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DIGITAL TWINS AND MODELING OF THE TRANSPORTING-TECHNOLOGICAL PROCESSES FOR ON-LINE DISPATCH CONTROL IN OPEN PIT MINING

This article discusses modern modeling technologies which open up new capabilities for creating a digital platform for open pit mining management. The specific details of the construction of an intelligent digital platform for the management of transport processes during mineral mining are discussed. A brief overview of the methods and tools for modeling technological processes in open pit mining is given. The stages to be overcome on the path of digital transformation of mines using dynamic 3D models are presented. It is proposed to use software environments of the gaming industry platforms and virtual reality systems as tools for the dynamic 3D modeling of objects. The classes of agents are introduced for the convenience of structuring the tasks to be solved. The basic functional and instrumental elements of the intelligent platform being developed at the present time are given, and also a simplified structure of the technological process control system in an open pit mine, including the prediction module, is presented. The principles of work are described, and the advantages of the specific tool for creating digital 3D models are also discussed. The results obtained in modeling a stage of a transport cycle in an open pit mine are reported.

Keywords: *digital transformation of industry, smart mining, transportation management, digital platforms, autonomous robotic systems, open pit mining, digital modeling, digital twins.*
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Introduction

Changing from conventional control to digital management in open pit mineral mining with partially or totally self-contained facilities of the mining-and-transportation system is a complex and long process accompanied with major modification of methods and models of control, as well as modeling tools.

Development and introduction of various inspection sensors for immovable and movable facilities in open pit mines, advance of telecommunication technologies and equipment, as well as progress in satellite telecommunications has resulted in creation of hardware/software systems for dispatching and management in open pit mining, with on-line decision-making and long-range control of machinery in open pit mines [1].

It is of the current concern to develop an intelligent platform for efficient interaction of robotic machinery (cutter–loaders, dump trucks, road building machines, etc.) capable of autonomous operation, as well as to design a control system of unmanned mineral extraction at certain stages of closed technology cycles [2, 3].

Automation, with its long history in open pit mining, used different models, starting from classical models of investigation and finishing with various tools based on geoinformation structural models. Until recently, planning and management decision-making was based on the simulation modeling as a major tool of dynamic modeling of such complex sociotechnical system as an open pit mine [4].

Advanced simulation modeling systems, such as AnyLogic, Enterprise Dynamics, FlexSim, Simio, feature detailing of mathematic core, comprise computational functions of expected maintenance time of mobile objects and include many other parameters to improve demonstrativeness of results. A major drawback of the listed systems is the loss of accuracy due to unavoidable abstraction from real-life processes and owing to rigorous operation in the mode of simulation with no ability to embrace all off-normal situations typical of real life, which means:

- Elimination of modifications in the course of modeling;
- Impossible incorporation of prototypes in other applications;
- Underdeveloped visualization.

Vividly evolving cyber-physical systems are based on dynamic 3D modeling of individual operations or integrated process flows and ensure then inaccessible level of integration of a model and a control object [5, 6]. This paper presents the research findings on applicability of dynamic 3D models in on-line coordination of movement of self-contained mobile objects employed in haulage services in open pit mines.

Principles of intelligent transportation control in open pit mines

In architectural construction of an open pit mining-and-transportation control platform, it is proposed to use the agent-based modeling for the unified description of different objects, auto-conversion of data and for the end-to-end digital modeling of current process situations [7]. In the framework of this approach, the construction and formalization principles are defined for various agents below:

- A_T — technical (mobile) agents—objects of mining-and-transportation system (heavy dump trucks, auxiliary transportation equipment—various purpose road machines, shoveling machines, movable drill rigs, etc.);
- A_I — technology infrastructure agents—characteristcs of the technology environment (roads, pit walls, shoveling and unloading sites, other zones in an open pit mine);
- A_G — geostructure agents—structural blocks–elements of a mineral deposit as in the classical geoinformation systems. Geometry of these blocks should correlate with specifications of mining machines (including their dimensions) and fit the preset positioning precision of the machines and their components (for example, bucket in case of a shoveling machine).

This multi-agent basis makes a functional framework for the intelligent process control in open pit mining [7, 8].

