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Augmented Reality Applications for Substation Management by Utilizing Standards-Compliant SCADA Communication

Miro Antonijević *, Stjepan Sučić and Hrvoje Keserica

Končar-Power Plant and Electric Traction Engineering Inc., Fallerovo 22, 10000 Zagreb, Croatia; stjepan.sucic@koncar-ket.hr (S.S.); hrvoje.keserica@koncar-ket.hr (H.K.)
* Correspondence: miro.antonijevic@koncar-ket.hr; Tel.: +385-99-364-8470

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Abstract: Most electrical substations are remotely monitored and controlled by using Supervisory Control and Data Acquisition (SCADA) applications. Current SCADA systems have been significantly enhanced by utilizing standardized communication protocols and the most prominent is the IEC 61850 international standard. These enhancements enable improvements in different domains of SCADA systems such as communication engineering, data management and visualization of automation process data in SCADA applications. Process data visualization is usually achieved through Human Machine Interface (HMI) screens in substation control centres. However, this visualization method sometimes makes supervision, control and maintenance procedures executed by engineers slow and error-prone because it separates equipment from its automation data. Augmented reality (AR) and mixed reality (MR) visualization techniques have matured enough to provide new possibilities of displaying relevant data wherever needed. This paper presents a novel methodology for visualizing process related SCADA data to enhance and facilitate human-centric activities in substations such as regular equipment maintenance. The proposed solution utilizes AR visualization techniques together with standards-based communication protocols used in substations. The developed proof-of-concept AR application that enables displaying SCADA data on the corresponding substation equipment with the help of AR markers demonstrates originality and benefits of the proposed visualization method. Additionally, the application enables displaying widgets and 3D models of substation equipment to make the visualization more user-friendly and intuitive. The visualized SCADA data needs to be refreshed considering soft real-time data delivery restrictions. Therefore, the proposed solution is thoroughly tested to demonstrate the applicability of proposed methodology in real substations.

Keywords: SCADA; augmented reality; IEC 61850; substation management

1. Introduction

In recent years, augmented reality (AR) and mixed reality (MR) technologies and devices (e.g., Google Glass [1], Microsoft Hololens [2]) have introduced a significant amount of technological hype by offering the ability to augment a user's real-world vision field with contextual information. These technologies, apart from some technical limitations, have the potential to be applicable in many different areas since they can move domain-specific visualizations from the computer screen to the real world. This paper presents a novel methodology for visualizing process related SCADA data to enhance and facilitate human-centric activities in substations such as regular equipment maintenance. The proposed solution utilizes AR visualization techniques together with standards-based communication protocols used in substations.

Research of human-centric industrial automation AR applications has been addressed by several research projects and activities. Tamaazousti et al. propose a solution to real-time augmentation of a 3D object by using a framework called Constrained SLAM (Simultaneous Localization And Mapping) [3]. They also created an intractable prototype application for training and education of the industrial automation field workers. S. Kim et al. tried to enhance sensory driven actions like driving a car with AR and Haptic technologies [4]. They concluded that technology-controlled sensory augmentation could impact human perception and improve the execution of those actions but depending on the targeted population and the amount of augmentation, can have negative effects like overloading the user with too much information. Sebillo et al. have used AR technologies to improve training of workers in the emergency domains [5]. Emergency domains have certainly benefited from the usage of information technologies regarding improving the emergency control processes by providing tools which support decision making in critical situations. The problem which arises is the fact that these critical situations cause stress and lower the ability to use these crisis systems especially if the workers are not familiar with them. The authors have proposed a solution to this problem by providing an AR-based training system which uses mobile technology to virtually offer two visualization techniques which train the users with visual metaphors.

Majority of AR/MR applications are not focused on a specific industry, therefore, exploring generic solutions in data visualization. However, each application domain introduces a new set of requirements with specific prerequisites. Considering the application of AR in the industry, Constanza et al. have researched its ways to use AR in the manufacturing and remote collaboration [6]. Tang et al. found that AR aided assembly tasks were improved by a significant amount when contrasting them with regular tasks processes being executed alongside manuals [7]. Ferrarini and Dede explain that virtual 3D visualization is a good way to model manufacturing systems and since these systems are usually used for supervision, control and maintenance they fall in the category of SCADA systems [8]. Soete et al. have created a functional AR monitoring application which uses a static camera, AR markers, OpenCV (Open Source Computer Vision Library, an open source computer vision and machine learning library) technology and computer vision techniques to provide enhancement of traditional SCADA functionalities [9]. They proved that AR and MR could, in fact, be used very efficiently in the monitoring domain of SCADA systems. Their concerns were the impracticality of hardware and software equipment they used stating that exporting similar functionalities to smaller devices like smartphones and tablets or even head worn equipment would significantly improve results. Also, improving the software by making it easier and more optimized would also offer enhancements to their concepts.

