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Architecture of a Universal Monitoring System for Transport Infrastructure Facilities

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Abstract—Based on many years of experience in the development and implementation of systems of continuous monitoring of transport infrastructure facilities, the authors have designed an architecture that allows the most efficient and rational arrangement of such systems. The paper notes the need for and importance of universalizing the development, design and implementation of technical diagnostics and monitoring systems of transport infrastructure facilities. It also gives detailed description of universal monitoring system architecture, as well as a roadmap for the development of universal hardware and software platform for this system. Main components of monitoring systems are de-fined. Recommendations are given to be followed when developing the monitoring systems. It is emphasized that a monitoring system can and should be built to make "energy management" possible through minimization of both energy consumption for implementation of operating procedures and reduction of the carbon footprint from the transport infrastructure facilities. Monitoring systems should be a means that help to build highly immune and energy efficient "green" transport infrastructure facilities.

Keywords—technical diagnostics and monitoring system, technical immunity, universality, system architecture, energy efficiency, minimal carbon footprint, high-immunity systems.

I. INTRODUCTION

Life cycle of engineering facilities created by man is remarkably like the life cycle of the over-whelming majority of living beings. Similarly, the idea of building a facility comes first, then it is completed by actions to build it (design, construction, etc.), thereupon, the facility takes a physical shape, the stage of running-in (in fact, some training) begins followed by a stage of normal activity (operation). Just like biological beings, for engineering facilities a time of gradual aging and loss of their basic properties (degradation) comes up, which ultimately always leads to the facility's death (in engineering sense, it is the dismantling and disposal of the facility, or total modernization). In the society, tremendous importance is given to medical advances and medical diagnostics, body status monitoring, which determines the opportunity for timely medical intervention to restore physical fitness. Without numerous achievements in diagnostics and monitoring of the body, a person would not have been able to avoid loss of physical fitness and, in some cases, death.

The area of technical diagnostics is developing similarly to medical diagnostics: with the advent of advanced computer technology, tiny measuring instruments, universal channels transmitting measured parameters to the points of their procession, etc., various opportunities arise in arrangement of technical diagnostics and monitoring systems [1–6]. Today, the main diagnostic parameter is time, or rather, the ability to predict occurrence of an event. This has a natural economic effect: the earlier the defect is identified and diagnosed, the cheaper is its treatment. Very often, such systems are implemented under the slogan of maintenance procedures automation, but the real purpose of their implementation is to provide the ability to predict events to prevent them. We can say that obtaining such property for engineering facilities will lead to the fact that such facility improves its technical immunity and becomes less vulnerable to external destabilizing factors (if we draw a parallel with the world of living things — to viruses).

The system of technical diagnostics and monitoring is not only a set of sensors, transducers, di-agnostic information transmission channels, means of their storage and procession. A monitoring system also includes a certain "skeleton" received from a developer — architecture, operation algorithms, ways of delivering the final data to the end user. Ideally, the technical diagnostics and monitoring system should be a link in the feedback chain of a control system and should automatically not only report a potential critical event, but also manage this information so that this event can be prevented, or, in the worst case, fended off in the best way possible with minimal economic and environmental losses. A monitoring system is an essential component for creation of technical systems in all activity areas: construction, industry, transport. At the same time, the availability of monitoring systems is a mandatory attribute in implementation of engineering facilities for which the "energy management" and maintenance of optimal characteristics of such components as energy efficiency, the use of renewable energy sources, minimization of the carbon footprint with the required and increased technical immunity (Fig. 1) is possible. Thus, monitoring systems are becoming the basic means of optimal "energy management".

It is no secret that there is a wide variety of monitoring systems that are used both for domestic purposes and in industry and transport. All these systems, in fact, have the same "base", but are implemented differently. However, the general features of monitoring systems remain unchanged. In this paper, the authors propose a universal architecture of monitoring systems that covers and generalizes known engineering solutions. Its use makes it possible to implement a better monitoring system than those known to date.

