Case Study of Using Virtual and Augmented Reality in Industrial System Monitoring

Dmitry Pavlov, Igor Sosnovsky, Vyacheslav Dimitrov, Vasilii Melentyev, Dmitry Korzun
Petrozavodsk State University (PetrSU)
Petrozavodsk, Russia
{dpavlov, sosnovsk, dimitrov}@cs.petrsu.ru, melentev.petrsu@gmail.com, dkorzun@cs.karelia.ru

***Abstract*—An equipment monitoring system is responsible for analytical services that assist the personnel in equipment diagnostics, fault prediction, and post-analysis. In this work, we consider a case study of using virtual and augmented reality (VR/AR) for effective analytics delivery to the production equipment personnel. The reference analytical services for our study come from our pilot development with metalcutting industry in Russia. The two service models are proposed: (a) Situation Center and (b) Virtual Assistant. We identify the VR/AR advantages compared with the traditional style of visualizing analytical services on computer screens. Our study is supported with prototype implementation of the VR/AR system for analytics delivery to the personnel.**

I. Introduction

Modern enterprises use advanced information systems for equipment monitoring to optimize the production operation and quickly respond to faults [1]. Multiple sensors are installed on machines to collect data and to transfer the data to server computers, where they are converted into a convenient form for the specialist to understand. The traditional method of checking equipment is long, and searching for faulty equipment can lead to long downtime of the entire production line, while the equipment monitoring system in the enterprise has the ability to check machine components in real-time and report the failure of specific equipment.

An equipment monitoring system collects big data to analyze the state of the entire production. Then a person (equipment personnel) makes decisions depending on the situation. In order to speed up understanding of the problem and finding a solution, the information from sensors and services needs representing in a human-friendly form [2], [3]. which can help virtual and augmented reality—VR and AR, respectively.

The VR technology provides a new level of image display through the use of a helmet [4]. The application of the stereoscopic effect, which gives a full immersion in the virtual world and allows you to feel the depth of the image, with which you can determine the distance to the object and better perceive three-dimensional objects.

The AR technology is an auxiliary tool for assessing (diagnosing) the equipment status situation [5]. By superimposing additional information on real objects, it is possible to evaluate the machine condition based on sensor data. Technical personnel can easier check the equipment and determine the cause of problems.

In this study, we select several reference analytical services that come from our pilot development with metalcutting industry in Russia. The two service models are proposed: (a) Situational Center and (b) Virtual Assistant. We identify the VR/AR advantages compared with the traditional style of visualizing analytical services on computer screens. Our study is supported with prototype implementation of the VR/AR system for analytics delivery to the equipment personnel.

The rest of the paper is organized as follows. Section II provides an overview of analytical services useful in production equipment monitoring. Section III considers our VR model for constructing analytical services for a situational center. Section IV considers our VR model for constructing analytical services for a situational center. Section V describes our prototype implementation of VR and AR based variants of analytical services.

II. Analytical Services in Production Equipment Monitoring

A. Problem

One of the tasks in maintenance is to analyze the condition of the equipment. Technical personnel need to detect problems related to equipment components in a timely manner in order to eliminate them with minimal harm to production. If the problem was not noticed, the situation may become critical, which may later stop the production line.

An equipment monitoring system is installed in enterprises to help detect problems. A system capable of collecting data from sensors on equipment for subsequent interpretation in a form that is understandable to a person. It is also possible to perform a primary analysis, in which the monitoring system is able to give advice to technical personnel on how to fix the found vulnerability or notify them of the found fault in a timely manner. Work [6] describes some representation of the monitoring system shown in Fig. 1, which is divided into two global worlds: physical and cyber. The physical world includes real objects involved in production (machines, equipment, people). Cyber world contains a software part consisting of services, modules, and algorithms and is able to control the physical world.

The monitoring system uses large data collected from a variety of sensors installed on the equipment. For their analysis, it is necessary to process the received data for subsequent analysis by a human [7]. The more clearly the information is