Applying state-of-the-art technologies in traditionally conservative power system automation domain is one of the Smart Grid pillars as already shown for the next-generation SCADA systems [10] and equipment monitoring [11,12]. This paper presents a novel methodology for visualizing process related SCADA data to enhance and facilitate human-centric activities in substations such as regular equipment maintenance. The proposed solution utilizes AR visualization techniques together with standards-based communication protocols used in substations and other power systems automation domains [13]. The developed proof-of-concept AR application enables displaying SCADA data on the corresponding substation equipment with the help of AR markers demonstrates originality and benefits of the proposed visualization method. The visualized SCADA data needs to be refreshed considering soft real-time data delivery restrictions. Therefore, the proposed solution is thoroughly tested to demonstrate the applicability of proposed methodology in real substations. The results have shown that the developed applications can be used to apply AR almost anywhere in a SCADA monitored system, removing the need for static hardware like a camera and that the applications can not only enhance monitoring but control and maintenance procedures. Faster and more user-friendly tools for development of these applications can be used nowadays, thus making the creation and maintenance process of the applications quicker and less error-prone.

2. Augmented Reality Applied in Industrial Systems

By using dedicated monitoring and control computers that allow full or partial automation of complex operations and can aid in making manual control more safe and accurate, automation and continuous feedback are made possible and industrial machines have become advanced tools [14]. With the readily available real-time information and the ability to control many parameters through computer interfaces, automation enables an operator to monitor multiple machines at the same time, reducing the number of staff for a machine pool. Nevertheless, many vital operations cannot be fully automated and operators may need to simultaneously monitor numerous quickly changing parameters while visually following and interactively controlling components of the ongoing procedure.

AR technologies have matured enough to be used in distinct industrial automation environments and successfully applied in manufacturing [14], smart building management [15], automotive and aerospace industries [16]. AR technologies are used in in substation environments in [17,18]. Nevertheless, AR is used for simulation and training purposes in both articles and none of the already mentioned articles deals with process related SCADA information used for substation maintenance purposes as proposed in this paper.

3. Augmented Reality and the IEC 61850 Standard

Frequently considered as just another remote control protocol for electric utilities, IEC 61850 [19] is more than a set of rules and encodings for information retrieval from field instruments as it determines automation architecture conditions for utility subsystems to implement communication and semantic interoperability among multi-vendor equipment. Even though it was primarily developed for substations [9,20], IEC 61850 has now been broadened for the wind power plant domain [21], Distributed Energy Resources (DERs) [22] and hydroelectric power plants [23]. This paper is based on analyzing the implemented IEC 61850 stack developed by Končar-Power Plant and Electric Traction Engineering Inc., Fallerovo 22, 10000 Zagreb, Croatia for its SCADA system PROZA NET v3.4.

3.1. IEC 61850 Standard

3.1.1. The Data Model

IEC 61850 offers data semantics which is closely linked to device functionalities in utility subsystems such as DERs [22]. Data models [24] defined by IEC 61850 use object-oriented modelling of relevant process automation data. Figure 1 shows connections between IEC 61850 data model classes. A physical device, i.e., a device controller, is represented by the highest parent class, the Server. The top parent class, the Server, is comprised of one or more Logical Devices (LD), which are virtual representations of devices used for control, protection and supervision of automated systems. Piecing together several Logical Nodes (LN) representing many different device functionalities creates an LD. LNs represent a vital component of IEC 61850 data semantics. More about the IEC 61850 data model can be read in

3.1.2. Exchange of Data

IEC 61850 introduced a new paradigm to describe data exchange procedures in subsystems of the utility industry (substations) called Abstract Communication Service Interface (ACSI) [24]. ACSI model classes define horizontal and vertical communication abstract information services used by IEC 61850 devices. The ACSI paradigm should not be considered a protocol but a method to link application layer protocols like MMS (Manufacturing Message Specification, an international ISO 9506 standard for transferring real time process data and supervisory control information between networked devices or computer applications) to IEC 61850 generic services [25].

Any IEC 61850 client software can fully exploit their remote control by utilizing ACSI model classes as standardized interfaces to IEC 61860 server enabled devices. Several authors have analysed

IEC 61850 data exchange with the help of network simulation environment such as OPNET [26–28]. However, this paper is based on testing in laboratory setup with real-world equipment. [24].

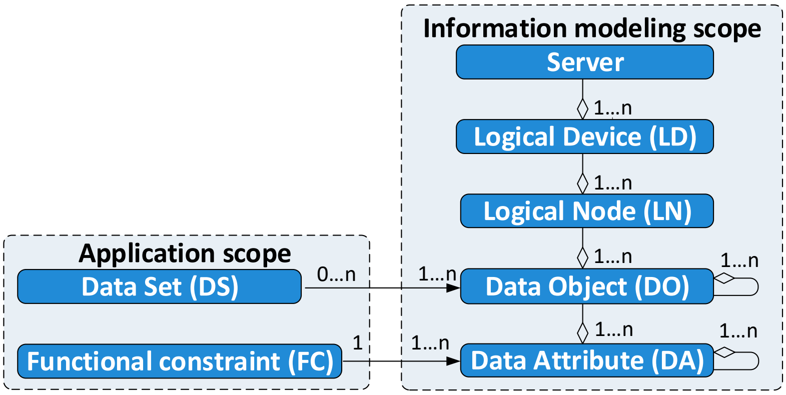

Figure 1. IEC 61850 data class model.

3.1.3. Management of IEC 61850 Systems

The exchange of XML documents formatted according to the System Configuration description Language (SCL) [29] is the basis of the engineering process for IEC 61850 systems. Depending on if they describe equipment or the integrated system itself, there can be distinguished several SCL document types. Communication system and electric network topology are predefined while the engineering process based on SCL document exchange is somewhat static and most commonly applied in substation automation systems.

3.2. Augmented Reality

AR is a computer science technology that visually alters real-world environments with virtual elements [16]. Finding best ways to apply AR in the energy industry will only be possible after a thorough analysis of AR and its capabilities. Main features of AR are as follows:

- By using a tracking system, it is possible to track the user's view and location.
- Virtual objects are placed into the view of the real world.
- Virtual objects placed into the real world are of correct position, orientation and scale each frame.
- It is possible to render both virtual objects and the real-world view in real time.

The need to use advanced visualization techniques in substation automation environments is visible while observing computers whose primary task is to control and monitor processes. The amount of information shown is considerable and it can be safely assumed that in time this amount will keep increasing due to the growth of the systems' size and complexity. It is of vital importance that only relevant information is shown so that the operators are not unnecessarily burdened with extra data.

Control computers display process data on a computer screen and also use the conventional input mechanisms like a keyboard or touch screens. Typical procedures often demand the operator to watch the process through a machine's safety glass and at the same time operate a computer to control the process and to receive automation feedback. This type of workflow creates the problem of splitting the attention of the operator when the need arises to simultaneously observe the computer screen for keeping track of automation values and to visually watch the process. Placing displays next to the machine can partly address this issue but it inherently separates the process from its automation data [14].

This paper research objective is to offer a solution of seamlessly integrating automation data into the workspace beyond the safety glass using features of AR technology. AR technology enables the use of computer-generated interactive virtual objects with real physical environments including industrial environments. The technology is very applicable in immediate attention demanding industrial machines because it allows easy to follow representation of relevant process information in real time at the spot where it would be needed the most.

Some examples where the option of annotating real-world procedures with real-time process automation data would be useful are as follows. Emphasizing locations of an industrial environment to a student or a co-worker. It would also be beneficial to annotate some aspects of the workplace with virtual information such as showing virtual labels with the type of machine, its current state of operation and any relevant information about its current job. Virtual visual warnings can show whenever any dangers with the ongoing activity are noticed. Virtual simulations of machine processes could also increase safety through learning essential methods before actually attempting them in real environments.

To get the best possible results from combining computer graphics with real environments, the execution of using AR needs to be seamless and without encumbering tools. Looking at the history of Virtual Reality (VR) and AR systems head-mounted displays (HMD) [14] which require complex tracking and large tools to be worn [30]. One such modern example is the Oculus Rift [31]. Video see-through systems have gone up in popularity recently because software libraries and products such as ARToolkit [32] (a cross-platform SDK for developing augmented reality applications) and the more modern Vuforia [33] have enabled rapid and easy prototype implementation. Spatial AR systems have been in research for some time now, for example, the ASTOR system [34] (a spatial augmented reality system developed by Alex Olwal et al.). Major AR systems today have developed into marker-based applications, meaning that they use AR markers to show virtual information and track real-world points of interest. This paper explores a fusion of markers, specifically Quick Response (QR) codes [35] and Vuforia frame markers [33] to create a new type of AR marker used in the first prototype application built as part of this research. Later versions of the application use Vumarks [36], a different type of Vuforia markers to achieve similar results.

3.2.1. AR Markers

Although there are many types of AR markers suitable for certain situations, the QR code, a 2D matrix barcode developed by Denso Wave Corporation in 1994 [35,37], name abbreviated from Quick Response (QR) Code, is used a more frequently than its adversaries.

Fusion Markers

Despite being able to encode up to 7089 numeric and 4296 alphanumeric characters, a QR code can be read by a simple smartphone or PC application with camera access that is a significant advantage over other 2D barcodes that require special scanners for decoding. It can also be generated by using one of the many free online tools or the Python qrcode library [38].

Another, much more sophisticated, option for markers are markers available in the library called Vuforia [33]. There are a couple of different marker types in Vuforia, mainly frame markers, image targets and Vumarks [36]. When the first version of the AR application prototype was in development, Vumarks were not available, so a combination of Vuforia frame markers and QR code markers was used. The goal was to use Vuforia frame markers for fast detection and QR code markers for encoding information inside the marker.

The first AR application prototype used QR codes inside Vuforia frame markers. Figure 2 shows a Vuforia frame marker, while Figure 3 shows a QR code marker. Since almost all AR markers including Vuforia frame markers do not encode data, they need to be preregistered. That means that each marker's function needs to be a priori decided. Encoding data inside a marker eliminates this step. That is why using QR codes is more optimal than other markers. A significant problem with QR codes is that QR code detection is slow. That is why we put them inside fast detectable Vuforia frame markers like in Figure 4.

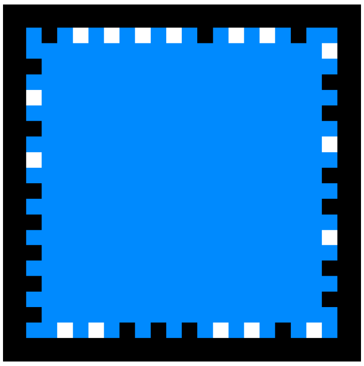

Figure 2. Vuforia frame marker.

Figure 3. Quick Response (QR) marker with its decoding features highlighted.