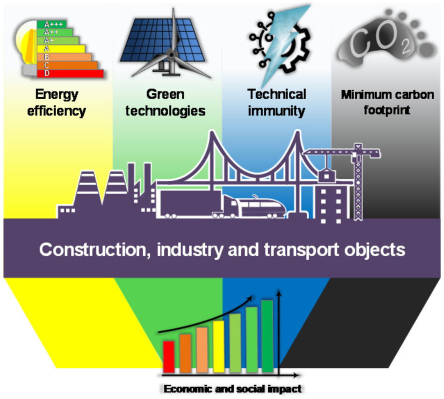

Figure 1. Basic components of technical systems of the future

II. Architecture of a Universal Monitoring System

The system of technical diagnostics and monitoring represents a combination of the item under diagnostics and monitoring (hereinafter simply referred to as "the monitoring object") and its test and monitoring equipment. Before implementing a monitoring system, a monitoring object should be modeled to determine a set of diagnostic parameters and control measuring points necessary for high-quality monitoring and identification of the required set of diagnostic events. This is the difference in all monitoring systems — the "nature" of a facility is to be known, the features of its arrangement and historical data of the operation processes (when it comes to equipping an already operating facility with a monitoring system). However, the architecture of monitoring systems itself can be universal.

Fig. 2 shows a universal architecture of a monitoring system designed by the authors based on the results of many years of development and operation of monitoring systems at various facilities of construction industry, manufacturing industry and transport.

In a universal architecture of a monitoring system, both hardware and software components are represented which make it possible to obtain primary ("raw") diagnostic data, transfer them to the database, filter and restore data [7, 8], as well as to perform complex processing in order to obtain diagnosis, forecast and assessment of the residual life of the monitoring object and provide this information to end users. The data source, as a rule, is a combination of a physical value detector (sensor) and a transducer. They are controlled by a data collector and a protocol converter (Bridge). This is where data is collected from the source (it can be hardware or a third-party application programming interface) and sent to an XMPP metering channel. Accumulation of "raw data" from metering channels and storage of this matrix in the bank of "raw data" is carried out using a STORE module. The raw data bank itself can be presented as a text file or any similar option. CALC module collects data from the measurement channel, converts them into physical values according to the information stored in the configuration manager and sends the data to the measurement channel. DATA module is an application programming interface providing data to the user interface. Access to data/events/channel statuses is provided here. RT-DATA interface is an application programming interface which is intended for viewing data in real time, for example, to analyze the situation. TRS interface is also an application programming interface that ensures transportation of a layer for control systems of SCADA type (or similar versions thereof). EVENT module generates data for data channels where the information from the data channel and the configuration manager is used. Configuration manager creates and records data in the database. The data is taken from the "raw" data bank, converted using information from the configuration manager and recorded into the database (or several databases). The data manager ensures operation of the application programming interface by reading data from the database (in similar versions, it can provide means of data recording directly to the database). The filtering and recovery manager then filters the "raw" data, searching for anomalies and recovering missing data. The complex analytics manager carries out intelligent processing of diagnostic data by means of machine analysis [9–13]. The configuration manager provides complete system configuration functionality and supplies data to all users.

When designing a universal hardware and software platform, it is necessary to define specific tasks and requirements in various areas that require monitoring tools, to identify key features of existing monitoring systems, and to structure current tasks and currently available opportunities for standardization. This allows developing recommendations for unification of components, in-crease the level of abstraction of the elements included in the monitoring system and divide the system into intelligent microservices. In turn, the achievement of such goals makes it possible to expand the capabilities and scope of application of the universal hardware and software platform, to simplify its composition due to the possibility of solving additional tasks by reconfiguring the existing components without developing new ones, to standardize and unify the approach to solving a wide class of monitoring problems.

Nowadays, there exist typical components of monitoring systems which are integrated into all systems of the kind (see Table 1).

