The analysis of the industrial safety providing and processes control multifunctional system via use of a hybrid modeling methodology

IOP Conf. Series: Materials Science and Engineering **537** (2019) 032087 doi:10.1088/1757-899X/537/3/032087

The analysis of the industrial safety providing and processes control multifunctional system via use of a hybrid modeling methodology

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Abstract. This article proposes the analysis of the multifunctional safety providing and process control system of a coal mine for the purposes of a hybrid modelling, provides the elements of the system at various abstraction levels, defines the goals and objectives of the modelling, and shows the practical significance of the work. The "Smart Mine®" system's personal positioning function considered as an example, the analytical and formal models of the system are provided. The utility of hybrid modelling for high-responsible systems' end-to-end design and for emergency prediction is shown.

1. Introduction

Modern industrial enterprises, following the trends of Industry 4.0, look toward to create "Smart production", to exclude a person from the production process as much as possible and to minimize the probability of potential accidents. In the mining industry, leading Russian enterprises are implementing projects such as "Smart Mine®", "SMART Ore", "Intellectual Open Pit" and several similar ones and equip "smart" production with the safety providing and processes control multifunctional systems (SPPCMS) [1, 2, 3]. Two global tasks of such systems are to ensure the safety of the production process and the actual management of the process itself (production control). The creation of such systems requires not only strict adherence to standards in this area, but also the implementation of additional measures by the designer, developer, manufacturer and operator to ensure increased system reliability. Errors made during the system design phase and in the period of the equipment development, as well as software development can create prerequisites for the emergency accidents occurrence or failures at the facility. Along with the introduction of robotics in production, artificial intelligence in analytical systems, the spread of the Internet of Things (IoT), which are also used in the mining industry, one of the Fourth technological revolution directions is the end-to-end design based on modeling. It is important to carry out modeling at all stages of the system life cycle, but today, when creating SPPCMSes, this technology is not fully applied.

In Russia and abroad, the composition and functions of SPPCMSes are governed by state norms and rules [4, 5, 6]. For example, a coal mine SPPCMS consists of fourteen subsystems (aerological safety, monitoring and forecasting of gas-dynamic phenomena, fire protection, communication, warning, locating personnel, explosion protection, etc.), which are in close interaction with each other and are subject to influences of external factors.

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In the context of the consideration of SPPCMS, there arises the modeling task of a complex system, characterized by many processes inside it associated with a large number of external events. Building a model of such a highly loaded system is not obvious, and the narrow specificity does not allow the use of ready-made tools. To build a model of SPPCMS, it is necessary to consider both its continuous and discrete behavior. The modern theory of hybrid systems (HS) is a universal apparatus for the mathematical description of complex discrete-continuous processes of different physical nature. In this article, the authors propose classify SPPCMSes via use of a hybrid systems theory to select the necessary levels of abstraction, methods and tools for modeling. The first stage of work was the real coal mine SPPCMS analytical model creation.

2. The analysis of the SPPCMS

Consider the analytical model of the complex "Smart Mine®" [3], built on the principle of identifying the functional roles of its elements, which shown in the figure 1. The principles of building such multiservice systems can be found in the articles [7, 8]. Consider the system function of determining the location of personnel in the underground mining workings. In the general case, the system performs the specified functionality, when at each time point we know the position of each person in the mine's mining workings, with an accuracy sufficient for the operational control of the situation from the control room. This is provided on condition that each worker is given a caplamp with an integrated module for determining the location underground, the mining workings are equipped with a continuous data network and equipment for human positioning, all equipment (for a person permanently located in the mine, server on the surface) operate in a normal mode and there is a connection.

