Virtual Reality Digital Twin for a Smart Factory

Gicu-Călin Deac, Crina-Narcisa Georgescu, Cicerone Laurentiu Popa, and Costel Emil Cotet

Abstract—**This paper describes authors' research in developing collaborative virtual reality applications as an interface for monitoring big data by creating a digital twin of the factory and sync the movement of virtual machines with the real ones. The platform allows an interactive reading of the sensor telemetry and processes data, maintenance information and access to a large technical library. For data acquisition and reports, a novel image data method was used. The data values that are encoded as pixel colors of images, using different encoding methods for each data type (text, integer, float, Boolean) are also encrypted using an image as a symmetric encryption key and are stored in the cloud in a time base folder structure, assuring a better data compression, security and speed, compared with the existing solutions based on JSON and NoSQL databases. The platform allows the remote access from the VR environment to the machines consoles and allows parametrization and remote commands.**

Index Terms—**Virtual reality, smart factory, digital twin, big data, Industry 4.0 .**

I. INTRODUCTION

Advancement in information technology has given rise to explosion of data in every field of operations and we are seeing an ascending trend of digitalization in all activities. Emerging technologies like Internet of Things (IoT) [1]–[3], big data [4], cloud computing [7]–[9], artificial intelligence, wireless sensor networks [5, 6], embedded system [10], and mobile Internet [11]) are being introduced into the manufacturing environment. A strategic initiative called "Industrie 4.0" was proposed and was adopted by the German government [12], as part of the "High-Tech Strategy 2020 Action Plan". The similar strategies were also proposed worldwide, for example, "Industrial Internet" [13] from USA and "Internet PLUS" [14] from China. The Industry 4.0 describes a production oriented Cyber-Physical Systems (CPS) [15]–[17] that integrate production facilities, warehousing systems, logistics, and even social requirements to establish the global value creation networks [18], which means that industrial machines have sophisticated communication and smart capabilities.

Industrial Internet-of-Things (IIoT) is a term used to refer to IoT applications in the industrial context and involves the use of sensors and actuators, control systems, M2M (from machine to machine communications), cloud storage of Big Data, data analysis and security mechanisms [20].

The main features of Industry 4.0 include horizontal integration through value networks to facilitate inter-corporation collaboration, a vertical integration of hierarchical subsystems inside a factory to create flexible and reconfigurable manufacturing system, and end-to-end engineering integration across the entire value chain to support product customization.

The smart factory is an implementation of Cyber-Physical Systems that is based on the extensive integration of information technologies to manufacturing.

A smart factory framework consists in four tangible layers, namely, physical resource layer, industrial network layer, cloud layer, and supervision and control terminal layer. The physical resources are implemented as smart things which can communicate with each other through the industrial network. Various information systems like Enterprise Resource Planning ERP, Client Relationship Management (CRM), Business Intelligence (BI), Predictive Maintenance (PM) exist in the cloud which can collect massive data from the physical resource layer and interact with people through the web or through the applications terminals. Thus, the tangible framework enables a networked world for intangible information to flow freely. This forms a CPS where physical artifacts and informational entities are deeply integrated. [19].

In the implementation of a control system, according to I. Gonzales et al. the key factor is the interconnection between sensors, controllers, tools, and cloud services, through a secure communications network.

Monitoring, tracking and automation of technological processes for both industrial and non-industrial settings requires efficient transmission of information through communications networks [20] Wired or wireless channels are used to communicate data. Due to mobility and flexibility, wireless communication has great advantages and will be widely used in Internet-of-Things (IoT). