System for Monitoring of Hot Spot Temperature of Power Transformer Windings Using Fiber Optic Sensors, Kalman Filter and SCADA Integration

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***Abstract*—This article presents the implementation based on LabVIEW of a monitoring system using fiber optic sensors for the measurement of hot spot temperature of the transformer windings, which employs a Kalman filter to reduce the measurement noise, and is integrated into a SCADA (Supervisory Control and Data Acquisition) system. The system shows the online evolution of temperatures, automatically creates and prints reports, stores the acquired data as TDMS (Technical data Management Streaming) type files and in a MySQL Server type database. The developed monitoring system implements a unit to access and transmit real time data over the Intranet or Internet, using JSON (JavaScript Object Notation) for the communication between the integrated Web Server and the Web Browser, provides warning reports and sends an e-mail to default addresses. The monitoring of the acquired data, the system operation and SCADA integration of the system presented have been tested using both synthesized virtual signals and real signals.**

Keywords—Power transformer; Fiber optics; Kalman filters; SCADA systems; Network servers

I. INTRODUCTION

The reliable operation of power transformers is of great importance to the operation of power equipment and represents a special problem, for the entire power system and inclusively for the environment. For cost related considerations, there is an ongoing effort to maintain the transformers in service for the longest period possible. "The capacity of the transformer to dissipate the heat generated inside to the environment is in part the basic principle which reduces the transformer load capacity and life span. The on-line comparison of a measurand, such as the winding temperature, with a calculated value, obtained using the physical model can be used to diagnose certain failures which develop rapidly. Winding temperature is a very important measurand in power transformers, which defines the condition, load capacity and operating life of power transformers" [1].

The direct monitoring of the transformer windings hot spot temperature has a lot of advantages and a various optical fiber sensors were presented in recent decades, with different operating principles [2-8].

The greatest problem was at first the dielectric failure and fragile equipment which led to breakage during handling or installation. It was then improved accordingly and it has now been determined as a reliable and accurate method to instantly indicate the real time winding hot spot temperature, so the transformers can be overloaded at optimal levels to comply according to the variable load demand without affecting or degrading their design life [9-12].

The data filtering module has an important role for a data acquisition system which will be integrated into SCADA system. In terms of suppression of the statistical measurement noise, the best performance is achieved by using a Kalman filter [13].

Modern SCADA provides proper monitoring of power transformer in order to maintain operations at an optimal level. In a monitoring system for transformer windings hot spot temperature, fiber optic sensors are located in remote locations, but they need centralized management, by integration in a SCADA network [14-26].

This paper presents a monitoring system based on fiber optic sensors for measuring the transformer windings hot spot temperature which uses a Kalman filter to reduce measurement noise. The system shows the online evolution of temperatures, automatically creates and prints reports, stores the acquired data as TDMS type files and in a MySQL Server type database in order to obtain the temperature evolution log and creates warning reports. For the connection between the monitoring system for windings hot spot temperature and the SCADA a new OPC UA (OLE Object linking and embedding for Process Control Unified Architecture) is used to address the above issues, and integrate services of traditional OPC into one OPC server, which simplifies the function collaboration and enterprise deployment. The developed monitoring system implements a unit to access and transmit real time data over the Intranet or Internet, provides warning reports for any emergency situation when the winding hot spot temperature exceeds the warning limits, and sends an e-mail to default addresses.

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The paper is organized as follows: Section 2 describes the main components of the monitoring and Section 3 presents the SCADA integration of the monitoring system. The implemented main software modules achieve data acquisition and filtering of acquired signals in order to reduce measurement noise by using a Kalman filter, write the filtered data in the OPC UA, MySQL, Web servers, show the instant evolution of the acquired values, achieve automatic reports, store the evolution in a database, manage the alarms by automatically sending to default email addresses, achieve integration into SCADA and allow the display of data on the Intranet/Internet via a Web Server which is embedded in the application. The paper ends with a section of conclusions describing the main aspects and advantages of the developed monitoring system for transformer windings hot spot temperature, some conclusions will be made and some ideas will be pointed out for continuation of work.

II. DESCRIPTION OF THE MONITORING SYSTEM

It's a well-known fact that the indirect method of thermal simulation measurement or indirect calculation estimation of the transformer hot spot temperature is influenced by nominal parameters and it is difficult to get the accurate temperature. In addition, in the last decade, the direct method using fiber optic monitoring enables actual hot spot measurement by sensing temperature directly in the windings [6-8].

The proposed solution for the windings hot spot temperature monitoring system using fiber optic sensors is presented in Fig. 1. The main components of the monitoring system are follows: fiber optic sensors and fiber optic external extension cables; enclosure monitoring with data acquisition board, signal conditioning module and electro-optical converters; computer for servers and applications for SCADA integration. The picture of the monitoring system is presented in Fig. 2.

The fiber optic temperature monitoring technology is based on the dependence between the temperature and the GaAs crystal property of light absorption [10, 17]. The temperature sensor outputs are processed by the LumaSHIELD signal conditioning module in order to obtain unified data for the acquisition data board. The data acquisition board and the electro-optical converters module are from ICP DAS family. The I-7000 and M-7000 modules ICP DAS are a family of network data acquisition and control modules [18, 19].

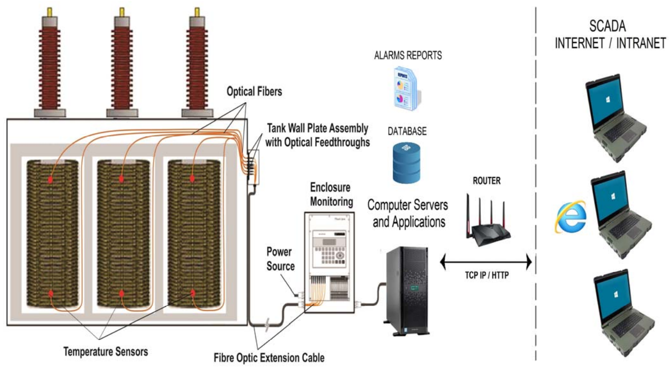


Fig. 1. The block diagram of the monitoring system.

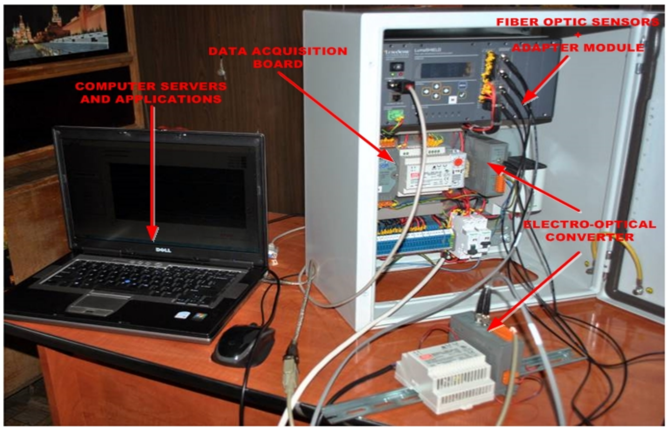


Fig. 2. Picture of the monitoring system.

III. SCADA INTEGRATION OF THE MONITORING SYSTEM

SCADA is a computer based system designed for the control and monitoring of technological processes and is the most modern concept and the tool used for the control and monitoring of technological processes. SCADA systems include both software and hardware components and processes the data in an acceptable time frame. A suitable development environment for the implementation of monitoring and SCADA integration applications is the LabVIEW environment, also referred to as G language, which is a graphical programming language using icons instead of lines of text [16, 20, 21].

The presented system contains sensors for temperature measurement based on optical principles and signal conditioning modules which transmit 4-20 mA signals to a data acquisition module. The signal is then conveyed through fiber optics via electro-optical converters to a dedicated computer. Fig. 3 shows the architecture of the transformer winding temperature measurement application and the integration in the SCADA.