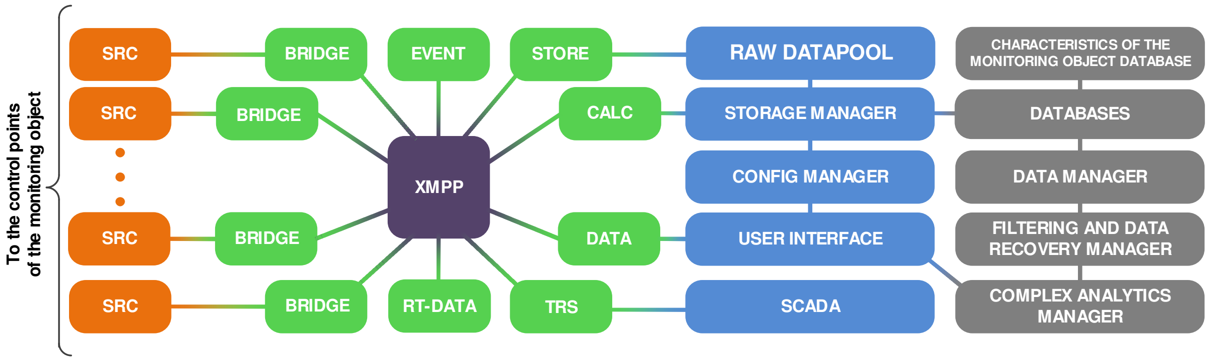

Figure 2. Architecture of a universal monitoring system

TABLE I. General Characteristic of Undetected Errors

Component	Solutions within a monitoring system
Sensors	Direct or indirect measurement of target parameters with an optimal set of sensors (subject to the operation environment, device features, economic and ecological factors).
Transducers	The earliest digitization of measured values from a sensor to transmit the signal in the form of a specific digital code with the possibility of pre-processing (averaging), detection of errors in the communication line, provision of noise immunity, and recovery of values.
Network	Transmission of the digitized signal to the upper level of acquisition, storage, processing and delivery to the end user through the optimal communication channels under a given conditions.
Data acquisition and processing units (DAPU)	Data acquisition and processing from all other units to the upper-level storage (usually there are intermediate data collectors (several sequential upper levels) between the signal digitizing devices and the end servers, and the servers themselves are clearly defined and are the top of the system structure, but technical solutions are also possible when there are no intermediate levels).
Software	Software or a set of interconnected software modules that ensure processing, accumulation and transfer of the data collected from the sensors to the interface, as well as the execution of related service and administrative tasks (archiving, backup, differentiation of access rights). The aggregates of this software are often distributed over several devices (DAPU of the lower and upper levels, automated workstations of operators).
Interfaces	Output of the processed data: – to operators in the form of values/tables/graphs/integration signals; – to systems of upper and adjacent levels in the requested format; – to actuators in automatic or automated mode in the form of control actions.

The larger the scale of a monitoring system, the more fully its components listed in the table manifest themselves within it: a large volume of various sensors, a variety of data digitization and acquisition systems, extended transmission networks, multi-level accumulation and processing of measurements, availability of root servers.

In small systems (semi-autonomous systems, systems for monitoring a small range of parameters, local systems), individual components can be combined within one device. For example, in autonomous temperature measurement systems the signal from a sensor goes directly to the ana-log-to-digital converter of the programmable logic controller which, at the same time, serves as a device that collects and processes data. However, even in this case, upon closer examination, all the components indicated above are present, i.e. the analog-to-digital converter is connected to the microcontroller by an internal digital bus (I^2C, ISP), division into levels is carried out within a single device software; the measurement processing software function plays the role of a "data collector", and the function of saving the result in the permanent storage device — that of a "root storage".

The monitoring system is developed according to the following roadmap (Fig. 3).

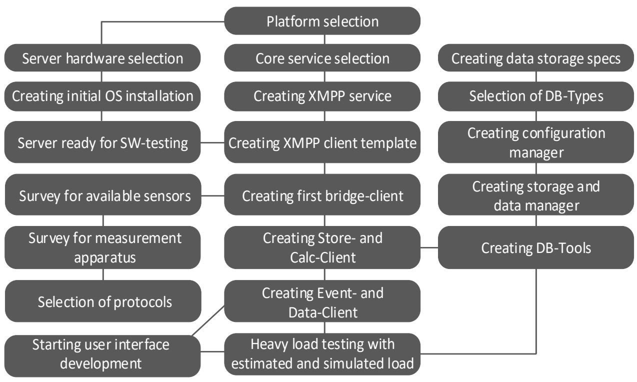

Figure 3. Roadmap for a monitoring system development

If monitoring systems for significant objects are considered, then in addition to central servers, monitoring data can be transmitted to regional-scale monitoring centers: from the city level and up to (if any) state-level or global systems.

