Principles of building competitive motion control systems for highly automated vehicles

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Abstract. The relevance of the issue of development of efficient motion control systems for highly automated vehicles capable to successfully compete with foreign systems of similar purpose is defined by importance of the issue of creation of competitive high-tech products under modern market economy conditions. The research objective was to scientifically justify the building principles for motion control systems for highly automated vehicles providing directed search for solution options for the issue of multi-criterion optimization in the software and hardware space. The research involved methods of system analysis and modern control theory. The research result is a set or complex of building principles for motion control systems for highly automated vehicles providing minimization of hardware environment while keeping observability of all vehicle state coordinates significant for safe control and their dynamic boundaries, as well as ensuring controllability via the channels of traction, braking and direction. The conceptual core or base of such integrated intelligent control systems is mathematical and programming support (software) of indirect measurements of the parameters of motion and control of traction, brakes and direction adapting to the vehicle state and environment changes.

1. Introduction
The issue of development of efficient motion control systems for highly automated vehicles (HAV) is in the spotlight of the leading foreign automobile manufacturers [1] interested in the increase of competitive ability of technical products being manufactured. To solve this issue, intellectual, financial and production resources of international corporations of the developed countries are being involved. Considerable results regarding creation of the advanced driver assistance systems [2] have been achieved including the anti-lock braking and traction control (antiskid) systems, adaptive cruise control and advanced emergency braking systems, tyre pressure monitoring systems, electronic stability programs, lane keeping assist, traffic sign recognition systems, driver awaken state monitoring systems and other driver assistants.

The motion control systems are composed of hardware and software united into hardware and software packages of information support for decision-making by the driver [3] and of automatic control via the channels of traction, braking and direction for some tasks, which do not demand participation of the driver.

The hardware means raw data sensors, actuators, computing devices, data entry and display devices, power sources, connection cables, etc.

Improvement of monitoring and control functions, increasing their number by using new data sensors, actuators and computing devices, data entry and display devices demand the use of new
materials, technologies, facilities, highly skilled manpower, etc., which results in constraints for this direction under modern economic conditions of the Russian Federation.

Improvement of mathematical and programming support (software) to facilitate and enhance monitoring and control functions with the minimum configuration of the hardware used is limited only by the developer's intellectual capacities, which opens the way for successful competition in this state-of-the-art technology sphere.

Acknowledging the achievements of the foreign scientists and engineers who created modern motion control systems for highly automated vehicles, it should be noted that far from all the functions developed by them meet the advanced requirements.

2. Objective definition
System analysis of the automobile transport traffic safety problem [4] shows that the task of preventing vehicle collisions with obstacles reduces to the task of dynamic stabilization of the state coordinates with limited control inputs via the channels of traction, braking and direction.

Vehicle state coordinate vector $X$ includes the variables defined from conditions of prevention of typical or standard collisions from a structured set [5] built according to the Zwicky Morphological Box method [6].

Dynamic boundaries of the state variables for each component of the state vector are also being defined from conditions of prevention of typical or standard collisions from the structured set.

The dynamic stabilization task or problem is formulated as the following system of inequations:

$$X_{1i}(X, U, t) \leq X_i(t) \leq X_{2i}(X, U, t), 1 \leq i \leq n, \text{ where } U \in U_{perm},$$

where $X_i(t)$ is the $i$ component of state vector $X$;

$X_{1i}(X, U, t)$ is the $i$ component of the lower border of permissible values of vector $X$;

$X_{2i}(X, U, t)$ is the $i$ component of the upper border of permissible values of vector $X$;

$U = (U_1, U_2, U_3, U_4)^T$ is the vector of control inputs to the gearbox ($U_1$), accelerator ($U_2$), brakes ($U_3$) and steering wheel ($U_4$);

$U_{perm}$ is the permissible area of limited control inputs $U$.

Considering that the control task is solved in the hardware and software environment, constraints defining the competitive ability of the selected solution are also imposed on the parameters of technical solution variants under consideration.

In real systems, the optimal control task formulated in terms of minimization of quadratic functional is solved for assessments of state vector $X$ and assessments of its upper and lower borders.

These $X$ assessments and control inputs $U$ are formed in the hardware and software environment characterized by technical solution space $R$ including the space of hardware ($R_h$) and software ($R_s$).