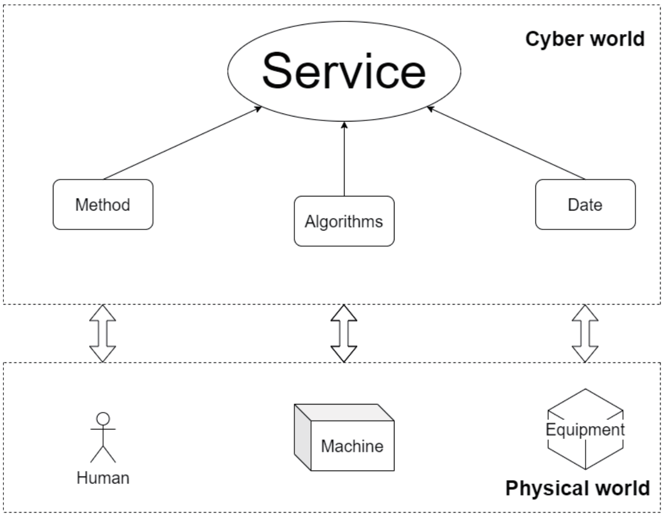

Fig. 1. Monitoring system scheme

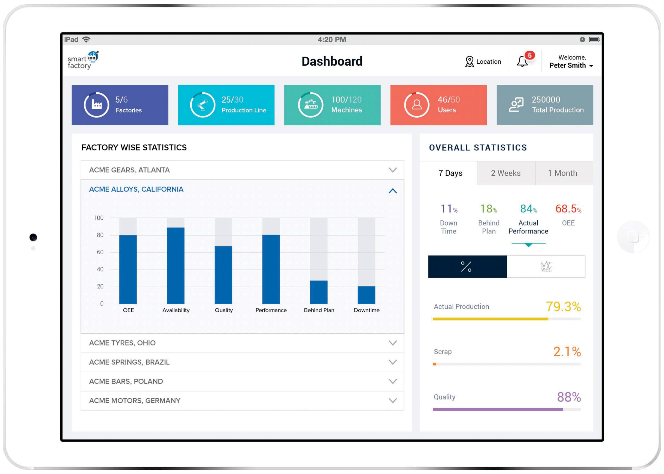

Fig. 2. Control panel example

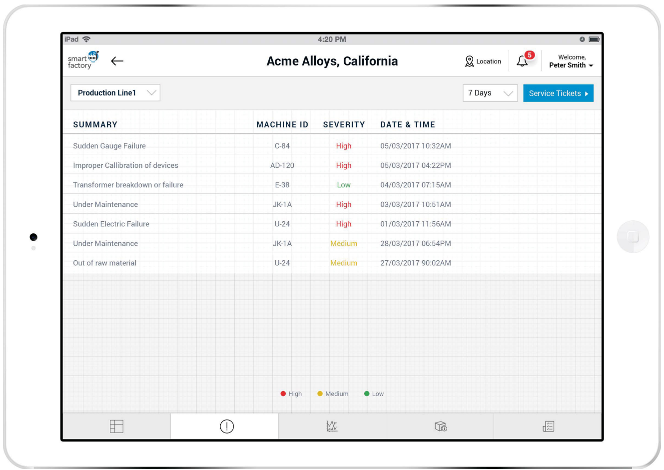

Fig. 3. Report example

presented, the more confident and faster the person will be able to make a conclusion and make a decision [2].

Virtual reality technologies are able to display three-dimensional objects and make it possible to interact with them. As an example, you can imagine a three-dimensional graph with data displayed on three axes at once and see the entire volume of the graph due to the stereoscopic effect. It is also possible to visualize a three-dimensional model of a production facility (machine, workplace) and show the location of sensors directly on the model for more detailed identification of the problem.

Augmented reality differs from virtual reality in that it overlays three-dimensional models and images on real objects. Thus, this technology can be used to quickly assess the condition of equipment when it is checked for faults by using data that is usually obtained from computers or paper documentation, while being near the equipment being checked.

Due to the development of technologies related to data visualization, it is possible to improve the perception of information and thus simplify and speed up the work of technical personnel and help them solve problems related to the maintenance of production equipment.

B. Existing solutions

Many existing industrial equipment monitoring systems suggest three types of user interfaces. The first type is dashboard for real time state in whole system (e.g., values of sensors, different charts, new and current tasks, user activities and so on). The dashboard is designed for quick decisions. A dashboard example is shown in Fig. 2 from Softweb Solutions Inc. (www.softwebsolutions.com/).

The second type of user interfaces is reports. Typical reports are generated for selected period and are shown system changes in this period. The report is designed for medium and long decisions. A reporting example is shown in Fig. 3.

The third type of user interface is assistance. The assistance provides sequence steps for operator. Each step describes list of operations which the user should perform. The system fix start time of step, finish time of step, state of system and allows the user to add some descriptions, photos, videos, etc.

All these three types of user interface are static. The interface binds the user to computer screen (desktop or mobile), where all the analytic information from services are visualized.

C. Advantages of VR/AR technologies

The types of interfaces for human interaction discussed in section II-B can be implemented in virtual reality, which will improve data perception and take advantage of the technology used to improve data perception. The advantages of VR, as well as examples of using VR, are shown in table I.

Overlay-based AR provides an alternative view of the object in question, either replacing the entire object with an augmented view, or replacing part of the object with an augmented view. In this case, object recognition plays a vital logical role. if the app does not know what it is looking at, it can't replace the original view with an augmented one [8].

Depending on what type of presentation is required, the technology can be used for several purposes [8].