Let us discuss the supervisory control performance in more details in terms of haulage process. Structurally, this component is implemented as a horizontally integrated multi-agent system A_C, with program modules grouped into 5 blocks: L_1—sensoring; L_2—monitoring; L_3—information; L_4—analysis and prediction; L_5—commanding. For each dump truck (a mobile object–agent), the normal mode is a closed cycle of a few stages. The highest effect of autonomous robotic objects can be produced at the stages of dump truck movement toward shovel site (loading point) and dump truck movement from shovel site to unloading point.

The process of coordinated motion control of autonomous agents, using program modules from blocks L_1–L_5, can be divided into three classes of problems:

1. Optimized routing of autonomous mobile objects, i.e., determination of a certain initial mover for construction of master digital traces;

2. Selection of velocity mode of each agent to ensure maximized efficiency of transportation at minimized risk of cross and counter movement, and queues—jamming;

3. Safe movement along the preset digital traces.

The latter objective is met using radar sensors mounted on mobile objects and thanks to on-board movement autocontrol, and is beyond the scope of this study [9].

The conventional approach to optimized routing and modes for self-contained agents assumes two stages. The first stage is baseline planning. The second stage of selecting velocity modes involves multiple solution of a linear optimization problem on minimized traveling time at limited intervals of possible approach of mobile agents. In this case, it is required to determine periodically dump truck engine behavior using prediction models of movement of mobile agents [10].

On the other hand, this approach, even with assistance of the advanced tools (fine-tuned multi-layer neuron networks, evolutionary optimization), lacks the desired accuracy as the technology environment of transportation process changes continuously (roadbed condition, route network design, etc.) [8]. More effective systems add the control loop with a prediction module to customize the control algorithm for longer time spans of the control object dynamics [8–11]. Evidently, the system of the transfer processes in an open pit mine fits all listed characteristics of a complex control object, while the idea of the prediction-based control is totally relevant to the specificity of the multi-parameter mobile object of control under discussion, with integrated optimality criterion, which is difficult to assess and calculate, and with considerable gap between the on-line management decision-making and the final evaluation of the criterion. **Figure 1** demonstrates a simplified flowchart of prediction-based control.

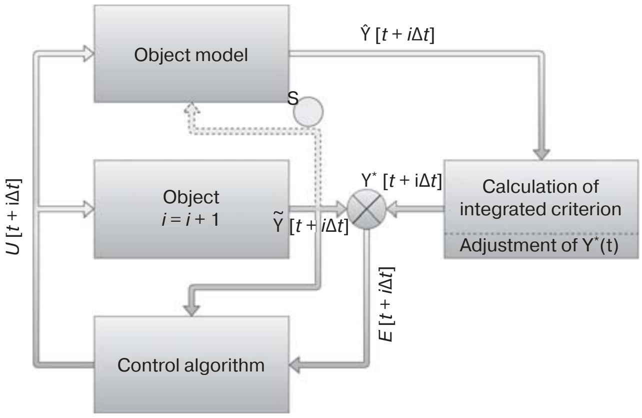

Fig. 1. Simplified flowchart of transfer process control in open pit mine using prediction models:
$\tilde{Y}$ [$t + i\Delta t$] — vector of controlled parameters; $\hat{Y}$ [$t + i\Delta t$] — predicted values of controlled parameters; Y^* [$t + i\Delta t$] — wanted values of controlled parameters; U [$t + i\Delta t$] — vector of command actions; E [$t + i\Delta t$] — vector of input values of control algorithm; Δt — uniform time span between command actions—control phase (practically logical real-life situation is $\Delta t \neq$ const); $i = 0, 1, \dots, n$ — counter of phases on a time interval [0, T], $n\Delta t = T$; S — information flow such that the volume and accuracy of the flow data govern validity of the model—digital twin technology process.

Digital representation of physical objects and processes

At the development stage of the most systems, the question of data interpretation and abstraction arises. The digital 3D modeling system described in this paper should provide graphical presentation of real-life transfer processes in open pit mines. Each mobile agent is considered as a digital interpretation of a physical agent, i.e. as a three-dimensional computer model constructed with certain assumptions but clearly identifying the purpose of an agent and its functional modules. Such abstractions include [12–15]:

- Digital Model or Digital Twin Prototype;
- Digital Shadow, Digital Traces or Digital Twin Instance;
- Digital Twin or Digital Twin Aggregate;
- Digital Platform.