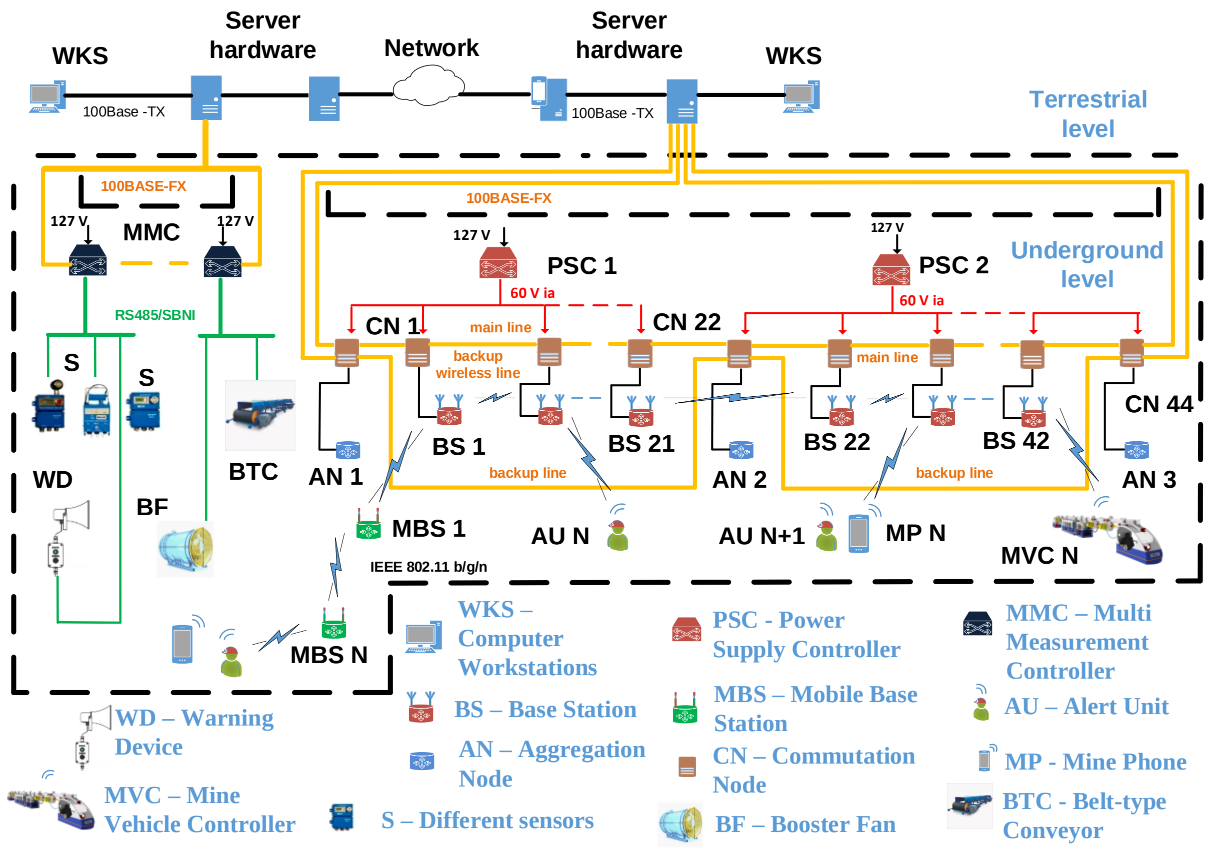

Figure 1. Hybrid system analytical model.

The accuracy of determining the location directly depends on the chosen method and accordingly equipment as well as on a number of external random factors (geometry and topology of workings, physics of radio signal propagation in a tunnel, method of equipment installation, presence of physical

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stationary or mobile obstacles, other interferences, etc.). In practice, today an error is achieved, not exceeding values from hundreds of meters to ± 2 meters. Ultimately, the question of cost-effectiveness arises, and the system designer is tasked with finding the optimal solution that provides the maximum number of working areas covered with more accurate positioning technology at minimal cost. From the point of view of process control, such a statement of the problem is probably justified, but positioning directly ensures the safety of people working underground and the safety of the mine itself. In such a situation, it is more expedient to consider other tasks: what is the probability that a person moves along a safe route; what is the probability that in the event of an accident a person will be able to leave the mine in a safe way; what is the likelihood that the victim in the event of an accident will be detected promptly, etc.

To give a complete picture other functions of the system must be considered too. But that example is enough to understand that the functions of analyzed HS this way or another depends on the following groups of parameters:

- parameters of each piece of equipment;
- parameters of the interaction process between the equipment;
- environmental parameters and external influences.

In the general case, the parameters can be both static and dynamic, vary by specifying the initial conditions or randomly.

SPPCMSes are referred to as "space-time hybrid systems" (STHS), because the processes simultaneously evolve in space and in time. To describe continuous processes in the HS the classical dynamical systems are used. In the generally accepted [9 - 12] a HS description the continuous behavior is considered with respect to the time variable varying in the interval $[t_0, t_k]$. An STHS is primarily distinguished by the way of representing continuous behavior. Continuous behavior is set by mapping $C: R^n \to R^n$. The mapping $C: R^n \to R^n$ is described by a system of partial differential equations (PDE) with initial and boundary conditions.

