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Remote Real-Time Structure Health Monitoring with MINI-SMIK

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Abstract—This paper describes real-time data acquisition for a structure health monitoring solution called MINI-SMIK (*sistema monitoringa inzhenernykh konstruktsii*—structure health monitoring system). The configuration of the equipment in this work includes two IN120 inclinometers and a DC200 strainmeter. An RC Module MB77.07 single-board computer (SBC) in a special sealed enclosure is used to log and transmit data. The SBC receives data over an RS-485 link then converts it to the miniSEED format and transmits the measurements in real-time to the data center using the SEEDLink protocol. Data can be sent over a local area network or the Internet via wireless (e.g., cellular) networking. Encrypted virtual private networks (VPNs) have been used successfully for secure data transmission via public networks.

Keywords: IN120 inclinometer, DC200 strainmeter, MINI-SMIK, NeuroMatrix, real-time data transfer, SeedLink, miniSeed, VPN

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INTRODUCTION

The success or failure of assessing building structure health directly depends on the quality and availability of measurement results (Galaganov et al., 2015). To date, there are a number of monitoring methods based on various physical processes and phenomena that can detect signs of hazardous and/or undesirable processes. The combined use of several types of measurements increases the monitoring reliability and is widely used in practice (Pashkin et al., 2008). As an example, let us consider the MINI-SMIK (*sistema monitoringa inzhenernykh konstruktsiy*—structure health monitoring system) developed by BAU-Monitoring in close cooperation with the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences (IPE RAS).

The equipment is based on joint measurements of the stress–strain state, angular displacements, and vibration effects; it includes two monitoring subsystems: strainmeter and inclinometer, which makes it possible to monitor the state of a structure based on different physical processes (Osika et al., 2017). The characteristics of MINI-SMIK make it possible, along with the main task of monitoring an object, to conduct observations required for basic research. In particular, the inclinometer included in the equipment can estimate angular displacements from the daily rotation of the Earth, and the strainmeter can separately monitor the temperature and force deformations of a material.

MINI-SMIK was developed to work autonomously, so it initially had no tools for real-time data transfer; the main emphasis was on reducing power consumption for long-term autonomous operation. However, at present, a significant number of monitoring systems are located in areas with a more or less reliable stationary power supply. In addition, as a rule, there is no problem connecting to a computer network via wirelink or wireless channels. Therefore, it was desirable to upgrade the existing equipment for real-time data transfer to the monitoring center. The real-time transfer of parameter measurement results, in addition to the obvious reduced delivery time of information to the consumer, consequently accelerating the response to a possible emergency situation, has other advantages: continuous monitoring of the device's state, data collection, managing of its parameters, the possibility of placing the decision center (DP) in an arbitrary location, maintaining several facilities simultaneously from one such center, reducing the cost of having highly qualified personnel on site, and automated forecasting of the dynamics of the monitored object.

In this case, public networks can be used, making it possible to engage virtually any communication channels available at the object, including a cellular network. Cellular networks, among other things, make it easy to organize area measurements without laying additional comms lines (see Fig. 1).

In this study, the ultimate goal was real-time publication of measurement data on the Internet. Note that such an approach implies the broadest and most flexible solution, including the ability to manage recording modes, restrict access to the collected data, and

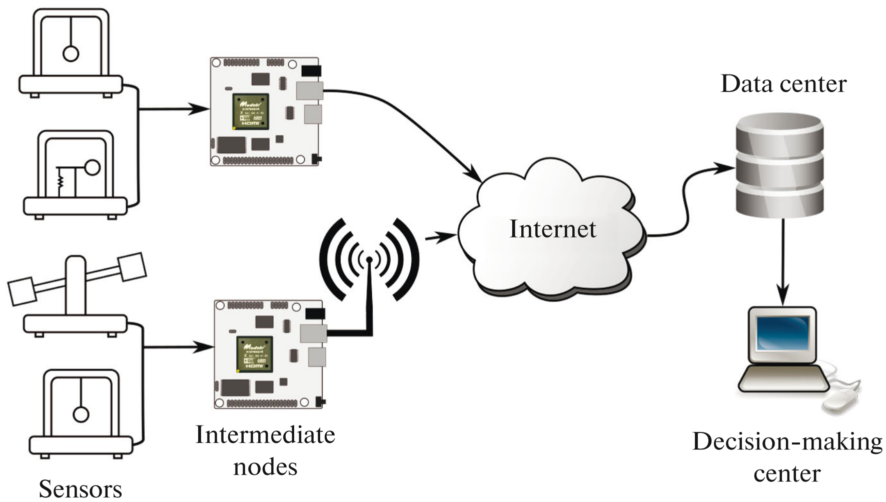

Fig. 1. Conceptual diagram of real-time monitoring system with data transmission over public networks.

solve other related tasks. Meanwhile, to ensure the greatest flexibility and adaptability, focus should be on the maximum use of standard software and hardware tools and solutions. In practice, this requires that several technical problems be solved, the main one of which is to organize sustainable data transfer from the sensors to the data processing center (DPC).

Of course, for a full-fledged monitoring system, it is also necessary to store measurement data at the DPC and provide users with access to current and historical data and on-line processing of this data in order to identify critical situations. Lastly, it is necessary to develop an effective alert scheme that provides adequate information responses to detected critical situations. This paper addresses tasks related to real-time data delivery to the DPC and then to users; we do not discuss the organizational and technical details of creating a DPC or predicting the dynamics of monitored objects.

We have excluded the MINI-SMIK's MS4812 recorder from the data transmission chain. Although it supports an Ethernet interface (Osika et al., 2017), it uses an RS485 Ethernet converter (Moxa, MiiNePort E1..., 2013), which, first, contains no access restriction mechanisms, and second, does not allow one to manipulate recording settings, such as the current time, set of sensors, and their sampling rate. Changing these settings is only possible by editing the configuration file in the recorder's nonvolatile memory; i.e., data receipt from the MS4812 via the Ethernet interface limits the ability to control the device.

The simplest way to transfer measurement data to a DPC is with a full-fledged computer as an intermediate node. This solution reduces development time, allows the use of modern efficient methods and tools, and facilitates the adaptation of ready-made solutions. In particular, a computer makes it possible to use existing drivers for various equipment, and full-fledged computers increase the flexibility of the developed system, because the software can easily be modified. This makes it possible to use the same type of nodes with different measuring equipment. In addition, this expands the range of solvable problems: primary data processing is now possible at the recorder level, which reduces the load on DPC servers and increases the system's efficiency as a whole. An additional valuable feature is standard remote access tools for management and configuration.

In order to reduce the cost of the node and power consumption, as well as simplify operation, it is first necessary to consider single-board computers based on the ARM architecture. On the one hand, they are sufficiently high-performance (although they are significantly inferior to ×86-based solutions). On the other hand, they are relatively cheap, compact, and low-power (an order of magnitude less than their ×86 counterparts). These platforms are also supported by certain popular distributions based on the open source GNU/Linux operating system, which include both development tools and application programs (Raspberry..., 2018b; Raspbian..., 2018).

For data transfer, it seems appropriate to use the SeedLink protocol (IRIS, SeedLink..., 2018), and for their storage, the MiniSEED format (IRIS, miniSEED..., 2018). Both the format and protocol are widely used in geophysical, primarily seismic, data transmission (see, e.g., (Zheng et al., 2010; Mariotti and Utheim, 2006)). Necessary software for working with these is available for all common operating systems (IRIS, Software..., 2018), and the close integration of the format and protocol, including built-in data compression, minimizes the resources for transmitting data to the DPC and thence to users.

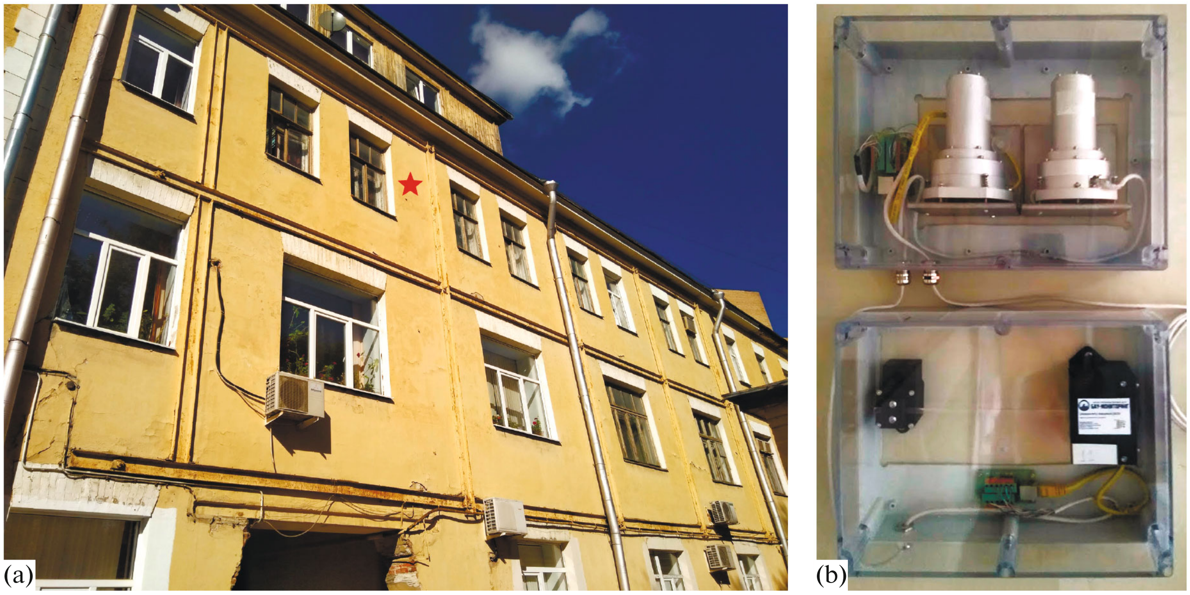

Fig. 2. Installation of system in building of IPE RAS: (a) installation site (marked with asterisk); (b) installed sensors: IN120 inclinometers and DC200 strainmeter.

In our previous versions of real-time data transfer systems based on single-board ARM devices (Aleshin et al., 2018a; 2018b), we used the BeagleBone Black (BeagleBone..., 2018) and Raspberry Pi (Raspberry..., 2018a) single-board computers, which are manufactured abroad. We describe the results of adapting the software to function in the our created monitoring system based on the MB77.07 single-board computer (NTTs Modul',..., 2018) produced by the Russian R&D company Module as an intermediate node.

MINI-SMIK INSTALLATION AT IPE RAS

In this study, we used two types of sensors in the MINI-SMIK: a detachable DK200 strainmeter and IN120 inclinometer. Both sensors are based on quartz mechanics, which guarantees stable long-term readings necessary for long-term measurements (Osika et al., 2017). The IN120 digital inclinometer, used for measuring angular displacements, has a measured angular displacement range of ±10 800″ with a resolution of 0.01″, a standard error of 0.2% (in the range of ±7200″), and an additional temperature error of 0.2″/°C (NPTs BAU-Monitoring, IN120..., 2018). The DK200 digital strainmeter (automatic extensometer) measures relative strain in the displacement range of ±200 μm with a resolution of 0.01 μm and a measurement error of 1%. Its operational resource is at least 100 000 h, and the operating temperature range is –40 to +50°C (NPTs BAU-Monitoring, DK200..., 2018).

The temperature sensors make it possible to estimate both the influence of temperature conditions on the structure and its long-term stability with respect to aging. The built-in temperature sensors have an accuracy of 2%. The measurement results are transmitted via a galvanically isolated RS485 interface (Texas Instruments..., 2014) via a text protocol. When queried, the device reports the current measured value and its own temperature, which is important when processing obtained measurements, since this it affects assessment of a structure's parameters.

To monitor a building at IPE RAS, the wall of an annex was chosen that contains cracks and has been reinforced with metal bands around the perimeter. The sensors have been placed on the south wall of the annex, on the third floor (Fig. 2a). The two IN120 inclinometers have been placed on the wall, which record angular oscillations along and across its plane, as well as the DK200 strainmeter, which records the compression/tension of this wall on a 200-mm shoulder (Fig. 2b).

The recorder has been positioned next to the sensors; it receives data from the devices, which it then transmits to IPE RAS servers. The recorder also converts sensor readings into physical values: angles of inclination and relative elongation. As a recording and data transfer node, we have employed the MB77.07 single-board computer, built with the K1879HB1Y system-on-chip, manufactured under the NeuroMatrix trademark and using the ARM11 microprocessor core of the ARMv architecture. This chip is a functional counterpart of the Broadcom BCM2835, a key component of the Raspberry Pi microcomputer (Raspberry..., 2018c). In our scheme, the sensor is connected to a single-board computer with the MINI-SMIK's accompanying RS485–USB adapter.

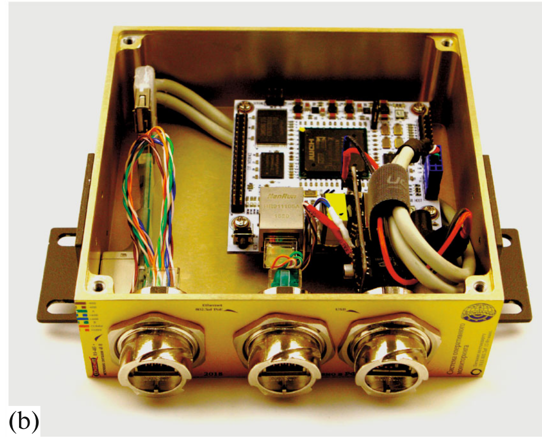

Fig. 3. Sealed metal case for MB77.07. (a) External view and peripheral connectors (from left to right): RJ45 for connecting sensors using RS485 protocol, RJ45 for connecting wired Ethernet network and power supply, USB-A for connecting external storage and peripheral devices; (b) internal device. MB77.07 board, RS485–USB adapter, and PoE power adapter are shown.

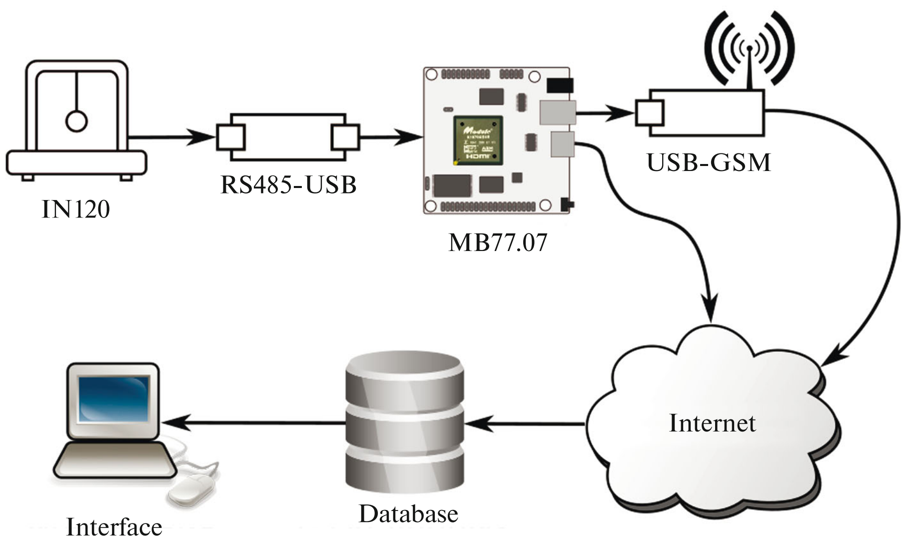

Fig. 4. Data transfer scheme used in this study.