Technical solutions $R$, in turn, have a set of consumer parameters defining their competitive properties. They include the following parameters minimized as follows:

- $q_1(R)$ – the integrity level of the implemented functions;
- $q_2(R)$ – the error level of monitoring and control;
- $q_3(R)$ – the level of power consumption from the electric power supply network;
- $q_4(R)$ – the reliability level;
- $q_5(R)$ – the level of external factors influence;
- $q_6(R)$ – the level of impact on adjacent systems;
- $q_7(R)$ – the level of flexibility (versatility) as to the control objects;
- $q_8(R)$ – the level of operation costs;
- $q_9(R)$ – the level of system cost.

All the given parameters depend on the vector of technical solutions in the hardware and software space.
Quadratic functional of control quality or performance in finite time interval $(t_1 \div t_2)$ represents an integral function of risks related to going beyond the dynamic boundaries of each state variable and becomes zero when all constraints for the state variables and for the control inputs are complied with.

$$Q(t_2) = \int_{t_1}^{t_2} \sum_{i=1}^{n} C_{i1}[X_i(\tau) - X_i(X, U, \tau)]^2 d\tau + \int_{t_1}^{t_2} \sum_{i=1}^{2} C_{i2}[X_i(\tau) - X_{2i}(X, U, \tau)]^2 d\tau \rightarrow \min$$

when $U \in U_{perm}$, $R \in R_{perm}$, $q_i(R) \leq q_{ilim}$, $1 \leq i \leq 9$,

$$R = (R_h, R_g)^T$$

is of high dimensionality defined by a significant number of various sensors, actuators, controllers, data entry and display panels as well as software for data processing and control and also by many variants of their design.

The best solution for the assigned optimization issue is a hardware and software system allowing minimization of the risk function and having advantages over the products of similar purpose as to all the parameters being compared. The complexity of solving this issue is defined by the huge dimensionality of space of variables of the hardware and software tools and by corresponding expenses for the exhaustive search or enumeration of possibilities.

The research objective is scientific justification of the building principles for the motion control system for highly automated vehicles providing directed search for solution options for the issue of multi-criterion optimization in the software and hardware space.

3. Research results

The analysis of the tasks of collision prevention and stabilization along an assigned driving trajectory shows that they come down to the task of dynamic stabilization of motion parameters with changing allowable boundaries of variables.

In order to solve the task of dynamic stabilization, a sequence of limited control inputs to the controls shall be generated. Various control scenarios executed depending on proximity of the state variables to their dynamic boundaries are different branches of the general control algorithm.

Extensions of the variety or set of particular algorithm branches and logical conditions of their execution ensure, among other things, transformation of emergency situations into regular or designed ones and constitute one of the key characteristics of intelligent systems.

The principle of state "transparency" implies monitoring of all state variables significant in terms of control as well as monitoring of all control inputs and state of the environment.

The composition of these variables is determined based on the conditions of typical or standard collisions prevention and stabilization along an assigned driving trajectory.

In case of incomplete observability of the motion parameters and their dynamic boundaries, prerequisites occur for a collision with obstacles and for inadmissible deviations from the assigned route.

Minimization of quadratic functional of control quality implies availability of reliable information on state coordinates, their dynamic boundaries and control inputs.

In systems built on this principle, minimization of quadratic functional of control quality becomes possible along with simultaneous decrease in parameters $q_1$ and $q_2$.

Realization of complete observability requires providing numerous physical data sensors of different types. This process is accompanied by cost increase, reliability degradation, increase of power consumption, difficulties with physical sensor placement, negative impacts of the environment, etc.

The principle of replacing physical data sensors with virtual ones assumes the use of programs of indirect measurements of motion parameters based on mathematical models and algorithms for solving incorrect tasks. The data from the wheel-speed sensors is used as input data for virtual data sensor programs.

The variables measured by the virtual data sensors include as follows: distance covered, center-of-mass longitudinal speed, longitudinal and lateral accelerations, steering angle, longitudinal wheel slip, additional angular rotation speed during under- and oversteering, tyre pressures and tyre air...
temperatures, brake overheat temperatures, top coefficients of wheel slip friction, center-of-mass position coordinates in the Cartesian coordinate system, etc.

Using virtual data sensors allows ensuring observability of major motion parameters with the minimum configuration of the used hardware.

In systems based on this principle, minimization of parameters $q_3, q_4, q_5, q_6, q_7$ and $q_9$ is achieved.