Let's consider the STHS local behavior description, which includes an PDE system as in equation (1) and contains the initial and boundary conditions of the first (Dirichlet problem) and second kind (Neumann problem).

$$
\begin{gathered}
\frac{\partial z}{\partial t} = \psi\left(z, t, p, \frac{\partial z}{\partial p}, \frac{\partial^2 z}{\partial p^2}\right), \\
pr: g(t,z) < 0, \\
z(t_0, p) = z_0, \;\; z(t, p_0) = \delta(t, p_0), \;\; z(t, p_m) = \delta(t, p_m), \\
\left.\frac{\partial z}{\partial t}\right|_{p_0} = n(t, p_0), \;\; \left.\frac{\partial z}{\partial t}\right|_{p_m} = n(t, p_m), \\
t \in [t_0, t_k], \;\; p \in [p_0, p_m],
\end{gathered}
\tag{1}
$$

where $z \in R^{N_z}$ – state vector; $\psi: R^{N_z} \times R \times R^{N_p} \times R^{2N_p} \to R^{N_z}$ – nonlinear vector function; p – vector of spatial coordinates; $z_0 \in R^N$ – vector of initial conditions; δ – vector of Dirichlet boundary conditions on the left and right border; n – vector of Neumann boundary conditions on the left and right boundary; $g(t,z): R^{N_z} \times R \to R^s, s = 1, 2, ...$ – event function, characterized by a predicate $pr: g(t,z) < 0, pr \in B = true$

In practice, a differential equation can only describe a continuous physical process, for example, the propagation of a radio signal, the diffusion of gases, etc. Such processes significant impact on the work of coal mines' SPPCMSes. For example, the first of it influences on the accuracy of determining the personnel location and on the communication, the second one directly influences on the emergency (methane is explosive). Given the fact that at the coal mines, SPPCMSes began to be introduced many years ago, a rather large amount of diagnostic information has accumulated, which in fact is a certain set of system states and which can be used in modeling and simulation.

Of course, to solve practical problems, you must select the appropriate class of equations with appropriate restrictions. Three types of discrete behavior of STHS are distinguished: discrete behavior with a discontinuity in the spatial variable; in variable time and phase variables; simultaneously in spatial, temporal and phase variables; in initial and boundary conditions. An example of a HS model with discrete behavior in the time domain can be systems in which the time domain partitioning into time segments at specified points in time is explicitly defined (control systems modeling with a given mode change schedule). Such a method can be applied to some subsystems of SPPCMS under the assumption of certain restrictions relative to real physical system (automated control systems for ventilation, for fire water supply, etc.). Discrete-continuous behavior in complex systems may be due to a number of external and internal factors.

Also, models of complex systems can be classified relative to the area in which the state changes. For STHS, the following areas can be distinguished in which hybrid behavior can take place: independent time variable, independent spatial variables, phase variables, mixed type, including any first three. As a rule, complex HS with a hierarchical structure, such as SPPMCSes, are of mixed type. In this case, in the considered HS a complex discrete behavior accompanies the complex continuous. As an example, in the literature, the model of a rocket following target is given, when obtaining information about the target and changing the flight characteristics is carried out only at discrete moments in time [13]. SPPMCS functions continuously, at discrete points in time, various external against to the system itself events occur, for example, turning off the power supply at the work site or turning on the booster fan reverse. Obtaining information about the equipment operation also occurs discretely. All the presented factors of the emergence of hybrid behavior are reduced to the appearance of discrete events acting in a certain way on the object of study.

Depending on the results of a discrete event, five types of hybrid behavior can also be distinguished. [14] Major of the subsystems of the SPPMCS can be attributed to the class of systems with the behavior of the 5th kind. This type of hybrid behavior is characterized by a change in the composition and/or dimension of the system with a dynamically formed law of functioning during the operation of studied object. Such systems examples are queuing systems. In the context of coal mines' SPPMCSes in this class can be considered communication, positioning, aerogas control subsystems and others.

Thus, according to the classification given in [14], SPPMCSes can be attributed to STHS switched in a mixed domain with 5th kind hybrid behavior.

3. Conclusion

All stages of model development — the projection of the real world into the world of models, the choice of the level of abstraction, and the choice of modeling language — are less standardized than the process of using models to solve problems. When building an analytical model of a hybrid system and working with it, the developer is tasked with finding the optimal solution to be able apply it in the real world. The success of the modeling project depends on the choice of the abstraction level. It is important to consider which modeling tools can be used when choosing the level of abstraction and analyzing the HS even on this stage. At the same time the hybrid modeling requires an understanding of business processes and equipment in a narrow subject area, while ready-made tools (Anylogic, MVStudium, RandModelDesigner, Modelica, etc.) do not cover the area of SPPMCSes. In addition, models and components developed in one environment are not always compatible and/or can't be imported to others, since all of them develop separately. There is no complete set of modeling tools for such complex systems in any existing software. Therefore, it is important to create a model in a specialized subject-oriented language. It can be created based on the ISMA language, developed at the Novosibirsk State Technical University (NSTU). Using the expert information on the SPPMCS' state for several years of its operation, it is possible to build the dependencies of the current state on the past and create a model that allows us to make a prediction for the future or at least support the technology of the high-responsible systems' end-to-end design.

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