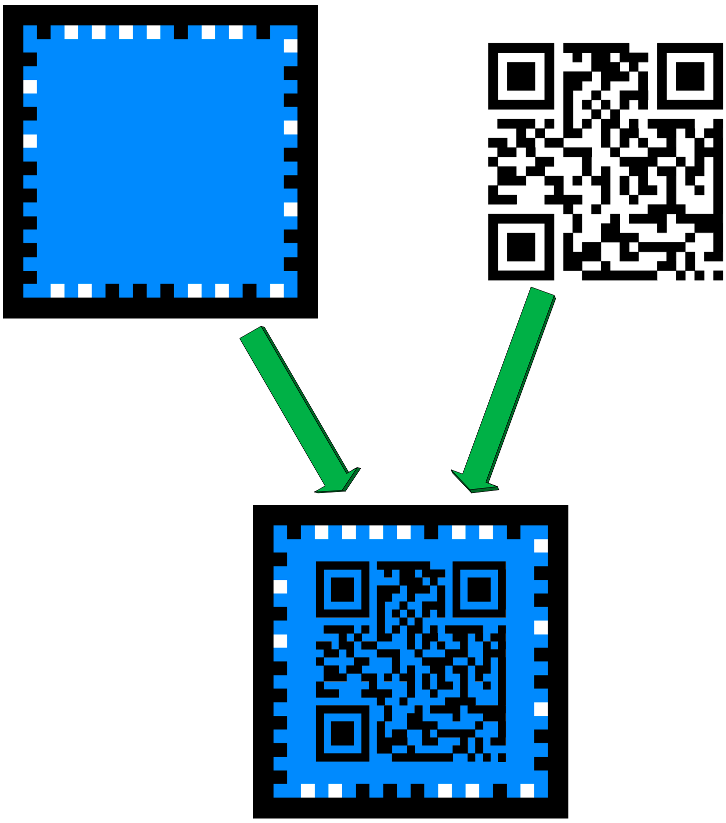

Figure 4. Vuforia frame and QR marker fusion.

Figure 3 shows an example of a QR code with its parts highlighted. The most important parts of the QR code are three large squares, containing smaller black squares with a white border, located in three corners of the code that are used to determine the position of the code. Version 2 (and above) added a square used to align the code after detection and the rest of the code is used to write a considerable number of small squares that encrypt the information in the marker.

Another asset of this form is the ability to reconstruct the code despite it being damaged or missing which is crucial when scanning with a camera as the lens will never be positioned perfectly thus omitting parts of the code. As seen in Table 1, higher correction levels result in allowing excluding more of the code in exchange for increased code size [27]. Table 2 [27] presents dominance of the QR code over other fiducial markers. Everything stated above advocates using QR codes in the substation automation AR application prototype.

Table 1. QR marker error correction levels [27].

Level	Percentage of Codewords That Can be Restored (Approximation)
L	7%
M	15%
H	25%
Q	30%

Table 2. Feature comparison of QR markers with other fiducial markers [27].

Feature	QR Code	Fiducial Marker
Need to pre-register	No	Yes
Model storing	Internet	Local
Limited number of markers	Larger	Smaller
Universality	Universal barcode	Standalone

Vumarks

In August 2016, Vuforia released a new type of marker called a VuMark [36]. This marker retained the fast detection that other Vuforia markers had and it enabled data to be encoded inside the marker. That is precisely why fusion of QR and frame markers were used in the first prototype, so a transition to this new type of marker was apparent. Not only does it encode text data like a QR code but a Vumark can also encode unique identifiers, strings and bytes making it more flexible than a QR code marker. It is constructed in vector graphics designer tools (specifically Adobe Illustrator [39]) and can be made visually very appealing as seen in Figure 5. The only downside to a Vumark is that the number of characters it encodes when you choose to encode a string is maximum 100 that is much less than a QR code. However, for proposed AR application needs, 100 characters are sufficient. A Vumark's most essential components are shown in Figure 6.

The tests conducted in this research showed excellent detection and instantaneous decoding capabilities of the Vuforia library when using VuMarks. As soon as the Vuforia library detects the marker, it also manages to decode the ID inside the marker processing the same frame in which the marker was detected. High-quality cameras enable detection under very unfavourable conditions, for example, a distance of a couple of meters from the marker or a high angle in regard to the marker—30 and even fewer degrees). That means that decoding is instantaneous and this fact sets Vumarks as the most superior AR markers as long as the code is of smaller length (ASCII 100 or fewer characters, 1000 numbers or 100 bytes).

Figure 5. Examples of previously created Vumarks.

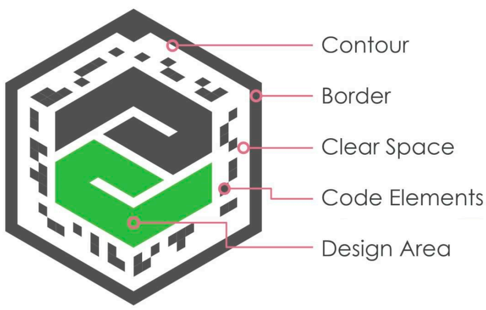

Figure 6. A Vumark with its decoding features highlighted.

4. Augmented Reality IEC 61850 Application

Development of the IEC 61850 AR application uses vertical IEC 61850 communication while also utilizing SCL data engineering and AR marker encodings to identify components of substation automation equipment abiding the rules of IEC 61850 data semantics.

