Computing information and control complex for control of road construction machines

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Abstract. The article considers a model of the digging process carried out during the operation of a road-building machine, identifies the controlled and control parameters of the model. Based on the results of numerical simulation, it is shown that a rigid control algorithm is capable of providing effective results only in cases where most of the operating parameters of the machine do not go beyond the optimal area. To improve the efficiency of control and expand the permissible range of parameters of the state of the machine, it is proposed to use control based on fuzzy logic. The structure of synthesis of algorithms for fuzzy control of road-building machines is given. For the purpose of practical implementation of a fuzzy control algorithm, a basic model has been built, which includes 10 linguistic rules, on the basis of which chains of actions are formed during the operation of a machine. When implementing a fuzzy control model for the main parameters of the state of the machine, it is proposed to use triangular membership functions. The fuzzy inference surface for the fuzzy control algorithm is obtained and visualized, which makes it possible to efficiently search for the optimal trajectory of the control parameter function. An agent-based traffic model is considered, which describes the movement of road-building vehicles on a site and uses active and proactive algorithms. The results of numerical modeling confirm the feasibility of considering a variety of road-building machines at the site of joint work execution as a multi-agent system with elements of self-organization (CDPS-system). The maximum effect of self-organization is observed when the distance between the machines is changed, when they are uniformly located on the site. The expediency of combining local systems of automatic control of road-building machines into a single information and control complex is substantiated, a list of information and control tasks to be solved by the complex is formulated, and its structural diagram is synthesized.

1. Introduction

On-board computer systems of road-building machines provide the necessary information and functional interaction of technological processes. Robotic systems create conditions for the transition to fully intelligent (smart) digital production of construction work and the emergence of new technologies [1]. Digital models of technological processes allow making planning decisions in an automatic mode. The introduction of information management systems (IMS) accelerates the timing of road construction works, this becomes possible through the use of digital twins of construction objects and technological machines [2].
The production of linear earthworks sets the task of organizing and developing optimal solutions for the coordinated management of all machines located at the construction site. Such control is possible only with a comprehensive consideration of all parameters of machine control at the time of execution of technological processes. Research of control models [3] and analysis of structures of automatic control systems (ACS) of machines [4] show the possibility of coherent control of technological operations, in this case it becomes possible to increase the productivity of earth-moving operations only by creating new control algorithms [5, 6] without making changes in the mechatronic organization of earth-moving machines for various purposes. The changes affect only the software and hardware control complex at the local level of machines, thereby increasing the efficiency of technological processes.

Possibilities of effective control of an autonomously functioning machine to a decisive extent depend on the full consideration of all physical laws that determine both its movement and interaction with the environment in the process of performing work functions. The design stage is the first stage at which the optimal relationship between mechanical, electronic and software components of the machine is formed, modeling and verification of both the physical model and the control logic are performed - before the actual implementation is made [7]. Already in the design process, the efficiency and reliability of control at the stage of future operation (necessarily taking into account numerous operational uncertainties) should be considered as one of the main goals [8].

A large number of works have been devoted to automatic control systems for the main elements of mobile machines, including the development of the necessary physical models. The control circuit of the steering wheel electro-hydraulic system, carried out with the joint use of the voltage servo controller and the noise rejection controller, is shown in [9]; the simulation results confirmed the effectiveness of the proposed method, taking into account the fast response and control accuracy. The construction and verification of a dynamic model of clutch control was performed in [10]; As a result, it was possible to satisfactorily solve the main control problems characteristic of this functional element: the presence of complex nonlinear dynamics of the interaction of a fluid and mechanical systems, a time-varying load, a short duration of time allotted for the development of a control action, and lack of information about the duration of the upcoming movement of the object. Optimization of automatic transmission control is considered in [11]: a dynamic model of the transmission system is built, a linear-quadratic regulator is used to achieve the optimal clutch pressure, software verification of two possible states is performed (in the absence of load without a slope and full load with a maximum slope). The application of impedance control to the active suspension system is shown in [12], automatic control was implemented using two internal loops, which were power control of the drive using reverse linearization and a fuzzy control loop according to the impedance rules.