Since the monitoring system may be installed in rooms with varying temperature, high humidity, and other adverse conditions, it is advisable to place the single-board computer in a sealed enclosure. For the MB77.07, a metal case with sealed peripheral connectors was manufactured on request (Fig. 3a). To cool the K1879HB1Y microcircuit inside the case, a special appendage is provided, which acts as a radiator. In addition to the MB77.07 and the RS485–USB adapter, the package also contains a Power Over Ethernet power converter (IEEE 802.3af..., 2003), which powers the device (Fig. 3b).

In our work (Aleshin et al., 2018a; 2018b), for embedded systems, the Arch Linux operating system is commonly used (Raspberry..., 2018b). However, the MB77.07 does not allow flexible control of the OS loader. In practice, a single core provided by Module is allowed for loading (GitHub, Official repository..., 2018). Therefore, the required OS is loaded after startup of this core via switching (chroot) to the Arch Linux environment.

DATA TRANSFER TO THE DPC

Our device allows for two types of data connection: wirelink using the local area network (LAN) of IPE RAS via an Ethernet interface, and wireless using a GPRS modem connected to a cell phone network (Fig. 4).

To control the sensors and obtain measurement results, we developed the control program as a plugin to the SeedLink server. This program, via the USB–

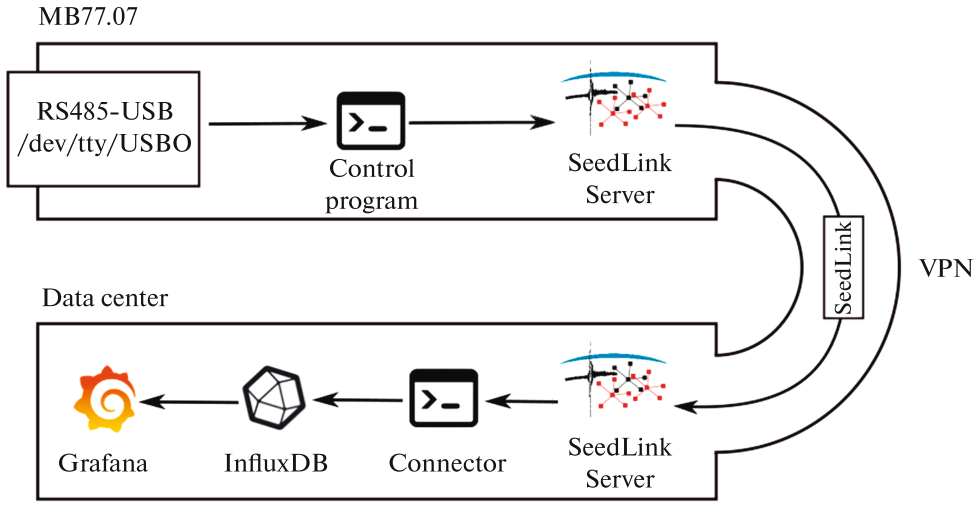

Fig. 5. Software model of data transmission in this study.

RS485 adapter, transmits control commands to the sensors, receives measurement data, packs them into the MiniSeed format using the libmseed library (GitHub, libmseed..., 2018), and then transmits them to the SeedLink server. The control program can work directly with MINI-SMIK devices, as well as receive data from the MS4812 controller via the LAN. When working with the instruments, the program, in addition to directly receiving measurement data, sets the sampling rate and time stamps. The recorder can acquire the exact time directly from the Internet using the NTP protocol (Mizrahi and Mayer, 2016), from an NTP server at the DPC, from a local NTP server, or from a local accurate time source, which can be a GPS receiver with PPS output (Mogul et al., 2000). The system clock is synchronized with the chrony tool (Chrony..., 2018). The general scheme of software implementation is shown in Fig. 5.