1) Doctors can use this technology to examine a patient from various points in real time. A live broadcast from an x-ray machine can be used to superimpose an x-ray image of a patient's body part onto a real body part to better understand bone damage. The app can be made to work with a head-up display or special glasses. In other cases, the image may be shown on a screen where the video is taken from a real camera and x-ray vision may be applied to it [8].
2) In military applications, an AR-based overlay can provide multiple views of the target object without showing additional information in the text and blocking the soldier's vision from other important objects around. If you were shooting at enemies with a computer mouse, you would already know what it would look like. Superimposing an infrared view or a radioactive view of an object or area can help save lives or win wars [8].
3) Overlaying ancient paintings on real objects can provide interesting views of historical places. Broken monuments can come back to life in all their original glory. Perhaps different eras complete with landscapes can be re-lived with AR [8].
4) Letting a tiger or snake get close to you can be an unpleasant experience with dangerous consequences, except when AR overlay is used. Placing a person in a place or situation that is otherwise dangerous can be done safely using AR overlay [8].
5) Overlaying a real object with its internal appearance can also be useful in education, for example, for studying the structure of bones [8].

According to the information provided in Table II, the advantage of AR over desktop PCs and text documentation is that in AR all data are presented in real time right in front of the person's eyes and, therefore, they do not have to spend time accessing the PC or text documentation. Also, in AR, the system itself can offer the necessary instructions for setting up, performing diagnostics or Troubleshooting, without being distracted by searching for information in the text documentation. AR will help reduce the time spent on site maintenance and reduce the likelihood of human error.

D. Reference analytical services

The monitoring system uses services for processing raw data from sensors that take readings from the machine, thereby tracking its status. Various services can read data from specific sensors to obtain specific conclusions, based on which the question of the serviceability of the machine component is decided.

Table III provides a list of services that are used in the monitoring system and their purpose. Each service is used in certain cases, these cases are described in the 3rd column of the table. The second column contains the name of the service, which indicates the scope of this service.

According to the description of services in Table III, one can say that for displaying information from most services, visualization can be used in the form of graphs or color indicators, as well as in the form of text data. For other services, one can use data visualization in the form of 3D models, checklists, or text and visual instructions.

III. Situation Center: Use of Virtual Reality

The situation center uses an autonomous Oculus Quest virtual reality helmet to view data. Management in the virtual space is carried out using Oculus Touch controllers, which are presented inside the situation center in the form of virtual hands. The application requires a free space of more than 4 square meters and an Internet connection via Wi-Fi.

The situation center model is shown in Fig. 4. The concept model includes four levels:

1) the target machine is located on the first level
2) at the second level, sensors capture data from the machine.
3) at the third level, services process data from sensors.
4) at the fourth level, the situation center accepts data from services and converts it into graphs and status indicators. it is also possible to change some parameters to change the request for data from services, for example, to output data for a certain period of time.

The situation center is a virtual room with a menu in the form of a screen fixed in the air. Fig. 5 shows how the menu will look on the screen and its variations depending on the user's choice. The screen shows the interface, which has buttons with the corresponding text. The initial screen is used

