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Creation concept and architecture principle for vehicle motion control competitive systems under road and climatic conditions of the Russian Federation

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Abstract. The urgency of traffic safety improvement is determined by the global significance level of this problem. Current research provides the scientific substantiation of the creation concept and building principles for competitive motion control systems (MCSs) under road and climatic conditions of the Russian Federation. The study was carried out using system analysis methods and modern control theory. The safe vehicle control task is formulated as prevention of collisions with moving and stationary obstacles on the route taking into account the road and climatic conditions of the Russian Federation. To estimate the quality of the dynamic stabilization solution modified quadratic functional is introduced. The results of the study are presented as an analysis of properties of the modified quadratic control quality functional and associated consumer indicators. Based on the analysis of results of the minimization problem for control quality quadratic functional and the multicriteria problem could be solved by software and hardware modification of intelligent systems realized in the minimal configuration of hardware. The novelty of the work is the scientific substantiation of the concept for the competitive vehicle MCSs creation based on virtual information sensors, the use of new mathematical models and control algorithms to solve the problem of collision avoidance.

1. Introduction

The problem of creation of competitive products is traditionally the central problem of the developed countries with market economy. To solve it, intellectual, financial and labor resources of both private firms and state organizations are involved.

One of the most intensively developing industries in the developed world is the automobile manufacturing. The achievements of the modern science and technology are successfully used to increase the competitiveness level of the manufactured technical products and expand sales markets. Leading foreign companies and domestic organizations are conducting large-scale research in the field of vehicle active safety systems [1] and in the field of driverless vehicles creation [2] [3].

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The aim of the research is the scientific substantiation of the concept and principles of creation of competitive motion control systems (MCSs) building under the road and climatic conditions of the Russian Federation.

The problem of collision prevention on the route is among the control tasks that should be solved with the help of MCSs. For driverless vehicles, the position stabilization is also necessary task [4].

To solve the first problem, various active safety systems are used, which are standard equipment of foreign cars.

To solve the second problem, navigation systems [5] and technical vision systems [6] are used, including radars, video cameras, lidars, ultrasonic sensors, etc.

The road and climatic conditions of the Russian Federation considerably differ from the conditions of car operation in Central Europe, North America and the countries of the Asian region.

For the Russian Federation, long periods of low temperatures, snowfalls, fog, ice slick are typical.

Unsatisfactory state of roads is added to the unfavorable climatic conditions: lack of visible marking, increased rutting, significant coating unevenness. These unfavorable conditions can affect the effectiveness of the active safety and technical vision systems and reduce it to unacceptable level, making the vehicles safe operation impossible.

The concept of creation of competitive systems for vehicles motion control under road and climatic conditions of the Russian Federation is a group of goals, the achievement of which is possible with the use of new technologies, models and principles of building of information control systems [7].

2. Task statement

Multicriterion optimization methods are used within hardware *(R_H)* and software *(R_S)* tools [8] for the scientific substantiation of the concept for competitive vehicle MCSs creation.

Summarizing the experience gained from work with the consumers of high-tech technical products in the field of automotive electronics allows us to determine the main consumer indicators of interest to the end user.

As general criteria for evaluating technical systems, the following consumer indicators can be considered:

- level of external design;
- completeness of implemented functions;
- level of observation and control errors;
- level of power consumption from external sources;
- degree of external factors influence;
- degree of influence on adjacent systems;
- level of fault tolerance;
- restrictions on installation;
- operating costs;
- price of the system.

The best solution to the multicriteria problem within software-hardware solutions $R = (R_H, R_S)^T$ is an R for which the system of inequalities is satisfied:

$$q_i(R) \le q_{imin}, 0 \le i \le 9, \text{ where} \quad (1)$$

$q_{imin} = \min[q_i(R_1), \dots, q_i(R_n)]$

$R_1 \div R_n$ – known technical solutions.

The known technical solutions R satisfying to the inequalities (1) form a region of record decisions that correspond to the creation of systems with the highest level of the competitiveness concept.

3. Research results

In order to carry out a comparative analysis of possible technical solutions for the vehicle MCS, we use the properties of the quadratic control quality functional and consumer indicators.

At the conceptual level, the MCS should provide the solution of the following applied tasks:

- detect the approach and exceeding the dangerous states boundaries;
- stabilize the longitudinal and lateral slip of the wheels within safe limits;
- stabilize the safe speed and distance to the obstacle on the lane;
- perform automatic braking to a complete stop before a stationary obstacle on the lane;
- stabilize the course and position of the car on a given trajectory.

As a final goal, the MCS must provide the solution to the task of object state coordinate dynamic stabilization.

To evaluate the solution quality of the vehicle dynamic stabilization problem, to which the collision avoidance problem is reduced, a modified control quality functional $Q(t_2)$ is introduced to the final time interval of operation $t_1 \div t_2$:

$$Q(t_2) = Q_r(t_2) + Q_{\text{con}}(t_2) + Q_{exp}(t_2), \text{ where} \tag{2}$$

$$Q_r(t_2) = \int_{t_1}^{t_2} \sum_{i=1}^{N} C_{1i}[x_i(\tau) - x_{ib}^U]^2 d\tau + \int_{t_1}^{t_2} \sum_{i=1}^{N} C_{2i}[x_i(\tau) - x_{ib}^L]^2 d\tau;$$

$$Q_{con}(t_2) = \int_{t_1}^{t_2} \sum_{i=1}^{5} C_{3i} \cdot U_i^2(\tau) d\tau\,;$$

$$Q_{exp}(t_2) = \int_{t_1}^{t_2} \Delta C(R,\tau) d\tau + Q(t_1).$$

The summands of the functional $Q_r(t_2)$ characterize the solution quality of the dynamical stabilization problem of the state vector $X(t)$ within the upper and lower dynamic boundaries $X_b^U(t)$ and $X_b^L(t)$. If the state vector components $x_i(t)$ are within the upper and lower bounds, the penalty coefficients C_{1i} and C_{2i} are zeroed, otherwise they denote large positive values $C_{1i} \gg 0$ and $C_{2i} \gg 0$.