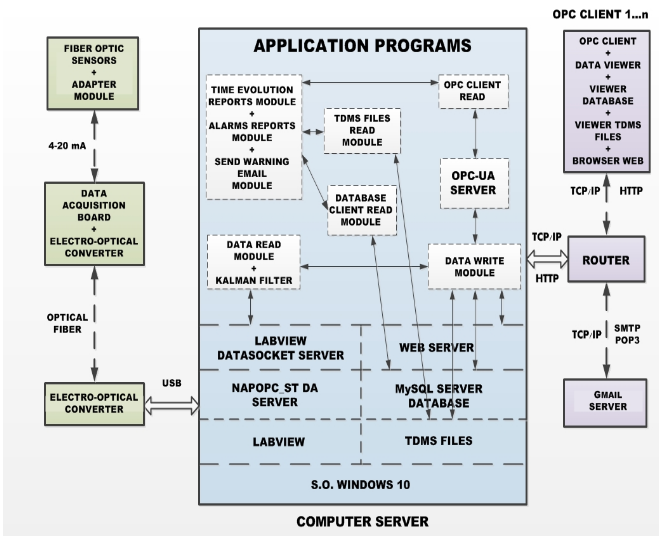


Fig. 3. Transformer windings hot spot temperature monitoring system integration in SCADA - Application architecture.

The applications running on the dedicated computer have been developed using the LabVIEW graphical programming environment and are based on the operation of dedicated function and network servers: NAPOPC_ST DA Server, DataSocket Server, OPC UA server, MySQL Server, Web Server and Gmail Server.

The main software modules of the application achieve data acquisition and filtering of acquired signals in order to reduce measurement noise (Data Read Module and Kalman Filter), and the filtered data are written in the OPC UA type Servers, MySQL Server, Web Server by using the Data Write Module. The following modules are used to view the instant evolution of the acquired values, to achieve automatic reports, to store the evolution as TDMS-type files and to manage the alarms: TDMS Files Read Module, Time Evolution Reports Module, Alarms Reports Module and Send Warning Email Module. The integration into SCADA itself is carried out by delivering the values of interest to an open and flexible OPC UA Server, and the display of data is done via the OPC Read Module, which runs locally but can be installed on any HMI computer from SCADA. The data can also be viewed on the Intranet/Internet via a Web Server that is embedded into the application.

For de-noising of the acquired winding temperature signals we use the time discrete Kalman filter with the predict-update equations as below [13]:

Predict:

$$\hat{X}_{t|t-1} = F_t \hat{X}_{t-1|t-1} + B_t u_t ; \quad P_{t|t-1} = F_t P_{t-1|t-1} F_t^T + Q_t \tag{1}$$

Update:

$$\hat{X}_{t|t} = \hat{X}_{t|t-1} + K_t (y_t - H_t \hat{X}_{t|t-1}) \tag{2}$$

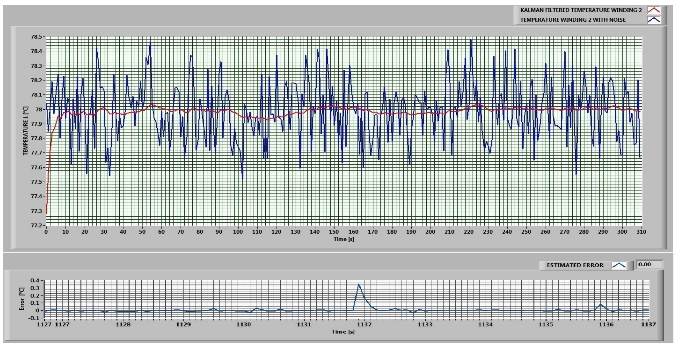
$$K_t = P_{t|t-1} H_t^T (H_t P_{t|t-1} H_t^T + R_t)^{-1} \tag{3}$$

$$P_{t|t} = (I - K_t H_t) P_{t|t-1} \tag{4}$$

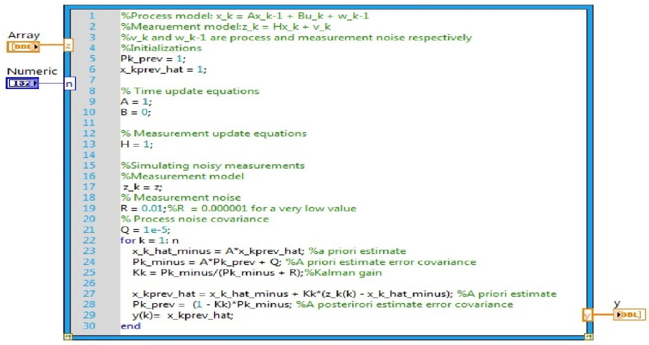
The equations (1)-(4) have the following notations: X hat - Estimated state, F - State transition matrix, u - Control variables, B - Control matrix, P - State variance matrix , Q - Process variance matrix, y - Measurement variables, H - Measurement matrix, K - Kalman gain; R - Measurement variance matrix.