Information about semantically annotated process data is provided by the contents of the SCL files. The information is then correlated with decoded data found in AR markers that were put on substation equipment (circuit breakers, feeders, transformers, switches, etc.). Using the software that recognizes AR markers in an image and decodes the contents written in the markers as AR projector draws virtual information on the smartphone screen of a maintenance engineer. By using this workflow, process information is placed overlaying substation equipment it relates to, directly connecting components with their corresponding process data in real time fetched through a SCADA system. It is clear that by integrating AR into substation environment, its maintenance activities will be simplified and will enable unambiguous identification of components while presenting real-time measurements data, thus easing substation monitoring.

4.1. Architecture

There were a few iterations of the AR application prototype. The most important two are the first and second major versions that were developed for the Android platform using the Java programming language. The first iteration uses Vuforia frame marker and QR code fusion and it shows promising results for marker-based AR process data visualization. The second major iteration was made with the Unity game engine framework [40] and it is also utilizing Vuforia libraries but with different markers called VuMarks. Since it was developed with Unity, it can be built for a variety of platforms including PC, Mac, Linux, Android, iOS and a few others and the application is functional as long as the platform has access to a camera.

The architecture of the application is comprised of several parts. A device's camera scans a marker and decodes it into a process data identifier based on IEC 61850. The identifier uniquely represents the path to the semantically annotated process data compliant to the IEC 61850 standard. Then, the acquired data is correlated with process data from the SCADA system and the SCADA itself is responsible for fetching its data from its internal database. Intelligent Electronic Devices (IED) are then contacted by the SCADA system to gather this data via vertical IEC 61850 communication. Figure 7 shows the application architecture.

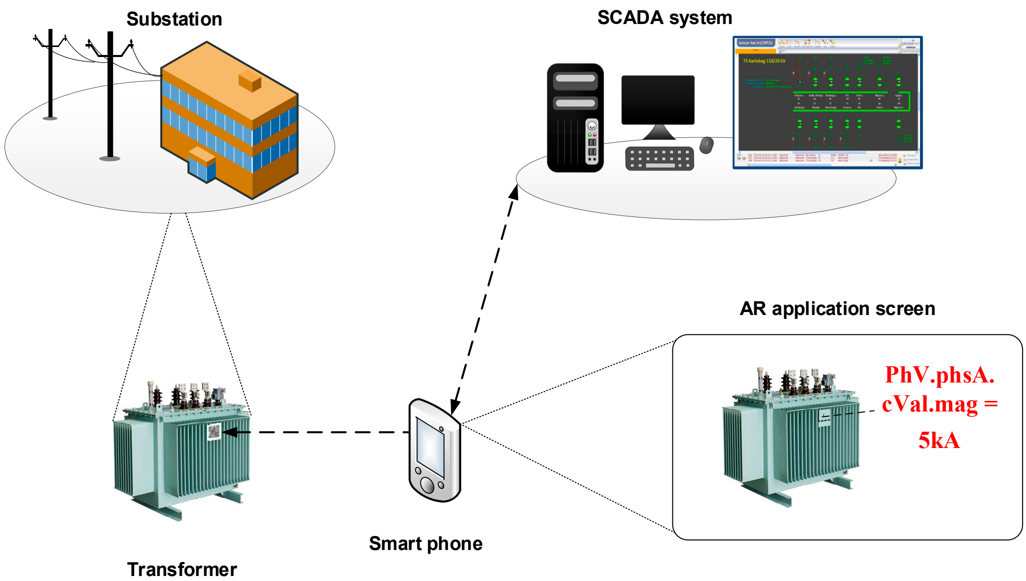

Figure 7. AR IEC 61850 application architecture.

4.2. Implementation

Application implementation includes several steps. The prerequisite is to have a substation automation environment with a variety of equipment and some IEDs connected to a central SCADA system. The SCADA system retrieves data in real time from IEDs via vertical IEC 61850 communication which is the most critical prerequisite for AR application implementation.

Markers need to be printed (Figure 8 shows one example of a Vumark with IEC 61850 encoded data) and positioned on substation equipment to enrich it with AR visualization of process data related to that piece of equipment. Markers have their corresponding IEC 61850 identifiers encoded which describe the path to uniquely identified process data according to the IEC 61850 standard. The identifiers correspond to process data of substation equipment and they are positioned on. Vumarks that are created using Adobe Illustrator and the Vuforia official website [33,36,39]. A portable device with a camera is needed (in this paper an Android device Samsung Galaxy Tab A 2016 was used) where the AR application was previously installed. Third, the substation environment needs to have Wi-Fi access to its internal network where a commercial SCADA system is connected and available. Integration with SCADA application is done via SCADA manufacturer provided API interface [30].

Figure 8. A Vumark encoding an IEC 61850 identifier.

The substation environment can be scanned by using a device with a camera. The application uses an instance of the Vuforia library to process each frame image from the camera. Once a marker is detected in a frame, the Vuforia library also starts processing the VuMark and decodes the string data encoded in the VuMark. This data is an IEC 61850 process data path that describes the process data path that is related to the corresponding piece of equipment. Now the application knows which information it needs to overlay over the view of the marker but it stills needs to fetch this SCADA information. It then connects via Wi-Fi to the SCADA system and once a successful connection is made, the application asks the SCADA system to fetch all information with the process data path. The SCADA system then communicates with IEDs and requests the appropriate device for the required information. Once the IED sends the data, the SCADA system forwards the data over Wi-Fi to the AR application. The application maintains its connection to the SCADA system and tasks it with sending real-time updates of changes made to the required data. Anytime information related to the process data path changes, the SCADA system will notify the AR application and the application will update the change on its display. This way a real-time display of substation IEC 61850 data is achieved.

