that the prototype column transport control system as a whole meets the requirements of the technical specifications.

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