Subscripts are as follows: t|t current time period, t-1|t-1 previous time period, and t|t-1 are intermediate steps. Because in this case F = 1, B = 0 we obtain the simplified equation and Matlab script implementation is presented in Fig. 3. The filter is applied with each measurement for the matrix process noise Q, the matrix sensor noise R, the matrix initial estimated error P_0 and the initial value X_0. As a good practice we initialize the state X_0 = 0, the state variance matrix P_0 = 10, the process variance matrix Q = 0.00001, and the measurement variance matrix R = 0.01 [13].

Fig. 4, (a) shows the evolution of a signal acquired and filtered using the Kalman filter for 310 seconds, but also the evolution of the error for 10 seconds zoom. These show the efficiency of the Kalman filter whose implementation in MathScript is shown in Fig. 4, (b).



(a)



(b)

Fig. 4. Kalman Filter for windings hot spot temperature monitoring: (a) Time evolution temperature and error filtering, (b) MathScript implementation.

The data acquired from the Data Acquisition board I-7017RC are read by the application program through the NAPOPC_ST DA Server which is a free OPC DA Server (DA stands for Data Access) for ICP DAS products. The NAPOPC_ST DA Server uses many subgroups of tags which belong to I-7017RC acquisition module when they are scanned for performing I/O modules.

The NAPOPC_ST DA Server reduced time through lower system integration costs, easy connection and interoperation to custom applications, synchronous and asynchronous writing to devices [22].

The SCADA/HMI/Database application software programs, contacts and obtains data from the NAPOPC_ST DA Server either on the same computer or on another computer.

Live data exchange between different applications is simplified by using DataSocket for LabVIEW. A variety of different technologies is used to share data between applications, including TCP/IP and dynamic data exchange (DDE).

The OPC UA includes all the functionality from OPC Classic and providing current DA (Data Access) and A&E (Alarm & Events). The OPC UA is based on a cross-platform, which expands the security and functionality from the OPC Classic [23-27].

The Data Read Module and the Kalman Filter read the data acquired from the NAPOPC_ST DA server via DataSocket server performs data filtering and communicates them to the Data Write Module. This module writes the filtered data to the OPC UA type server (to be accessed by SCADA), in the MySQL Server and as TDMS type files (to achieve the logging and data archiving) and in the Web Server (to be accessed on the Intranet/Internet in a simple way through a web browser).

The tree structure of the project containing the main modules of this application is shown in Fig. 5, (a), and the OPC UA server interface is shown in Fig. 5, (b). The block diagram for the communication made by the application between the NAPOPC_ST DA Server and the DataSocket Server is shown in Fig. 5, (c).

DataSources (ODBC) type connection, through which the application program performs the writing and querying of the MySQL Server type database will be used to store the acquired temperatures in order to recreate the logging and create automatic reports [28].

Fig. 6, (a) shows the structure of the database for logging the winding temperatures, and Fig. 6, (b) shows the block diagram of the Database Client Read Module.

Fig. 7, (a) shows a sample of the database from which a Word type report can be automatically generated and printed. The application program automatically generates warning emails with alarm reports, to default email addresses when the winding temperature exceeds the alarm threshold. Fig. 7, (b) shows the block diagram of the Send Warning Email Module.