Now that the application has the data required, it needs to display that data over the view of the marker. Earlier application versions used OpenGL ES2 [31] technology (a subset of OpenGL technology, a cross platform application programming interface for rendering 2D and 3D vector graphics) for displaying complex models. The current version uses game engine framework Unity [40]. It is a flexible system that enables all kinds of graphical models to be shown and animated. The intuitive way of displaying data is to overlay a rectangle over the marker with the data written on it like in Figure 9. Moreover, a custom texture is created with the information written on it and applied to the rectangle using OpenGL ES2. In Unity engine, a default text Object is created and overlaid over the rectangle with the information as its text. These techniques enable immediate update of the required data and show data to the operator. This method was used for the testing application.

Different helper visual effects can significantly improve the time needed to observe essential data and its changes. Figure 10 shows a pie chart next to the data. This visualization method is used whenever the data, according to the semantics of the IEC 61850 standard, represents a percentage value. It fills the chart with the corresponding percentage and keeps it updated along with the data overlaid over the marker. This approach achieves additional visual feedback, shortening the time needed to observe the information. Full video of demo application can be seen in [32].

Figure 9. A Vumark marker (**left**) and a screenshot of the camera view (**right**) while using the AR application showing IEC 61850 information.

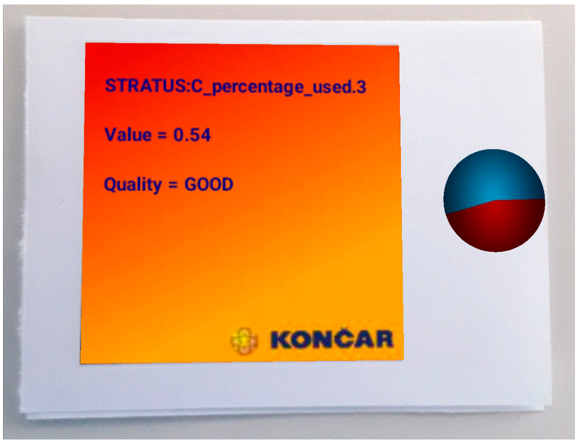

Figure 10. Screenshot of the AR application in use (the camera view) virtually showing real-time IEC 61850 percentage data (value and a pie chart).

Another example of a sophisticated visualization method is shown in Figure 11. The figure shows a model of a diesel-electric generator next to a marker. Any piece of equipment in a substation environment can be modelled this way and it is possible to highlight important parts and add information visually. Highlighting essential elements and adding IEC 61850 real-time data on a piece of equipment can be used for maintenance purposes. An operator can quickly view the data needed when going through the process of checking equipment. Animations can also be added to showcase specific maintenance procedures and for learning purposes. For example, every inexperienced operator needs to go through a learning process to be able to handle different equipment in a substation environment. These animated models can then be used as a quick and visual way of enhancing the education process.

Figure 11. Screenshot of the AR application in use (the camera view) virtually showing real-time IEC 61850 temperature data with the model of its corresponding object—a diesel-electric generator.

4.3. Prototype Evaluation

A detailed model of a substation was also developed which is displayed whenever the camera sees a marker with a specific ID encoded. This model can be seen in Figure 12. After the model is shown, the user can zoom in and out and rotate it in any direction they prefer to get a better view of the substation. IEC 61850 real-time information was also added to the model, highlighting parts of the equipment that the chosen data semantics relate to. This feature can be useful when the user needs to get a general overview of the entire substation with the possibility of monitoring certain parts of the substation and micromanaging them. It can also be used to control the whole substation remotely.

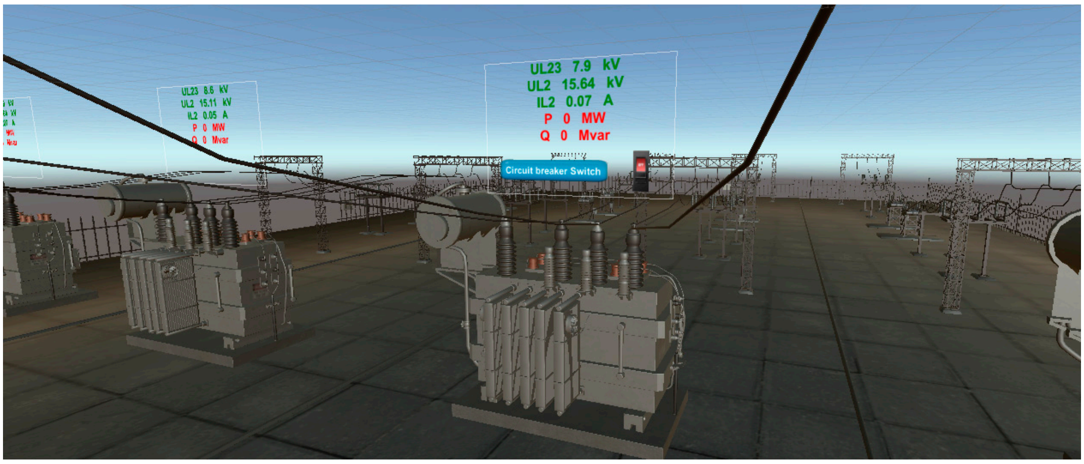

Figure 12. Model of a substation containing four transformers with their IEC 61850 data annotated over the transformers.