The basic means of automatic control of the operation of road construction machines are PID controllers. A promising direction of their use is data control (or modelless control). As a result, it is often possible to improve the closed-loop behavior of linear, and especially non-linear systems, using very simple control structures. As a result, the unknown or poorly known dynamics of external influences on the object is compensated by control actions, and random disturbances are discarded without any training or online identification [13]. Systems with delays are of particular interest due to the increased difficulty of automatic control. In [14], using the Hermite-Beeler theorem, a complete set of stabilizing parameters of the PID controller is determined for both stable and unstable systems with an open control loop; in the second case, a necessary and sufficient delay condition for the existence of stabilizing controllers is determined. It was revealed that the stabilizing set in the space of the integral and derivative gain is a trapezoid, triangle or quadrangle. Based on the analysis of the stability of control based on PID controllers, it was shown in [15] that, in the parameter space, the stability regions in the general case are convex polyhedra.

The issues of developing and optimizing the trajectory of movement, both for single machines and for their combination, are traditionally given great attention. A simple automatic trajectory tracking system for a single unmanned vehicle moving over rough terrain is shown in [16]. The successful use of an agent with a hybrid behavioral architecture for autonomous vehicle navigation is considered in [17], where more specific actions associated with the performed technological operation are determined.
from a set of basic motion actions (forward, turn, and so on). Planning the optimal path is essential for the efficient operation of autonomous machines. A heuristic algorithm based on the principles of cuckoo search is shown in [18]; as a result of the algorithm execution, a smooth optimal trajectory is formed. Comparison of two algorithms for trajectory planning in real time, providing an optimal trajectory with avoiding static obstacles, was performed in [19]. The first of the compared algorithms corresponds to the method of an artificial potential field, modified with the help of dummy loads; the second algorithm uses Voronoi diagrams and includes Delaunay triangulation to avoid routes on which traffic blocking is possible. Both of the considered algorithms are quite efficient. Saving computational resources is discussed in [20], where it is shown that navigation can be provided using a relatively small number of if-then rules using the Tagaki-Sugeno fuzzy inference method and fuzzy sets represented by normalized triangular functions.

Automatic control systems have hierarchical levels of control, in which three are usually distinguished: strategic, tactical and executive [21]. In modern electromechatronic systems at the strategic level, control subsystems with elements of expert systems and artificial intelligence are often used, and at the lower levels - fuzzy and neurosubsystems [22].

2. Models and algorithms

2.1. Digging process model

Bulldozer and scraper are considered as the main types of earth-moving vehicles (EMV), as machines with similar principles and control structures at the local level. The process of digging with a bulldozer on a crawler track can be represented by the equation:

\[
\frac{dV_A}{dt} = \frac{1}{m(P_T - P_R)}
\]

(1)

where \(P_T\) is the total driving force of the bulldozer; \(P_R\) is total resistance to movement; \(t\) is time; \(V_A\) is the actual speed of the bulldozer when digging; \(m\) is the reduced average mass of the bulldozer.

It is customary to evaluate the driving force of the propellers by the amount of their slip:

\[
P_{T,i} = f(\delta_i),
\]

(2)

where \(\delta_i\) is the slip coefficient of the \(i\)-th propeller.

The slip coefficient evaluates the positive slip of the propellers and is determined by the expression:

\[
\delta_i = \frac{V_{T,i} - V_{A,i}}{V_{T,i}}.
\]

(3)

The theoretical speed of the propeller at a constant rolling radius of the tracked course is a linear function of the angular velocity of the propeller:

\[
V_{T,i} = r_i \omega_{A,i},
\]

(4)

herewith

\[
\frac{d\omega_{A,i}}{dt} = \frac{M_{A,i} - P_{T,i}r_i}{J_i},
\]

(5)

where \(\omega_{A,i}\) is the angular speed of the engine; \(M_{A,i}\) is torque; \(J_i\) is reduced moment of inertia; \(P_{T,i}\) is driving force of the \(i\)-th mover; \(r_i\) is rolling radius.

Torque value:

\[
M_A = \frac{M_{iM}i_M}{K_A},
\]

(6)

where \(\eta_m\) is the efficiency of the engine transmission; \(i_m\) is the total gear ratio.

The analytical expression of the engine torque \(M(\omega)\) when solving the problems of machine dynamics for the regulatory characteristic has the form:
where $M_N$ is the rated torque of the engine; $\omega_\text{х}$ is the maximum angular speed of the engine shaft at idle; $\omega_N$ is nominal angular speed of the motor shaft. Current value of angular velocity in the range from $\omega_\text{х}$ to $\omega_N$:

$$\omega_e = i_m \omega_{\lambda,i}.$$  

(8)

2.2. Algorithm for hard control of the digging process

The structure of the automatic control system is shown in Fig. 1. The executive bodies are usually electro-hydraulic servo drives with fixed displacement pumps. This determines the relay characteristics of the control unit and the entire device as a whole. The automatic control device maintains the value of the controlled variable $X_p$ at a given level $X_{0}$ by changing the position of the working body of road-building machines $h$. This is done as follows. When the value $X_1$, proportional to $X_p$, deviates from its specified value $X_0$, an error signal $\text{сигнал}$ appears. Depending on the magnitude and sign of the error signal, the control unit moves the working body of the road-building machines through the servo drive of the executive body and changes the digging depth towards decreasing the error.