The principle of software adaptation for different vehicle types assumes implementation of an input mode for setting parameters of the used indirect measurement mathematical models. Application of this principle allows reduction of the time required for the control system preparation in the course of its adaptation to individual parameters.

For vehicles with different design parameters, adaptation of the information part of the system is required which may be performed both by using specialized sets of physical data sensors and units for processing their data and by software without changing the hardware design.

In order to successfully implement the software adaptation principle, adequate and proper vehicle mathematical models shall be available, parametrically and structurally adaptable within the wide class of vehicles, which makes it possible to minimize parameter $q_7$.

The principle of autonomous functioning implies minimization of power and informational connections with adjacent systems. The motion control systems designed according to this principle shall have their own power sources that allow remaining functional in case of failure of the standard vehicle power system.

Minimization of informational connections with adjacent systems implies maintenance of operating capability in case of communication channel failures or unreliable data coming from external sources.

Equipping of vehicle fleets in operation with active safety systems is easiest to implement with the use of "add-on" systems that do not require connection to the standard vehicle systems. In systems based on this principle, minimization of parameters $q_4, q_5$ and $q_6$ is achieved.

The principle of compensation for algorithmic errors provides minimization of influence of periodicity and delay in execution of programs for data processing and control on the control system dynamics.

Signal time quantization and delay in forming of output data in computer control systems are accompanied by occurrence of dynamic errors in the output data and negative phase shifts resulting in oscillation processes.

A trivial solution used to minimize these effects comes down to periodicity intervals decrease and overstated requirements for the used computation equipment in terms of processing speed. The higher and increasing processing speed requirements demand usage of a distributed multiprocessor computing system and lead to increase in device cost.

The longer periodicity interval without loss of solution accuracy under conditions of measurement noises, on the one hand, requires usage of non-standard computing schemes, and on the other hand, allows reduction of the required computing resource and increase in the number of tasks being solved by one computing device. In systems based on this principle, minimization of parameters $q_2$ and $q_9$ is achieved.

The principle of combination of devices' functions implies use of multi-functional devices for data entry and display, computing devices, physical sensors for data used in different virtual sensor programs, as well as multi-functional actuators to control traction, brakes and direction in both automatic and manual control modes. Application of this principle allows reducing technical means redundancy and ensuring integration of the control function with the minimum configuration of devices required therefor.

The result of this principle application is reduction of the expected power consumption, reduction of the weight and scope of technical means, lowering of the crosstalk level, reduction of cost and expenses for operation and maintenance, i.e. of parameters $q_3, q_4, q_5, q_6, q_8$ and $q_9$.

Thus, usage of the considered set or complex of principles is focused on minimization of the whole group of consumer parameters within the assigned issue.
4. Discussion of results
The analysis of the properties of the considered building principles for HAV motion control systems that have a set of consumer parameters required for successful competition with foreign benchmarks was carried out within the framework of solving the dynamic stabilization task. Each of the mentioned principles setting out the direction of search for technical solutions for the general task in the hardware and software space is focused on minimization of a specific group of consumer parameters.

Joint application of the formulated principles is aimed at resolving the issue of multi-criterion optimization, which lies within the field of integrated intelligent systems. The conceptual core of such systems is mathematical and programming support (software) of indirect measurements of parameters of state of the controlled object and the environment, as well as effective laws of adaptive motion control in a changing environment implemented within the minimum hardware configuration.

The formulated principles became the basis for the INKA-SPORT computer active safety system [5] and its modifications for passenger cars and trucks developed in FSUE "NAMI" from 2015 to 2020.

5. Conclusion
The results of the conducted research allow formulating the main principles for building motion control systems for different types of vehicles, which assign the research focus areas when choosing the technical solutions providing the high scientific and technical level of the products being developed.

The set or complex of principles for building motion control systems for highly automated vehicles is as follows:
— principle of state "transparency";
— principle of replacing physical data sensors with virtual ones;
— principle of different vehicle type software adaptation;
— principle of autonomous functioning;
— principle of algorithmic error compensation;
— principle of combination of devices’ functions.

Practical use of the research results allows minimizing the number of raw data sensors, actuators and computing devices, which is accompanied with decrease of all the consumer parameters, and solving the problem of dynamic stabilization in its fullest algorithmically solvable statement.

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