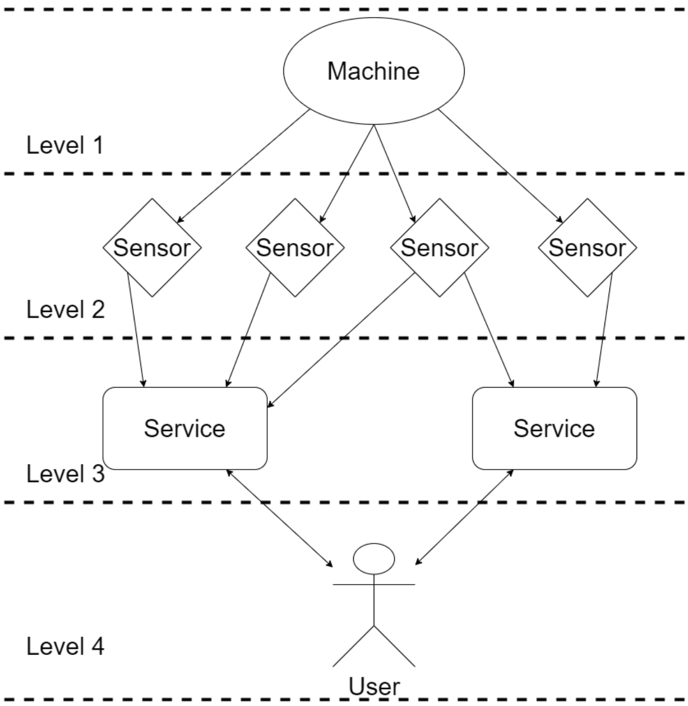

Fig. 4. Situation center model

TABLE I. VR ADVANTAGES

Advantages	Example of use	Justification
Real-time data visualization with easier pattern recognition in large data sets and more intuitive data understanding	Virtualitics recently launched its VR product that puts the researcher directly into the data. It also uses machine learning to help analysts determine which factors will ensure the best display and creation of a multidimensional view of data. [9].	In contrast to conventional data visualization models, virtual reality allows users to walk and view data from different angles. in addition, it is easier for people to perceive information in the form of three-dimensional shapes, objects, compared to flat images.
Reduce production time and costs	One of the world's leading car manufacturers, Ford, has created a virtual reality laboratory. This allows engineers to quickly and easily improve the quality of early concepts by actually designing new car designs. With VR, Ford manufacturing crew can now design cars before creating a physical prototype. This speeds up time to market and reduces production costs [9].	In VR, the user reacts faster to all events because the entire interface is intuitive, which allows faster data analysis.
Building and implementing various three-dimensional shapes and objects	1) A similar concept is already used in Balfour Beatty Rail. This railway infrastructure contractor integrates the benefits of VR into the design process. It provides planning, prototyping and construction of objects, helping in the implementation of projects [10]. 2) Another example is the design of a car. The car itself is a complex structure. There are many important details in the design of even the simplest cars. A car design created in VR can increase the efficiency and productivity of creating a real car design. The JLR virtual reality center in the UK takes advantage of virtual reality and turns VR into a work of art. This service offers both semi-immersive and CAVE systems with projection and advanced tracking. Probably the biggest part is that this VR center is being used to design the next-generation Land Rover [10].	In VR, you can display any 3D objects and manipulate them, which allows you to understand what the object from which the readings come looks like, and display the color statuses of individual nodes of this object.

TABLE II. AR ADVANTAGES

Advantages	Example of use	Justification
Free access to technical and expert information on site	Elevator manufacturer thyssenkrupp has announced that its specialists will start using Microsoft HoloLens technology as a tool in service operations. Using HoloLens, service technicians can visualize and identify problems with elevators before working, as well as have remote, free access to technical and expert information on site. As the first fully Autonomous holographic computer running Windows 10, Microsoft HoloLens helps companies and industries innovate in completely new ways. Using the Skype app without any additional development, thyssenkrupp service engineers can now perform their work more safely and efficiently. Sorting out service requests in advance of a visit and getting a hands-free holographic guide when you are on site has reduced the average duration of thyssenkrupp service calls by up to four times [11].	AR allows a person to reduce the time needed to solve a problem by setting up equipment, performing maintenance, or identifying and fixing a problem that has occurred.
Superimposing digital information on a real object	1) AccuVein, a new York-based company, uses AR to help nurses find veins easier when installing IVS. This makes life easier for nurses and patients, increasing the success rate of the IV by 350% [12]. 2) AR also helps some patients in their recovery process. One company, called NuEyes, uses special AR glasses to help people with severe visual impairments. With this technology, NuEyes can help blind children see well enough to read and recognize their classmates [12]. 3) There is evidence that AR can help reduce the excruciating phantom limb pain experienced by amputees. By projecting a digital limb onto a patient, researchers were able to trick their brain into thinking that the amputated limb was still there. This projection, paired with electrodes, allowed patients to practice relaxing the digital limb to ease pain [12].	AR allows you to overlay a digital image on a real object, which allows you to analyze the situation, plan an action plan without leaving the object itself.

TABLE III. SERVICES AND THEIR APPLICATION

#	Service	Application
1	”Control of the swivel head installation”	Service is used to determine the correct positioning of the swivel head
2	”Fixing various errors that occur on the machine screen”	the Service is designed to recognize errors that appear on the machine monitor in order to determine the most complete description of new errors that appear (their interpretation) and notify the working staff about their appearance
3	”Creating tasks for technical personnel”	the Function allows you to create maintenance or inspection points for technical personnel, as well as to record the implementation of these points (fixing the passed stage, adding photos, adding descriptions and comments)
4	”Mobile element impact Detection”	the Service records the occurrence of a mobile element impact event, records the readings of all sensors, video sequences from surveillance cameras, and a set of events preceding and following the impact for a certain period before and after the event
5	”Monitoring the current of the motor axes and spindle”	when detecting abnormal consumption or current changes informs the user of sudden increases in load or deviations from normal values, and also allows you to analyze the readings from all current collectors
6	”Help in hardware diagnostics”	the System provides the ability to display data from various sensors and services on a single screen, which allows the employee to track the status of the system as a whole
7	”Control of spindle bearings and motor”	Service allows you to track the occurrence of vibrations and warn the user about it
8	”Temperature control of auxiliary devices”	Service allows you to monitor the temperature of pumps and inform users about deviations from the norm, which will allow you to service or replace the unit in time
9	”Control of coolant supply during processing”	the Service is used to display the current status of the coolant supply (present, absent) and in case of atypical behavior of the feed notifies the responsible persons
10	”Control of counterweight installation of the processing head”	Service controls the installation of counterweights for the processing head
11	”Tracking the location of the operator”	the Service allows you to track the presence of the machine operator and warn interested parties in case of his absence from the workplace or when he performs actions for which he does not have sufficient rights (for example: opening the electrician’s Cabinet, entering the machine during operation)
12	”Monitoring of machine load”	Using data obtained from installed sensors, the service will allow you to determine the level of machine load and generate reports indicating the time of operation/downtime of the machine and the nodes involved
13	”Diagnostics of linear guide axes X, Y, Z”	the Service provides the user with an interface (”assistant”) for performing a sequence of steps for diagnosing linear guide axes