![Fig. 1. Functional diagram of the ACS by the process of digging the soil. MU - measuring unit; CB - comparing block; MB - master block; CU - control unit; X is the controlled value; h - control value (digging depth); Y - output signal of the control device, under the action of which the executive body changes the value of the digging depth.](image)

The controlled value of the contour that maintains the maximum tractive power is the slip coefficient of the most skidding propulsion unit, which is determined by expression (3) through the theoretical and actual speed of the machine. The setpoint (setpoint) in this circuit is equal to the optimal value of the slip coefficient $\delta=10\%$, at which the maximum traction force and traction power are realized. The controlled value of the contour that maintains the set value of the free power of the engine is the angular velocity of its crankshaft $\omega_e$. The value of the setpoint of the angular speed of the engine $\omega_0$ is determined by the operator during tuning, which achieves the equality of the implementation of the free power of the diesel engine and the maximum tractive power for specific soil conditions and parameters of the propellers.

The algorithm allows to develop control actions, while analyzing the current value of the angular speed of the engine $\omega_e$, the theoretical speed for each propeller $V_{t,1}$ and the actual speed of the machine $V_{t,2}$. The optimal system of automatic control of the bulldozer digging process is double-circuit. One circuit: it maintains the given free power of the diesel engine during the digging process, by automatically changing the depth of cutting the soil as a function of the angular speed of the diesel engine shaft. The other, with excessive slipping of any of the propellers, forcibly pushes the dump.

2.3. Fuzzy algorithm of digging process control

Fuzzy logic control model for EMV is shown in Fig. 2. The control principle consists in the implementation of fuzzy closure of the system, i.e. introduction at the tactical level of feedbacks on controlled parameters, as well as the introduction of a fuzzy setting of the control law. The system under consideration is not rigidly controlled. The task of control is the sequential implementation of some evolutions by the working body of the bulldozer, leading to the achievement of the optimal mode, for
example, a steady motion with the necessary characteristics for cutting the soil; in other words, the goal is reflex control.

![Diagram](image_url)

**Fig. 2.** The structure of synthesis of algorithms for fuzzy control of technological processes of EMV.

The main function assigned to the fuzzy controller is the formation of corrective corrections to the coefficients of the PID controller, depending on the current coordinates of the system. In this case, a PID controller with a corrective fuzzy controller is a non-linear system.

### 2.4. Agent model of traffic of road construction vehicles

The totality of EMV at a road construction site is considered as an agent-based model. Taken together, many machines form an agent-based system such as CDPS (Cooperative Distributed Problem Solving). In this case, individual agents interact in a single system based on the general technological plan of movement and the design depth of soil removal. Modeling motion within the framework of the accepted CDPS paradigm allows us to identify patterns that must be taken into account when developing an autopilot algorithm. To formally represent an individual agent in a multi-agent system, two sets are distinguished: a set of states of the working environment \( E = \{e_1, e_2, \ldots, e_n\} \) and a set of agent actions \( A_c = \{a_1, a_2, \ldots, a_n\} \).

Three sets of agent movements are taken into account:

- **R** is the set of all possible displacements (E and AC);
- **RAC** - set of all movements that ended with the action - soil removal;
- **RE** - the set of all possible movements that led to a change in the agent's environment.

Changing the environment of the agent for one turn of the agent, the condition for completing his work and the description of the environment as a tuple are written as:

\[
\begin{align*}
t &= (e_0, a_0, \ldots, e_n, a_n) \\
\text{If } t(e_0, a_0, \ldots, e_n, a_n) &= \otimes \text{ then end}
\end{align*}
\]

(9)

In a more compact form, the behavior of the scraper agent is described by the following function:

\[
Ag : R^6 \Rightarrow A_c.
\]

(10)

Within the framework of the model under consideration, two algorithms for the functioning of the agent can be distinguished: reactive and proactive. Reactive behavior requires the agent to have a subsystem of perception of the environment (analysis of the state of the soil, the presence of obstacles, the presence of a number of other agents) and perception of the subsystem of action (removal of soil, bypassing obstacles, making a maneuver to avoid collisions with other agents). Modeling the behavior of a reactive agent is performed using the functions:

\[
\begin{align*}
\text{action} : \{\text{information}\} &\rightarrow A_c \\
\{\text{information}\} = E &\Rightarrow \text{action} : E \rightarrow A_c
\end{align*}
\]