Digital models, shadows, twins and platforms differ in levels of integration with physical objects. Each previous level is the minimum essential basis for implementation of the next level. **Figure 2** shows the diagram of the listed abstractions and their connections with physical objects.

The main idea of using these abstractions for the construction of an intelligent control, in particular, for the optimization modeling, consists in reliable and visible interpretation of a process flow using the integrated production data. For the correct modeling, it is required to use both telemetry data from mobile (technology) agents, as well as geological and spatial geoinformation from dedicated soft hardware.

Thus, the key objective of simulation modeling toward construction of efficient cyber-physical control systems is finding and application of platforms capable of complexing of heterogeneous information from numerous sources. A candidate alternative for the current implementation of such system can be assumed the gaming and virtual reality platform. The authors of this paper have adopted Unity [7, 8]. This is a real-time 3D development platform including pack of environments, physical and mathematical core and preset expandable API (set of instructions and commands) for 3D graphics and visualization.

Digital modeling experimentation

Considering multistage construction of a digital platform for the transport flowchart control, the authors have focused on coordination of movement of autonomous mobile agents. Apparently, for every single dump truck, a set of transport processes can be assumed as a closed cycle composed of a few stages. The authors select two key stages of dump truck

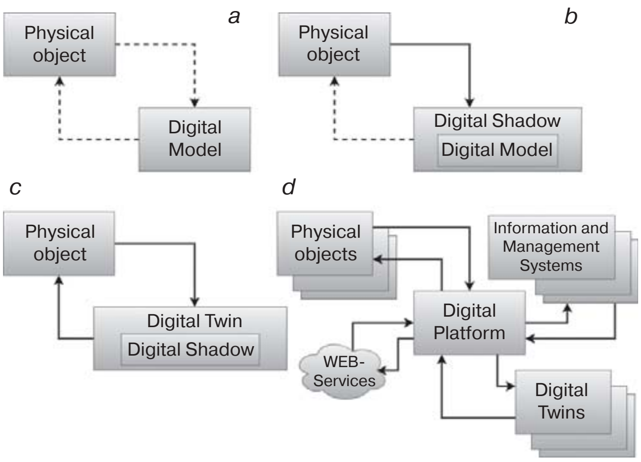

Fig. 2. Object–model–control system interaction chart in digital modeling:
(*a*) dynamic 3D model; (*b*) Digital Shadow (on-line updated 3D model); (*c*) Digital Twin (digital shadow with adjustability of object condition as per model values); (*d*) Digital Platform (an integration of a real-life object, digital twin and control system based on optimization criteria).

movement toward a shovel site (loading point) and dump truck movement from the shovel site to the unloading point. All processes within these stages are governed by interaction between information arrays and models related with two classes of agents—A_T and A_G. The present paper authors scrutinized these classes of agents and developed some algorithms for the digital model testing:

- f_{11}—Unity-based development of digital infrastructure framework of an object;
- f_{21}—optimized routing based on preset graph of roads for each agent;
- f_{22}—predictive computation of coordinates for each mobile agent;
- f_{23}—calculation of current velocity for each agent—this parameter acts as a set point for automated control of autonomous dump truck movement;
- f_{31}—road survey;
- f_{51}—update of digital layout of open pit mine roads;
- f_{52}—adjustment of routing algorithm and dump truck velocity calculation procedure based on the current intergal values.

Naturally, the main production data should be: volume of transferred rocks with regard to rock composition; minimized downtime of shovels, etc. The authors selected one of the most convenient indices for the experimental calculation (as well as for the reality)—total number of cycles (unloading–loading–unloading) for all dump trucks over a certain period of time. This index was used in the initial design engineering, develpment and analysis of functional capabilities of the digital platform intended for the intelligent control of transport processes in open pit mines.

The prototype engineering of the platform was carried out using data from the real-life information and management system operated by one of the mines in Russia. These data were obtained from the geological information archives and from the mining and transporation equipment dispatching telemetry. The agents of the technology and infrastructure were shaped on this basis. **Figure 3** depicts some results of stage-by-stage integration of heterogeneous data during Digital Shadow development.