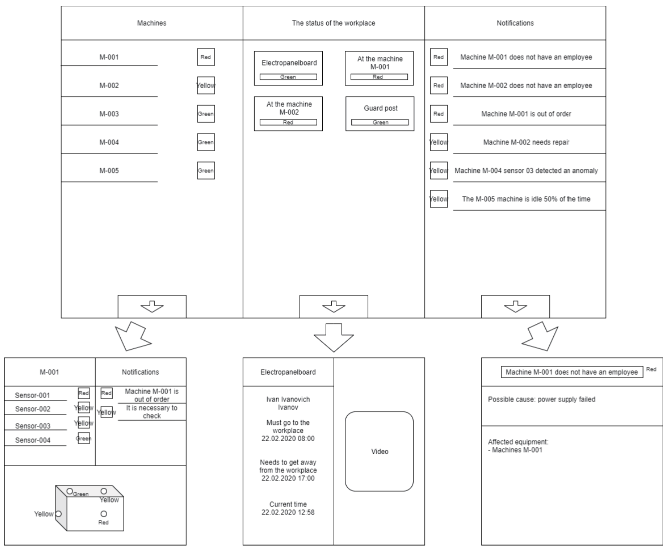

Fig. 5. On-screen menu

for a quick assessment of the situation. it shows the status of all machines, the workplace (whether there is a person in the workplace), and a column with notifications. The status of the machines is shown as a set of lines, each of which contains a unique ID of the machine and its status as a color indicator (green - everything is normal, yellow-needs repair, red-out of order). The workplace is shown as a list with a description of the location, who should go to work and an indicator of the person’s presence in the workplace. The notification column displays a list of recent notifications and sorts them by importance. An example of a situation center implementation can be seen in Fig. 6.

When you select a specific machine, a new screen appears that includes:

1) list of sensors used in the machine
2) recent notifications related to this machine,
3) the location of the machine.

Each sensor in the list of sensors has a unique identifier, and when you select one of the identifiers, a new screen opens, which displays a visual representation of data from this sensor in the form of a graph, chart, etc.

When selecting a specific job from the list, a screen appears that contains information consisting of:

1) location of the workplace,
2) for the purpose of the workplace,
3) information about the employee who should currently be at the selected workplace,
4) images from a security camera.

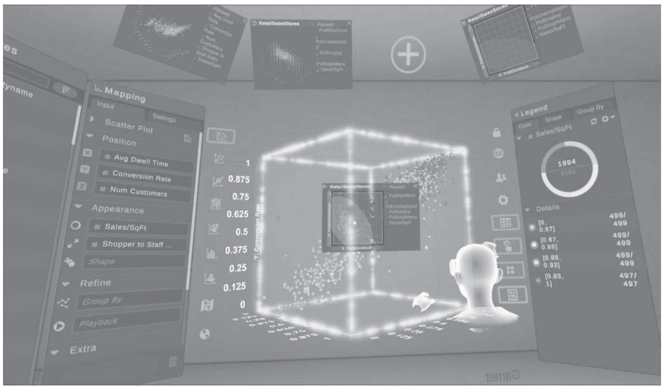

Fig. 6. Example of the interface

Events of varying degrees of importance appear in the notification column. The most important notifications are displayed first in the order they appear (events of equal importance are sorted by the time they appear in the column). When you select a specific notification, a screen opens with a description that indicates the reason for the notification and the associated equipment (machine, sensor), and the notification can also be associated with the workplace (the employee is absent from the workplace for a long time, is late, etc.).

Graph visualization is a three-dimensional object in the form of a screen that can be grasped, stretched, compressed, or fixed in space. Multiple graphs can be combined into a single graph based on data from two other graphs. Services that use graphs to display data are shown in Table III under the items 4, 5, 6, 7, 8.

Another way to provide information are statuses. Using color indicators, you can quickly understand the status of the equipment or the importance of information, which gives a quick assessment of the situation. Status indicators are used in services under items 9, 10, 11, 12 in Table III.

Some services use a method for delivering important information, such as notifications. Using this method, you can find out important information in a timely manner and study the situation in more detail. Notification support is provided for services under items 1, 2, and 3 in Table III.

IV. Virtual Assistant: Use of Virtual Reality

The virtual assistant entity is shown in Fig. 7. The picture shows that the entity consists of 5 layers. Sensors collect information from the machine, then transmit it to the server. The server, in turn, processes this information and passes the information to the virtual assistant upon request. The virtual assistant interacts with the user and generates requests to the server based on their actions.

Virtual assistant is an application for augmented reality glasses or a mobile phone / pad that allows you to add useful information to the world around you in real time. The assistant can be installed on hololens 2 augmented reality glasses. Control in this case is performed by simple hand gestures, focusing the eye on the object or voice commands.

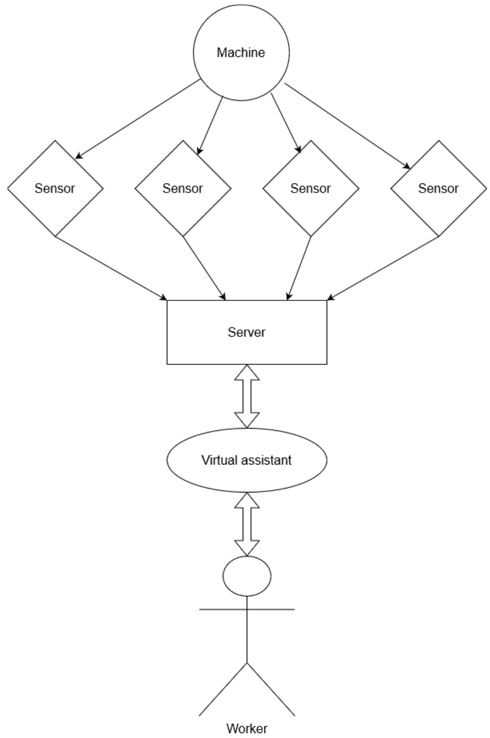

Fig. 7. Virtual assistant model

The assistant can also be installed on a mobile phone/pad that supports ARCore.

This app can highlight the position of the sensors on the machine in a color that indicates the state of the sensor (for example, red-the sensor readings are out of the normal range, green-does not go out, yellow-close to the limit), when the AR device camera is pointed at the machine. After that, the user can view information about the sensor of interest in more detail by selecting it with a hand gesture, focusing the camera on the object or tapping on the phone screen on the object of interest to us. More detailed information can contain graphs, tables, and color and text status displays, with a description of the status and offer instructions for correcting situations, which can also be selected by focusing the AR device's camera, using a hand gesture or tap.

Instructions can be presented in the form of checklists, text or visual algorithms for actions to correct the situation that caused the sensor indicators to increase above the norm.

The app can also display a check list, for example, for passing something that the user marks on their own.

It is possible to display the current date and time with an accuracy of seconds.

In AR, graph visualization is a small screen that appears when you hover over the module. You can stretch the graph using gestures, head movements, or taps on the phone screen. Services that use graph data visualization are listed in Table III under numbers 4, 5, 6, and 8.

Also, in AR, visualization can be represented as statuses (color or text indicators) of States. They can be used to quickly

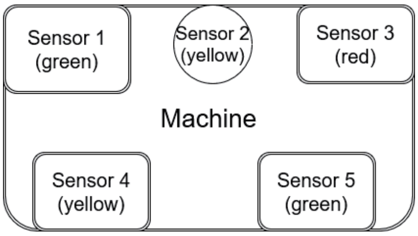

Fig. 8. Example of virtual assistant interface

assess the status of the sensor, module, machine as a whole, or the importance of information. Visualization using indicators can be used to display services presented in Table III with numbers 4, 5, 9, 11, and 12.

In addition to schedules and statuses, a virtual assistant can be organized in AR, which will provide graphical or text instructions for resolving a problem, configuring equipment, or performing maintenance. The virtual assistant can be used in the services listed under items 6 and 13 in Table III.

Two other possible ways to display data are reports on events that occurred prior to the failure, and a checklist for personnel to perform diagnostics or configure equipment. This data display can be used in services with numbers 3 and 13 in Table III.

In Service 1 of Table III, data can be displayed as a 3D model corresponding to the current position of the rotating head, indicating the current position of the rotation angle.

Fig. 8 shows an example of displaying the virtual assistant interface. This interface is displayed when the machine image is recognized. Successfully recognizing machine, the assistant will highlights place, or will form a small 3D model of the sensor with the color corresponding to the current state of the sensor with a small status, for example, the green color sensor values in the normal range, yellow - readings a little above normal, but are not critical and red - readings are off the charts, it is necessary to conduct urgent maintenance.

When you hover over a specific sensor model, a graph will open with its readings, which can be adjusted to receive real-time data or to display the history. An example of this is shown in Fig. 9.

In addition, there will be a check list on the side of the entire interface, which can be either hidden or opened. A checklist example is shown in Fig. 10.