The risk functional $Q_r(t_2)$ is zero if control of the object U provides the satisfied constraints on the state vector. If the boundaries are violated, it means that the conditions for preventing one or more typical collisions are not meet for the control object and prerequisites for an accident arise. The more time the object is in a dangerous state, the more accumulated risk becomes.

The summand of the control cost functional $Q_{con}(t_2)$ corresponds to the equivalent energy of the driver spent for control. The control vector components $U = (U_1, U_2, U_3, U_4, U_5)^T$ correspond to the control actions on the gearbox (U_1), the throttle (U_2), the braking system (U_3), the steering wheel (U_4) and the clutch pedal (U_5).

The choosing and justifying problem of the MCS optimal version at the content level is reduced to modified functional $Q(t_2)$ minimization due to the controls U, realized in the hardware and software environment R:

$$Q(t_2) \to min \tag{3}$$

at $U \in U_{add}, R \in R_{add}$

The best or optimal solution meets the criteria (3) is the control U (t) = F (X, X_b^U, X_b^L) realized by the driver and control system using data generated by the software and hardware environment R, providing solution of the dynamic stabilization problem and characterized by minimal acquisition and operation costs.

The summand of the cost functional for the software and hardware acquisition and operation: $Q_{exp}(t_2, R) = \int_{t_1}^{t_2} \Delta C(R,\tau) d\tau + Q(t_1, R)$ is determined by the number $N_c = N + N_m + N_D$ used the information sensors on object state variable – N, driver – N_D, actuators for control – N_m and software:

$$Q(t_1, R) = \sum_{i=1}^{N_c} C_{Hi} + C_s \tag{4}$$

where $C_{Hi}, 1 \le i \le N_c$ – the cost of information sensors and actuators purchased or produced by the manufacturer;

C_s – cost of special software replication for the developer, incommensurable with C_{Hi}, $C_{Hi} \gg C_s$.

The costs intensity for operational state maintenance is also determined by the number of serviced primary information sensors:

$$\Delta C(R,\tau) = \sum_{i=1}^{N_c} \Delta C_i(\tau). \tag{5}$$

To reduce the cost $Q_{exp}(R, t_2)$ in the information processing and control systems virtual sensors that replace physical ones are used. Their operation principle is based on the use of mathematical models and algorithms of indirect measurements, which allow using the minimum number of physical information sensors and actuators $N_{min} \ll N_c$.

In this case, for all $R \in R_{add}$ the following inequalities are observed:

$$\begin{cases} Q_{\exp}(R_{min}, t_2) < Q_{exp}(R, t_2); \\ Q(R_{min}, t_2) < Q(R, t_2), \end{cases} \tag{6}$$

where R_{min} is a technical solution with a minimum set of sensors for primary information and actuators N_{min} and virtual sensors for measuring N_c components of the object and the driver.

For consumer indicators, this means that $q_i(R_{min}) < q_i(R), 0 \le i \le 9$ and the developed MCS acquires competitiveness properties in a certain segment of applied technical systems.

Thus, for the motion control of a driverless vehicles platoon with a leading controlled vehicle, it becomes possible to significantly reduce the influence of external factors such as illumination, fog, precipitation in the form of rain and snow, the lack of recognizable markings.

The use of data from the wheeled navigation system for distance estimation between objects in a platoon equipped with means for exchanging information about the traveled distance and the angle of steered wheels rotation makes it possible to almost completely eliminate the influence of external factors on the results of stabilization problem solution. The use of video cameras to determine the deviation of the car axis from the center of the leader vehicle tailgate and the distance to it makes it possible to exclude the need for recognition of marking and compensate the accumulation of distance measurement errors by the wheeled navigation system.

The use of new anti-lock system algorithms based on identification of the wheel slip friction coefficients top values allows avoiding the intermittent braking mode and using only one actuator to act on the brake pedal.

To implement the stabilization functions the same brake actuator is used, which is controlled in accordance with the original algorithm.

The principle of replacing of physical information sensors by virtual ones involves the use of indirect measurements of physical variables. For its implementation, mathematical models and algorithms are used, which allow obtaining reliable information about object state parameters without additional equipment.

4. Conclusion

The concept of creation of competitive system for vehicles motion control involves the achievement of the following objectives:

- implementation of the proposed MCS in the minimum configuration of equipment by using algorithms for indirect measurements (virtual sensors) and knowledge about the control object in the form of formalized descriptions of its properties;
- increase of efficiency and safety of cargo and passenger transportation;
- reduction of maintenance costs for vehicles due to the timely detection of critical failures;
- ensuring better connectivity of the Russian Federation territory through the creation of intelligent transport and telecommunication systems, as well as engaging and retaining leadership positions in the creation of international transport and logistics systems;

- increasing the capacity of the road network, reducing the amount of harmful emissions to the environment by increasing the average speed of traffic flow due to decrease in the number of accidents.

The analysis of the accumulated experience, modern scientific, technical, normative and methodological literature on the problem of MCSs allows us to state that the application of mathematical models and algorithms of indirect measurements, along with more sophisticated control algorithms are the basis for creation of efficient technologies and applied control systems in this area.

The implementation of the proposed MCS in the minimal possible configuration of hardware, by using algorithms and mathematical models of indirect measurements (virtual sensors) is accompanied by an abrupt improvement in almost all consumer indicators, including reliability, operation costs, energy consumption and total cost.

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