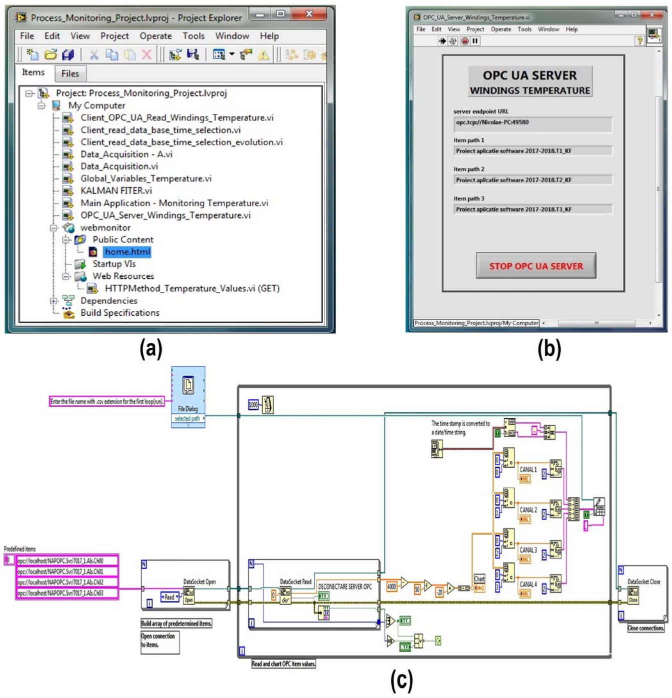


Fig. 5. Monitoring system – SCADA integration: (a) Tree structure of the project, (b) OPC UA Server interface, (c) Software block diagram data communication NAPOPC_ST DA Server and DataSocket Server.

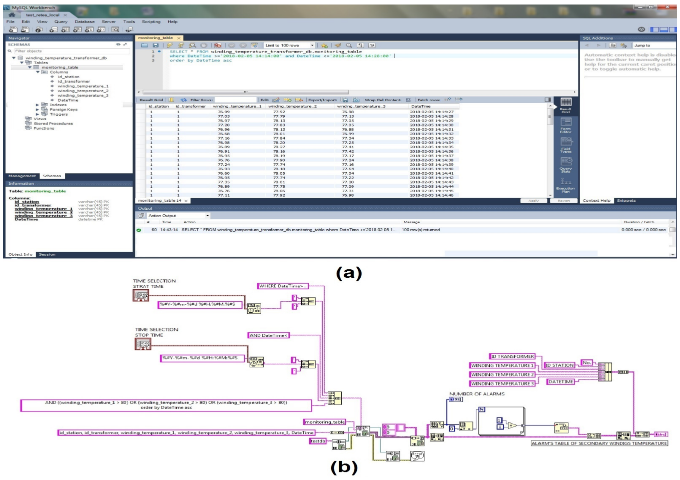


Fig. 6. Monitoring system – connection Database and Gmail Server: (a) Database structure, (b) Database Client Read Module software block diagram.

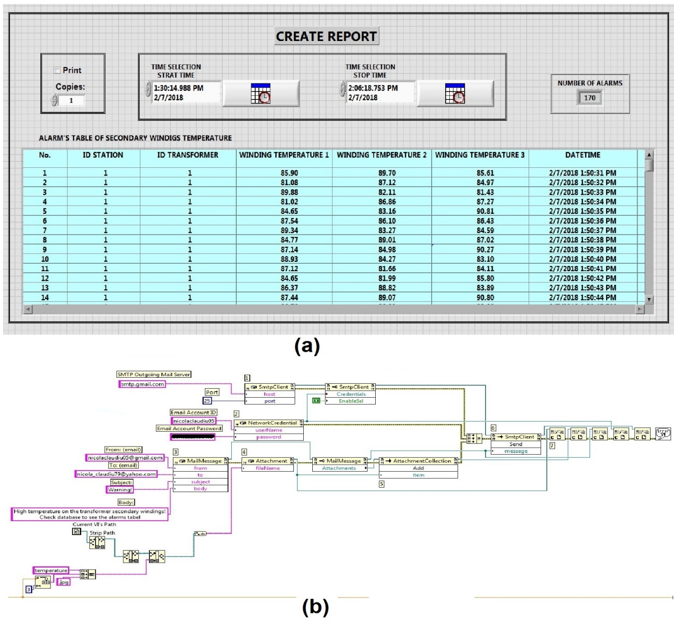


Fig. 7. Monitoring system – connection Database and Gmail Server: (a) Database selection, (b) Send Warning Email Module software block diagram.

For the exchange of live data with other applications on different computers from Intranet/Internet the presented application program integrates a Web Server through which the application receives queries from a Web Browser and provides the requested data to it for the online display of the transformer winding temperatures (See Fig. 8, (a)). The block diagrams of the communication modules between the application program and the Web Server integrated into LabVIEW are shown in Fig. 8, (b).

The exchange data with a remote LabVIEW application is realised with a Web Client over a network through LabVIEW Web Services. A Web Service consists of VI (Virtual Instruments) from LabVIEW and other files running on a server that respond to HTTP (Hypertext Transfer Protocol) requests from clients. The application program uses URLs and HTTP methods to transmit data directly to controls on the connector pane of Web method VIs, as well as send values as post data using the POST HTTP method. The HTML code takes care of most of the visual aspects of the web page and is similar to the front panel which contains indicators and graph charts to display the results.