(11)
Proactive behavior requires an agent to process the information received from its environment to make a decision on further actions and is described by the following relationships:

\[
\begin{align*}
    \text{action}: I & \rightarrow A, \\
    \text{see}(e) &= \text{Perception}, \\
    \text{next}(i_0, \text{see}(e)) &= I, \\
    \text{action}(\text{next}(i_0, \text{see}(e))) &= I \rightarrow A, \\
    \text{next}: I \times \text{Per} & \rightarrow I
\end{align*}
\]

where \( i_0 \) is the agent's internal state, \( I \) is the set of internal states.

To study the agent's behavior, we will use a safe movement model based on the Nagel – Schreckenberg movement model [23]. The agent inspects the environment in the direction of its movement in a cone of a given radius and angle. If there are other agents (road-building machines) in the cone of view, then it is necessary to identify the nearest agent and if the distance to it is less than the critical one, then braking is performed, otherwise a further increase in the scraper speed is permissible.

3. Results of numerical modeling and structural synthesis of the control system

The main dependences obtained using the model of the digging process (1) - (8) are shown in Fig. 3. These dependencies underlie the control carried out according to a rigid algorithm and, as will be shown below, significantly limit its efficiency.

![Fig. 3. Dependence of traction power \( N_T \), actual speed \( V_T \) and slip coefficient \( \delta \) as a function of driving force \( P_T \).](image)

The base of fuzzy linguistic rules, developed as part of the implementation of the fuzzy control algorithm, describes the necessary sequence of actions, in which the values and directions of movements of the working body are determined. The basic model consists of ten linguistic rules governing the choice of control commands. Control parameters are reduced to three terms. The proposed rules are based on the analysis of the results of interviewing management experts, based on the linguistic descriptions of the management rules, chains of action sequences are formed:

1. IF “n is PS” AND “a is Z” THEN “h is NB” (engine speed is increased, the speed is unchanged, a signal should be given for the maximum lowering of the working body);
2. IF “n is ZP” AND “but there is NS” THEN “h is NS” (the engine speed is slightly higher than the set ones, and it drops, a signal should be given for a slight lowering of the working body);
3. IF “n is Z” AND “but is Z” THEN “h is Z” (engine speed is set and unchanged, do not send a signal to the working body);
4. IF “n is NS” AND “but there is NS” THEN “h is ZP” (the engine speed is lower than the specified one, and it drops, then a signal should be given for a small rise of the working body);
5. IF “n is NM” AND “but there is NS” THEN “h is PS” (the engine speed is minimum and the frequency drops, a signal should be given to raise the working body);
6. IF “n is NB” AND “but is NS” THEN “h is PB” (the engine speed is less than the minimum allowable and the frequency drops, then a signal should be given for the maximum lift of the working body);
7. IF “n is NB” AND “but there is PS” THEN “h is PM” (the engine speed is less than the minimum permissible, and the frequency is increasing, a signal should be given for a large lift of the working body);
8. IF “n is NM” AND “but there is PS” THEN “h is ZP” (the engine speed is minimal, and the frequency is increasing, a signal should be given for a small lift of the working body);
9. IF “n is Z” AND “but there is PS” THEN “h is ZP” (the engine speed is set and the frequency increases, a signal should be given for a small rise of the working body);
10. IF “n is ZP” AND “but there is PS” THEN “h is Z” (the engine speed is slightly higher than the specified one, and the frequency increases, stop the movement of the working body).

The fuzzification procedure is performed for the following input variables:
- "Engine speed": a set of values T1 = {less than the minimum allowable; minimum; below specified; given; slightly higher than specified; elevated};
- "Actual speed": many values: T2 = {decreases; is equal to zero; growing};
- "Change of position": a set of values T3 = {maximum lowering; slight lowering; Stop; slight rise; climb; big rise; maximum lift}.

The membership functions for the control used in the fuzzy control algorithm have a triangular shape.