Employing the developed application prototype in a real-world substation is the footing of the assessment. The first results demonstrate that VuMarks, with immediate decoding results and QR codes, although slower than VuMarks, combined with Vuforia frame markers display an excellent choice as markers for IEC 61850 data semantics.

The application has evolved since the first prototype version and its usage of IEC 61850 real-time data has also changed from just showing data as text to using graphical models with annotated data. Using the semantics of IEC 61850 data, it is possible to get any information from the SCADA systems inside substations. The visual aspect of the application has also been changed. From ARToolkit's standard markers to Vuforia frame markers combined with QR codes, to VuMarks as the fastest detectable markers with the ability to encode different types of data. The graphics were done using the OpenGL ES2 technology explicitly targeting the Android platform [33]. The current version draws graphics using the game engine framework Unity which is then also used to port the application to different platforms.

5. Augmented Reality and Real-Time Communication

By definition, real-time computing (RTC), or reactive computing describes hardware and software systems subject to a "real-time constraint", for example from event to system response. Real-time programs must guarantee a response within specified time constraints [30]. The real-time system is one which sends updates to clients as soon as they happen and can be said to be real-time constrained by a certain (usually relatively short) period called the "deadline". That means that as soon as a change happens, the client is guaranteed to receive the update notification at the end of the deadline period that starts when the change occurred.

In presented research, the tests measured the time needed for AR application prototypes to receive an update of a data change in the SCADA system. Two experiments were done; the first is SCADA response time when transferring data over a 100 MBit local Virtual Private Network (VPN) and the second is the same response time using the 4G mobile Internet as a network mediator. Both tests measured SCADA change response times by changing a data instance 1000 times. The graph shown in Figure 13 shows results from both of these tests.

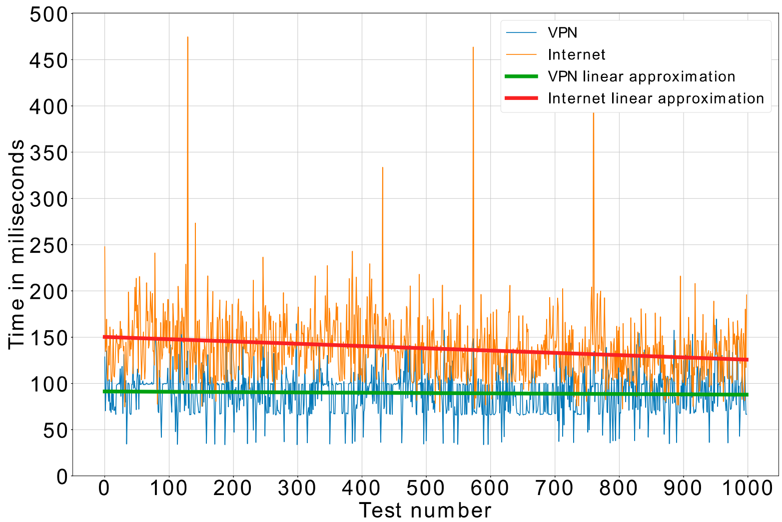

Figure 13. SCADA response time test results using local VPN and the 4G mobile Internet.

The vertical axis of the graph represents the time needed to receive a change that happened in the SCADA system. As can be observed in Figure 13, this period spans from 0 ms to 500 ms. The horizontal axis represents ordinal numbers of data changes in the current test. There are several graphs plotted on Figure 13; the blue graph represents the test over the local network and the orange over the 4G mobile Internet. Median graphs represent linear and quadratic approximations of the two main ones and serve as a means to simplify and eliminate peaks which happen in the orange and blue graphs.

As expected, using a local VPN is much faster than using the 4G mobile Internet and peaks happen far less frequently than over the Internet. The worst response time using a local VPN was 169 ms. The best response time over a local VPN was approximately 34 ms and means that changes will always be received in the period between 34 ms and 169 ms after the change physically occurs. Analysis of the Internet response times shows that the worst response time 478 ms and the best one is 69 ms. Comparison of the two best-worst case scenario periods shows that the 4G mobile Internet response times can be more than twice as long as local network times what is the result of uncontrollable 4G mobile Internet network availability. Approximation graphs comparison shows that local VPN response times are usually around 92 ms on average, while 4G mobile Internet response times are approximately 136 ms.

Figure 14 shows the tests histograms. The histogram shows test times in ms on its x-axis and the number of test queries on the y-axis. It is readily observable that using a local VPN 652 out of 1000 test queries were achieved in 50 ms to 100 ms, 287 queries took 100 ms to 150 ms and only 10 took 150 ms to 200 ms. On the 4G Internet network, just 52 queries took 50 ms to 100 ms, 663 queries took 100 ms to 150 ms, 252 took 160 ms to 200 ms, 27 took 200 ms to 250 ms, 1 took 250 ms to 300 ms, 1 also took 300 ms to 350 ms and the worst 3 took 450 to 500 ms.

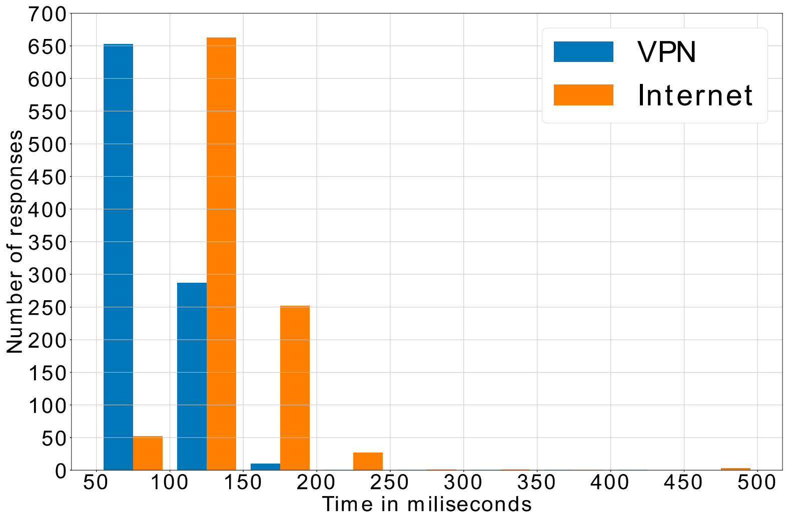

Figure 14. SCADA response time histogram test results using local VPN and the 4G mobile Internet.

The last graph on Figure 15 shows a boxplot of the same results. On the x-axis, the time in ms is plotted but the vertical axis does not serve the same function as on the other graphs. The upper box shows quartiles of Internet response times and the lower one shows the same for a local VPN network. The median is shown with a yellow vertical line. It can now be observed that the median of private network response time is 92 ms and the median of 4G mobile Internet response time is 136 ms. Outlier values are also clearly visible for both tests with maximum values corresponding to maximum values in Figure 14. The lower quartile of local VPN response time is 70 ms, while the upper quartile is 101 ms. The lower quartile 4G mobile Internet response time is 112 ms, while the upper quartile is 154 ms. This information means that 50% of response times with a local VPN network are in between 70 ms and 101 ms and that 50% of response times with 4G mobile Internet is in between 112 ms and 154 ms.

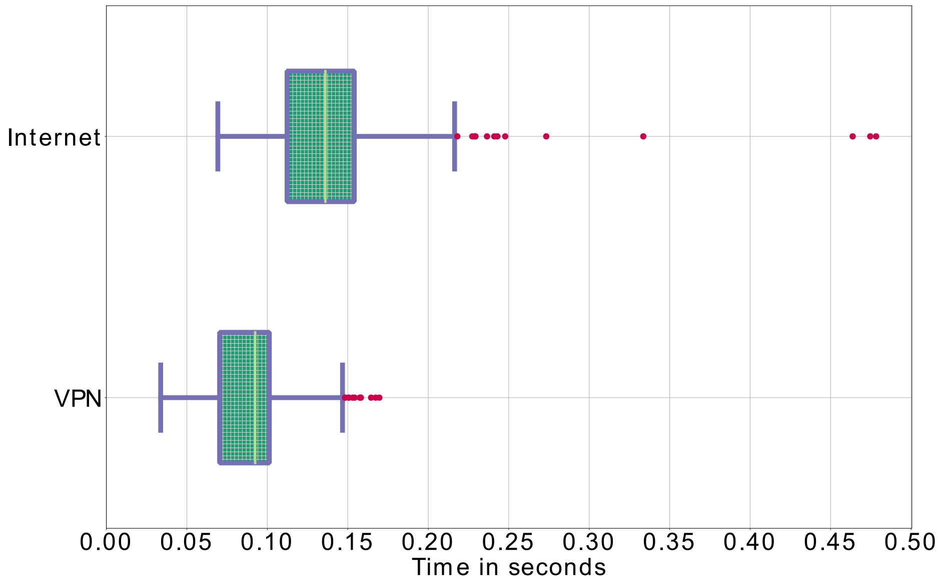

Figure 15. SCADA response time boxplot test results using local VPN and the 4G mobile Internet.

6. Conclusions

This paper presents a novel approach in visualizing process related SCADA data to enhance and facilitate supervision, control and human-centric maintenance activities in power system substations. The proposed solution utilizes AR visualization techniques together with standards-based communication defined by IEC 61850. The developed proof-of-concept AR prototype application was tested in KONČAR's (Končar-Power Plant and Electric Traction Engineering Inc., Fallerovo 22, 10000 Zagreb, Croatia) in-house research laboratories and a real-world substation environment. The application enables visualization of automation data anywhere where it is relevant by combining standards-based communication to fetch real-time SCADA information and show it near its corresponding equipment. It also enables using full 3D equipment models along with helpful animated widgets to quicken the interaction with the user. Maintenance engineers that participated in application testing were able to execute their common procedures significantly faster and requiring less effort confirming the usefulness of the applications. The solution is also tested regarding the real-time SCADA response requirements. The mean response times for fetching data are 92 ms over a local Virtual Private Network (VPN) and 136 ms over the 4G mobile Internet. Future work will be based on developing a software platform capable of making maintenance activities in substation environments more accessible by providing an adaptable workflow procedure to increase user satisfaction. Since the proposed solution is based on IEC 61850 standard, any domain that uses such communication, including centralized generation, wind power plants, DERs or battery systems could be easily integrated into the future versions of the application.

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