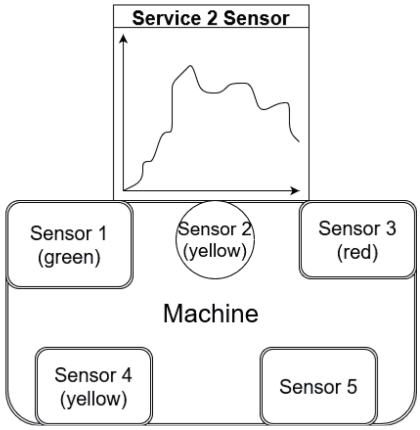

Fig. 9. Example of displaying graph data

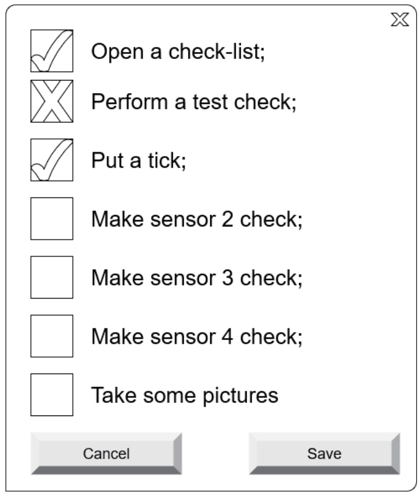

Fig. 10. Example of a checklist in the expanded state

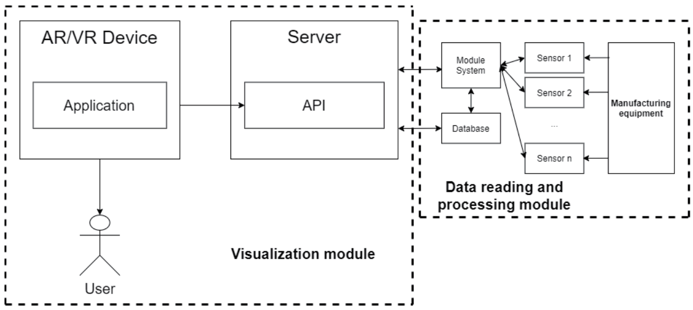

Fig. 11. Hardware and software components

V. Prototype Implementation

A. High-Level Architecture

Hardware and software components of implementation are represented in Fig. 11. Each user uses AR/VR device with application for interaction with UI. Application has the following function: requesting the server for data and visualizing the data for the user.

The application uses specified API for getting data from server. API extracts data from database or getting those direct from the module system for visualization data in real time.

The module system gathers data from the machine sensors and save to the data base or notify about this server (API). The RabbitMQ message system is used for this purpose.

B. Data Scaling

Sensors of the module system generates huge values of data (for example, 200000 values in one second). In this case visualization of this data using some components (for

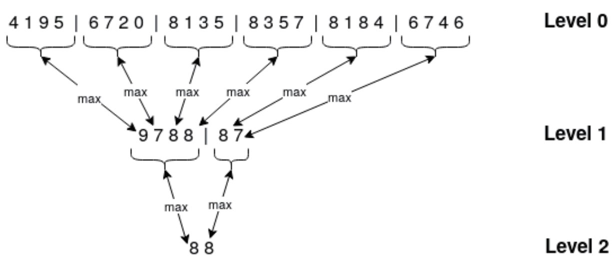

Fig. 12. Example of calculating the detail levels with the max aggregation function

example, chart) is not a trivial task. All data in one chart is non informative, and user cannot analyze this chart.

We develop a concept for visualization this data in more informative way. The idea is using levels with details. Each new level has new details. This principle is used in interactive maps (for example, Google Maps, Apple Mas, Yandex Maps and OpenStreetMaps): when the user increases the detail level of new raster images are loaded with new details. When the user decreases level of details new raster images are loaded with less details. In this case, for representation of whole world more than 10 images are used.

For solving our problem with visualization of large amount of data we used the same principle. The more data for visualization, the less details on the chart. For decreasing data on the chart aggregation function is used (for different sensors different aggregation function may be used (max, min, avg, and so on).

One of the main parameters of details is "window" of aggregation. This parameter defines amount of data for applying aggregation function. In case amount of data less than this parameter, then levels of details are not required. For example, we have 24 values of data and window of aggregation is 4 and max as function of aggregation. Zero level of aggregation (without any data processing):

4 1 9 5 | 6 7 2 0 | 8 1 3 5 | 8 3 5 7 | 8 1 8 4 | 6 7 4 6

Amount of data more than defined window aggregation, and we decided construct next (first) level of details. This level has values which are calculated by applying aggregation function (in our case is max) for which data sets with window aggregation amount:

9 7 8 8 |8 7

First level of details has amount of data more than defined window aggregation again. We applied aggregation function another time and now we have next (second) level of aggregation.

8 8

Now we have three levels of details. These levels may have loaded for user as necessary. The example of calculating levels of details is shown in Fig. 12.

The algorithm splits the data in levels after user request for data and user has view chart with max level (minimum data). In case the user understands that some data is interesting, he/she may select this period and chart loaded new levels of details. Each selected point transforms to next level of details.

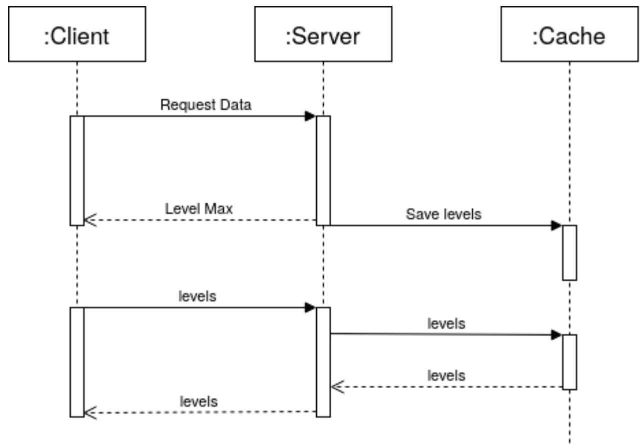

Fig. 13. Interaction scheme

First version of implementation was done for WEB client. The server splits data into levels of details, the client selected necessary data from levels, constructed and redraw charts. But loading all levels of details from server to client in one request may spend a lot of time (for example in case data in period several months). For levels cache was developed. In first request server sends to client only max level of data and caching other levels. In case user want to get next detailed data next request will be done. Common scheme of interaction is represented in Fig. 13.