Data is transferred to the DPC over public networks. This approach requires security during data transfer and both client and server authentication. A good solution to this problem is virtual private network (VPN) technology (*Internetworking*..., 2003). We chose a common version of this technology called OpenVPN (OpenVPN..., 2018) and used a configuration in which the data transfer node is supplied with its own public and private keys, as well as the public key of the server. When connecting to the server, mutual authentication occurs and further data exchange takes place over an encrypted channel. Thus, the authenticity and integrity of the data transmitted to the DPC is guaranteed.

We have tested data transmission schemes using the LAN of IPE RAS and a cell phone network. With sampling rates typical of such monitoring systems (from thousandths to tenths of hertz), the data transfer rate is not a significant problem; however, disconnection may be a problem, especially on mobile networks. The SeedLink protocol can download missing data packets in the event of a disconnection, although this requires adjustment taking into account the amount of transmitted data and the expected duration of the break. The VPN infrastructure also automatically recovers a broken connection. However, the USB-GSM modem we chose did not always restore these. In addition, the modem itself does not inform the system about loss of connection. Therefore, a special Python script was written that monitors the connection status and when a break occurs resets the modem, forcing a reconnect.

DATA DELIVERY TO USERS

As part of this study, we employed three methods of data delivery from a DPC to users. The first is direct access to the stream via the SeedLink protocol. For this, an intermediate Seedlink server was launched within the DPC on a computer with an external IP address. This method is intended primarily for data acquisition by automated systems.

The second method is access to the file archive of observation results via HTTP/HTTPS, SFTP, or FTP protocols. To maintain the archive, we used the slarchive tool. Measurement data is stored in MiniSeed format as daily files in the view hierarchy. (year)/(month)/(day)/. Since slarchive operates with the number of the day of the year, its source code had to be supplemented with support for calculating the month and day according to the Gregorian calendar. This delivery method is convenient for receiving archived data for certain periods of time for further processing.

The third method is direct visualization of observation data on a web resource. We have chosen the specialized InfluxDB database management system (InfluxDB..., 2018) as such a tool, which makes it pos-

Fig. 6. View of data for month of observations in Grafana interactive dashboard.

sible to view data both for short periods of time with high resolution and for long periods with low resolution. This system focuses on storage of time series and successfully operates in conditions of channels with limited bandwidth. The client developed by us stores the measurement results using the Seedlink protocol in a database managed by InfluxDB. To enable access to data, including from mobile devices, we used the ready-made Grafana software for building interactive dashboards (Grafana..., 2018). This software includes a server and a set of client libraries that can be used to create interactive dashboards, including indicators of various types. It is integrated with InfluxDB, which can reduce the creation of a web interface to working with the visual designer (Fig. 6).

CONCLUSIONS

In this study, the authors created a prototype for a real-time structure health monitoring system based on MINI-SMIK and the domestically manufactured MV77.07 single-board computer. A plugin for the SeedLink server was developed, which makes it possible to operate with the sensors included in the MINI-SMIK, and a plugin for exporting data obtained in Seedlink format to the format used in the InfluxDB database for storing time series. Data access to end users was implemented through the web interface of a Grafana interactive dashboard. Thus, data delivery to users is achieved in three different ways, two of which are real-time.

As an example, an observation point was set up directly in a building of IPE RAS. The measurement results are available in real time on the website of the Data Aggregation Center of IPE RAS (http://data.ifz.ru/) under “Monitoring of the IPE Building”; the measurement archive is also stored there. It is planned that, over time, the observations will be used to determine the dynamics of the IPE RAS annex.

The additional possibility of MINI-SMIK transmitting data in real time expands the scope of its application. In addition, the ability to construct monitoring systems on its basis using only domestically manufactured components is a valuable achievement, although a similar solution can be built with any other common single-board computer.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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