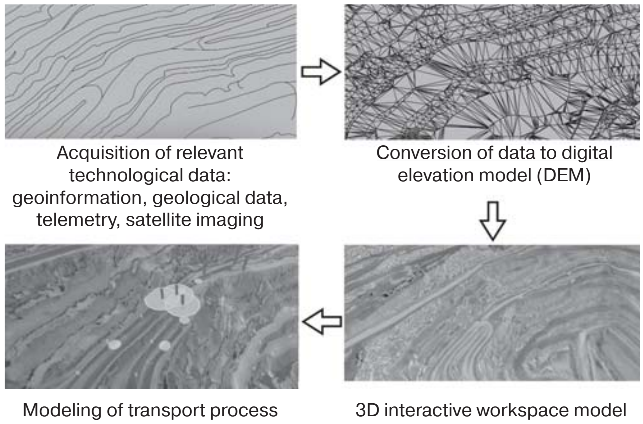

Fig. 3. Some outcomes of stage-by-stage integration of heterogeneous data during digital 3D modeling (Digital Shadow).

The experimental yields some primary results for the on-line complexing of heterogeneous technological information in the form of a unified integrated virtual environment relevant to the current production situation, which proves fitness of the platform and feasibility of its development to a full-fledged simulation environment of intelligent control over transport processes in open pit mines.

Conclusions

The summary of the studies is presented below.

1. The main trends in the modeling methods and tools for transport processes in open pit mining are reviewed. The basic notions and levels of integration of an object and dynamic 3D models in production control systems are systematized.

2. A version presented for the transportation control in open pit mines adds the control loop with prediction modeling using dynamic 3D models (including Digital Shadows and Digital Twins). The integration level of these models and an object (which means the model accuracy) is of the highest concern for the control quality. The experiments performed by the present paper authors show that transition to a next integration level necessitates also highly precise computation (prediction and analysis) models to estimate optimality criteria and to adjust command variables.

3. The Digital Shadow concept has actually been implemented for some stages of a transport process. That is, a hardware/software system is created for the real-time modeling of *Movement* process using multi-dimensional production data arrays. The software enables visualization of actual technological situation during modeling.

4. Using a real-life technological object, the authors have tested dynamic clustering of real-time telemetry data from a dispatch system. During the tests, we improved operation of integration software tools for sending data to a local server, as well as for data sorting and transfer to individual technical agents in Unity, which enabled proving the serviceability of basic modules of the system.

5. The proposed system can already be trialed as an auxiliary tool of the dispatch control. The present paper authors are going to launch implementation of a prototype of the digital control platform with integration of the intelligent transportation control in open pit mines.

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MULTIFUNCTION WALKING ROOF SUPPORT FOR UNDERGROUND MINING OF STRATIFIED DEPOSITS AND PLACERS

The article shows the urgency of technological advance in coal mining in difficult geological conditions and describes the application prospects for an integrated multi-function platform in underground mining of different minerals. The international practice of mobile roof support design and creation of a work environment in mines is reviewed. The authors propose an integrated multi-function platform as a walking roof support module which ensures safe and efficient mining in difficult geological conditions. Within R&D project supported by the Foundation for Assistance to Small Innovative Enterprises in Science and Technology, Project No. 2566GS1/41340, the kinematics of the platform is developed so that to ensure uniform loading of the walking support systems owing to constructional linkage between the support units, and to provide stability of the support system on a composite topography floor thanks to four couples of hinge supports with adjustability of height and position. Arrangement of structural elements is proposed, and their kinematic linkage is described. The walking support advance algorithm is developed in the form of a working cycle. Within R&D project supported by the Russian Foundation for Basic Research, Project No. 18-37-00356, the control operation algorithm and control automation circuit are developed for the walking roof support. The automated control is integrable in the standard electrohydraulic control system of mine roof supports. As a result, the walking roof support with the automated control can be considered as a framework (a platform solution) for the robotic system engineering for safe and efficient underground mining of stratified deposits and diamond placers.

Keywords: *mining, underground mining, complex environment, thick seam, steeply inclined coal seam, mining machines, powered roof support, walking support, control algorithm, kinematic scheme, automated control system, robotic complex.*

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