JSON (JavaScript Object Notation) is configured to exchange with a Web Service and load data in JavaScript. This is done by the JSON.parse function (See Fig. 9, (a)). JSON is very similar to LabVIEW clusters [29].

The LabVIEW Web Service Request is a LabVIEW service which provides communication with the Java Script, and requires the creation, writing and reading of global variables to achieve the data exchange (See Fig. 9, (b)).

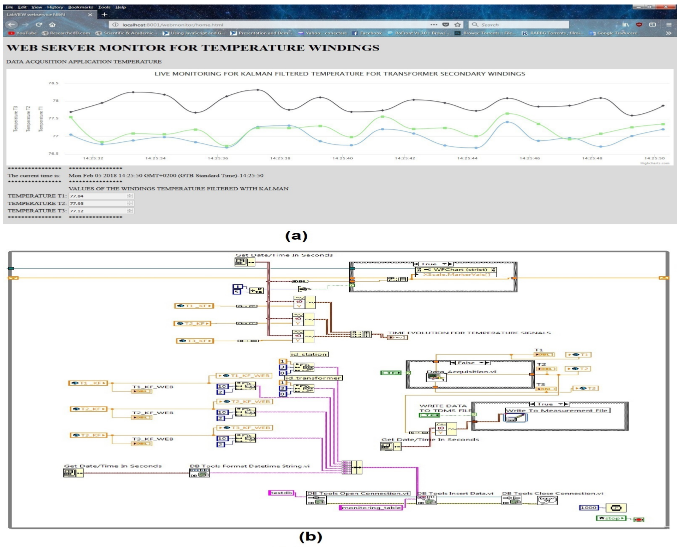


Fig. 8. Monitoring system – Intranet/Internet integration: (a) Windings temperature Web Browser time evolution, (b) Web Server communication software block diagram.

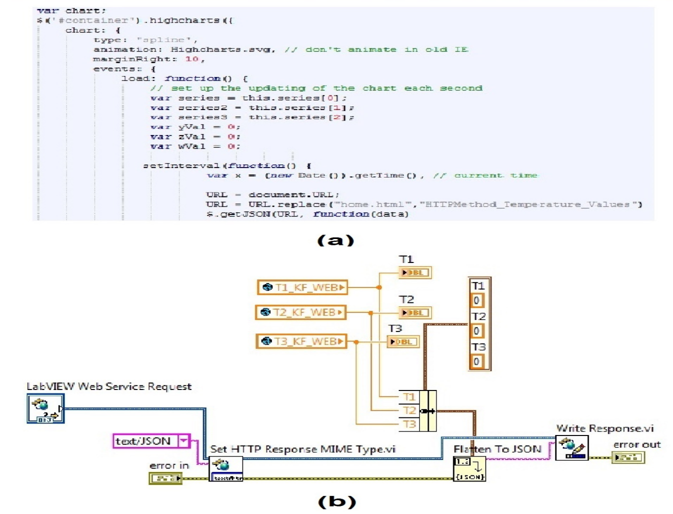


Fig. 9. Monitoring system – Intranet/Internet integration: (a) JSON – HTML implementation, (b) LabVIEW WebService request for HTTP Method software block diagram.

IV. CONCLUSIONS

This article presents the implementation of a monitoring system based on fiber optic sensors for measuring the transformer windings hot spot temperature which uses a Kalman filter to reduce the measurement noise, and is integrated into a SCADA system.

It presents the architecture and the main components of the monitoring system for transformer windings hot spot temperature: fiber optic sensors, data acquisition board, signal conditioning module, electro-optical converters and computer for servers and applications for SCADA integration.

The implemented main software modules achieve the following: writing of the filtered data with Kalman Filter in the OPC UA, MySQL, Web servers, showing the instant evolution of the acquired values, achieving automatic reports, storing the evolution in a database, managing the alarms by automatically sending to default email addresses, achieving integration into SCADA and allowing the display of data on the Intranet/Internet through Via a Web Server which is embedded in the application.

Extensive and optimized versions of the implemented system will be approached in the future, especially in connection with the safety of data transmission and redundancy of main hardware

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