After testing algorithm and interaction with WEB system, the component was be moved in API for AR/VR application. And WEB client uses API now.

C. API implementation

For getting data HTTP-requests are used. There are two types of requests:

1) Getting list of services (parameters not needed)
   Result of this request is JSON document with list of service, where each element is JSON document with identification, name and description of service.
2) Request for data of service (parameters: identification of service, start and finish time of data for period in UNIX timestamps)
   Result of this request is list of data where each element is JSON document with value and timestamp of data.

The Unreal Engine 4 can do requests due to TCP connection plugin:

1) Connect to IP-address and TCP-port.
2) Send request to server.
3) Wait response from server.
4) Get request in one string.
5) Close TCP connection.

After the data is received from the server, the data is "pulled" from the string and further processed. This part is implemented by describing the function in C++ using Visual

Studio C++ and specifying metadata so that the function can be used as a blueprint. After data is extracted from the server response, it is written to a structure that stores arrays of data: an array of values, an array of timestamps in UNIX Timestamp, and an array of timestamps in the classic date and time representation.

Next, the data is displayed using a loop on the graph. Each point of the graph has two values that correspond to the index elements of the value and timestamp arrays.

VI. Conclusion

This paper considered a case study of using virtual and augmented reality for effective analytic delivery to the equipment personnel. We selected several reference analytical services from our pilot development with metal cutting industry in Russia. The two service models were proposed: (a) Situation Center (VR-based) and (b) Virtual Assistant (AR-based). Our prototype implementation indicated that the proposed service delivery models have certain potential for production equipment monitoring in industrial enterprise.

Acknowledgment

This research is financially supported by the Ministry of Science and Higher Education of Russia within project no. 075-11-2019-088 (Creating the high-tech production of mobile microprocessor computing modules based on SiP and PoP technology for smart data collection, mining, and interaction with surrounding sources).

References

[1] D. Hasselquist, A. Rawat, and A. Gurtov, “Trends and detection avoidance of internet-connected industrial control systems,” *IEEE Access*, vol. 7, pp. 155 504–155 512, 2019.

[2] M. D. Lee, M. A. Butavicius, and R. E. Reilly, “Visualizations of binary data: A comparative evaluation,” *International Journal of Human-Computer Studies*, vol. 59, no. 5, pp. 569–602, 2003.

[3] F. Ansari, P. Hold, and M. Khobreh, “A knowledge-based approach for representing jobholder profile toward optimal human–machine collaboration in cyber physical production systems,” *CIRP Journal of Manufacturing Science and Technology*, vol. 28, pp. 87–106, 2020.

[4] H. Qin and J. Lei, “The application of virtual reality technology in advertising communication,” in *2019 International Conference on Virtual Reality and Intelligent Systems (ICVRIS)*, 2019, pp. 73–76.

[5] P. Fraga-Lamas, T. M. Fernández-Caramás, Ó. Blanco-Novoa, and M. A. Vilar-Montesinos, “A review on industrial augmented reality systems for the industry 4.0 shipyard,” *IEEE Access*, vol. 6, pp. 13 358–13 375, 2018.

[6] F. Tao and Q. Qi, “New IT driven service-oriented smart manufacturing: Framework and characteristics,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 49, no. 1, pp. 81–91, 2019.

[7] F. Tao, Q. Qi, A. Liu, and A. Kusiak, “Data-driven smart manufacturing,” *Journal of Manufacturing Systems*, vol. 48, pp. 157–169, 2018, special Issue on Smart Manufacturing.

[8] *Different types of augmented reality*. Digit community, chapter 3 in FastTrack To Augmented Reality [accessed 01.04.2020]. [Online]. Available: https://www.digit.in/technology-guides/fasttrack-to-augmented-reality/different-types-of-augmented-reality.html

[9] Y. Velykholova, “6 ways to empower the enterprise with virtual reality solutions,” Dec. 2017. [Online]. Available: https://www.n-ix.com/ways-empower-enterprise-virtual-reality-solutions/

[10] Rooney, “6 examples of virtual reality applications and how it works,” blog in Category “Virtual Reality” [accessed 01.04.2020]. [Online]. Available: https://howtocreateapps.com/examples-virtual-reality-applications/

[11] I. Wright, “What can augmented reality do for manufacturing?” May 2017. [Online]. Available: https://www.engineering.com/AdvancedManufacturing/ArticleID/14904/What-Can-Augmented-Reality-Do-for-Manufacturing.aspx

[12] A. Collins, “The ultimate guide to augmented reality,” Oct. 2018. [Online]. Available: https://blog.hubspot.com/marketing/augmented-reality-ar