The numerical implementation of the agent-based motion model was carried out using the NetLogo software environment for multi-agent modeling [24]. When building an agent-based NetLogo model, the movement of agents took place in a two-dimensional virtual space. The simulation was carried out in a discrete mode of operation of a model processor. The agents worked in a closed cycle: removing soil at the site, leaving the site, entering the site, etc. The work continued until the soil sample was reached to the specified depth. It was assumed that the agent moves with a speed, the nature of the change of which obeys a uniform distribution law, while taking into account the distance to the driving agent ahead. Upon reaching a critical distance, the agent performed braking. This behavior of agents led to different variants of their positioning on the track, depending on the value of the critical technological distance. The scraper speed was maintained in the range \( 0 \leq v \leq v_{\text{max}} \) where \( v_{\text{max}} \) is the maximum speed allowed on the road section during operation. In addition, the size of the distance to the agent in front was supposed to ensure that there was no collision. The simulation results are shown in Fig. 5.

![Fig. 4. Visualization of the fuzzy inference surface for the fuzzy control algorithm: n - engine speed; dn / dt = a is rate of change of engine speed; h is the amount of movement of the working body;](image-url)
Based on the proposed control model, it becomes possible to synthesize a self-organizing structure that unites at the information-hardware level any number of construction machines of various technological purposes and thereby allows synchronizing their interaction at a construction site. Such a complex interaction is possible only with the use of methods and technologies that will make it possible to divide the entire data stream into two streams: the first is the macro-level, where an expert assessment of the situation as a whole is carried out, and the second is the performance of an accurate calculation or synthesis of the target control function after the expert assessment is made. The hardware implementation of such systems can be implemented using structured hierarchical computing systems, which are based on local control systems for technological machines. Figure 6 shows a scraper control complex, a distinctive feature of which is a distributed monitoring and control system for its aggregate-functional purpose.

**Fig. 5.** Optimal and critical travel distances

4. **Discussion and conclusions**

In Fig. 3 it can be seen that in the process of digging the soil, the maximum productivity is achieved when the maximum tractive power $N_{T,max}$. The $N_T=f(P_T)$ function is extreme and reaches its maximum
at maximum driving force stability, which is achieved at $\delta = 10\%$ for tracked propellers. Fig. 3, it can be seen that when digging, as the resistance forces increase, the driving force grows and, despite the decrease in the actual speed, the tractive power increases. With an optimal slip ratio, power is maximized. In this case, the engine should not be overloaded, for which it is necessary to stabilize its angular speed of rotation at the level corresponding to the implementation of the maximum driving force $P_T, \text{max}$. In general, the analysis of single-loop automatic control systems that implement a rigid algorithm for controlling the digging process shows that such systems can only give an effect if the other parameters do not leave the optimal zone.

So, when stabilizing the angular speed of the engine of the machine, a large margin of adhesion mass is required to ensure the absence of any noticeable slipping of the propellers. When driving by slipping the propellers, the installed engine power should be overstated and not used when digging. To eliminate these disadvantages, it is proposed to control the digging process along two circuits: according to the maximum free engine power and according to the maximum tractive power. One circuit in both cases stabilizes the engine power at a predetermined maximum level, and the other traction power or slip coefficient. There is no technical implementation of these principles, which makes it impossible to assess the structure of the system and the quality of control over the digging process.

The mathematical apparatus of fuzzy logic is most appropriate for use in control control and analysis of large arrays of heterogeneous information. Visualization of control parameters (Fig. 4) makes it possible to efficiently search for the optimal trajectory of the control parameters function. In this case, the accuracy of the data obtained depends on the number of ACS training operations performed and the accuracy of fuzzy control rules. In general, the use of fuzzy control methods makes it possible to obtain a high-quality transient process without using cumbersome computational procedures typical of the classical control method.

The results of modeling the interconnected work of agents allow us to conclude that road-building machines in the technological process of road construction can be considered as a multi-agent system with elements of self-organization. The self-organization effect is observed when the distance between the scrapers changes (Fig. 5). The optimal choice of distance allows you to evenly position the equipment on the site when performing road works. The simulated algorithms for the movement of agents can be the basis for the construction of an adaptive mechanism for the autopilot of road construction equipment.

Automation of technological processes of earth-moving and other types of machines and equipment, carried out at the level of individual types of machines, leads to an increase in their productivity, but does not allow increasing the efficiency of work in the composition, a set of machines. Accordingly, the unification of the local automatic control systems of the EMV into a single information and control complex is an objective necessity. For this, it is effective to use hardware and software computing systems built on the components of expert systems, and fuzzy decision-making logic. At the same time, the control of the flow of cars based on the agent-based motion model allows you to control and manage technological interaction. The principles and technologies shown in this work for constructing information and control systems based on robotic control principles and implementing control algorithms based on fuzzy logic open up new opportunities for construction production and support the life cycle of roads.

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