There are autonomous/semi-autonomous monitoring systems that accumulate data in the internal storage. Often, they do not have a permanent stable connection with the central storage (due to the environment unfavorable for

TABLE II. Existing Monitoring Systems and Monitoring Systems of the Future

System characteristics	HBM	Avangard	Master-SCADA4D	Prometheus	SAVCOR	Wonderware	System of the future
Country	Germany	Russia	Russia	USA / international	Finland	USA	Not relevant
License of the software	Proprietary, commercial	Proprietary, commercial	Proprietary, commercial	Free open-source software	Proprietary, commercial	Proprietary, commercial	Proprietary, commercial
Universality	+ / –	–	+	+	–	+	+
"Closed" principle	Yes + API	Yes	Yes + API / protocols	Open-source software + API / protocols	Yes	Yes + protocols	Yes + API / protocols
System completeness							
Sensors	+	+	–	–	+ / –	–	+ / –
Transducers	+	+	–	–	+	–	+
Network	+	+	–	–	+	–	+
Data acquisition and processing units	+	+	–	–	+	–	+
Software and interface	+	+ / –	+	+	+	+	+
Interface and software							
User Interface	Native web panel	Native	Native web Interface, HMI-panels	Web Interface	Web Interface	Native web Interface HMI-panels	Web Interface, mobile applications
Interface Operating System	Windows Android (web) Cross platform. (web)	Windows	Windows Linux, QNX, Android * Cross platform. (web)	Cross platform. (web)	Cross platform. (web)	Cross platform. (web)	Cross platform. (web)
Platform Operating System	Windows	Windows	Windows Linux	Windows Linux FreeBSD	Linux	Windows	* Windows Linux
External API	+ (ActiveX)	–	+ (C#)	+	–	–	+ (JS, JSON)
Programmability	–	–	N/A	N/A	–	N/A	+
Interfaces	CAN Ethernet USB	ZigBee GSM	N/A	N/A	RS-232 RS-485	N/A	* GSM, * CAN Ethernet, USB RS-232, RS-485
Autonomy	+	+	N/A	N/A	–	N/A	+
Network	CAN	ZigBee GSM Ethernet	N/A * Ethernet	N/A * Ethernet	* RS-232 -> Eth SLS (RS-485)	N/A * Ethernet	Ethernet
Transducers							
Channels	4	1	N/A	N/A	1 / 2 / 3 / SER	N/A	3 + RS-232/485
Power supply (V)	12…24	*Autonomous (battery) operation	N/A	N/A	7…20	N/A	7…48
Data processing							
Method of diagnostic data processing	Thresholding of individual parameters						Filtering, recovery, intelligent complex processing

signal propagation, remoteness from the root post, the need to minimize power consumption), but periodically the reading of accumulated values is performed (by the operator when connecting to the unit or after transporting the unit to the central post and connecting on site). Here, too, there is a division into levels with the presence of a root center, and the communication channel is characterized by a large discreteness of data retrieval and the need to move the devices, nonetheless it exists. Optical measurement systems with a length of 100 [m] ... [km], despite the significant distances covered, do not contradict the "early digitization" clause as they are considered as a single sensor with a digital module directly placed on its input. Table 2 summarizes the basic data on several world-known monitoring systems for complex engineering structures and provides the characteristics of a prospective monitoring system. It is worth emphasizing that a monitoring system itself should be supplied and maintained by the developer (life cycle contract), and the customer should only obtain the end result in the form of a forecast and residual resource using this data at its own discretion. In fact, the informational support should be provided to the operating personnel of the engineering facility along with the provision of high-reliability monitoring results. This can even make possible the division of responsibilities between the operating personnel and the supplier of the monitoring system in the event of violations, accidents, forced outages, etc. Such feature of a monitoring system, however, requires the developer to pay more attention to data collection technologies and to the performance of diagnostic equipment itself, as well as pushes him/her towards the creation of monitoring system components with controllable and self-checking structures [14, 15].

In general, the basic platform of a monitoring system should provide:

- advanced intelligent self-diagnosis of the system;
- assessment of the monitoring results reliability;
- data message retrieval;
- archiving of events;
- application of certified equipment at every level of implementation.

At the same time, the functionality should cover the following components of a truly high-quality monitoring:

- generation of a "digital twin" of the facility to be diagnosed;
- modeling of the complete life cycle of a system;
- complex analytics of the diagnostic data;
- generation of a real state index;
- predictive analytics (residual life assessment);
- long-term roadmap for the facility;
- short-term recommendations to optimize maintenance;
- recommendations for optimization and/or redundancy of systems.

III. Recommendations for Design and Development of Monitoring Systems

Effectiveness of a monitoring technology can be significantly increased by following these recommendations.

A. Designing of a digital hardware and software complex:

- exclusively digital hardware and software should be designed, such as:
  - transducers;
  - network;
  - data acquisition and processing units;
  - server software;
  - interfaces;
- the level of sensors as devices with analog elements available on the market in sufficient quantity and not subjected to rapid obsolescence is excluded from the development process (it is applicable and effective to develop only unique diagnostic devices).

B. Ensuring of versatility and augment ability of the designed components:

- support for operation with third-party products is required to be able to integrate the developments into existing systems or to optimize costs when developing new systems;
- expanding of the system functionality by engagement of third-party solutions the development of which by own efforts is not planned.

C. Three main macro-blocks of the system (transducers, data acquisition and processing devices, software) should be developed jointly while observing the basic principles:

- constant coordination of the actions when creating the basic system components;
- priority in allocation of resources should be given to software being the most versatile component of the complex that allows for early use on top of/instead of other already developed systems.

D. Using Ethernet as the industrial network:

- widespread use of the technology and equipment;
- inexpensive industrial microcircuits;
- a wide range of repeaters;
- availability of active switches and splitters to design "star" buses;
- availability of converters for all interface types (RS232/422/485-Ethernet, USB-Ethernet, Fiber-optic Ethernet, etc.);
- high noise immunity and data transfer rate;
- ability to transfer an arbitrary data stream.

When developing the measuring equipment, it is necessary to follow the principles of environmental friendliness. Environmental friendliness and minimization of the carbon footprint are priorities in the most developed countries, such as the countries of the European Union, Great Britain, Norway, and Switzerland. Therefore, when developing the components of monitoring systems, environmentally friendly materials should be chosen, and the operation modes of the facilities should be adjusted in accordance with the assigned energy efficiency class of the device [16, 17]. Moreover, it is necessary to consider the possibility to use the monitoring tools for "energy management" in accordance with the current climatic situation and rational energy consumption to solve a particular task.

It should be emphasized again that the configuration of monitoring systems allows not only to endow complex objects with technical immunity, but to manage technological processes in the most rational way, considering the minimization of energy consumption and damage to the ecological environment as well. And here we can give a few examples from the field of transportation. An installed monitoring system for railway overhead catenary system [18] makes it possible to determine the conditions under which ice formation occurs and to control the process of preventive heating, rather than to carry it out continuously during certain periods; owing to locomotive monitoring systems [19] the time spent thereby in service locomotive depots can be reduced as the time for troubleshooting decreases, etc.

IV. Conclusions

Monitoring systems should have versatile structures with easily replaceable components, and their application should bring the main effect in the form of information on the technical condition of a monitoring objects, predictions, and assessment of their residual life. At the same time, during their development, the most environmentally friendly materials should be selected, and energy-efficient solutions should be used to the maximum extent. Monitoring systems themselves should become tools that allow both to increase the technical immunity of systems and to "manage energy" optimizing its consumption and minimizing the carbon footprint.

Attention is to be paid to the issue of monitoring system development in all fields, including the transport industry. For each of the transport components, new regulatory documents should be developed, and the existing ones should be revised: from monitoring concepts to regulations for the set of technical means and monitoring tools, as well as their development, design, and construction. A more subtle knowledge of the monitoring issues will allow obtaining not means of storing large amounts of data, but a true operating tool to provide facilities with technical immunity and design high-immune transport systems.

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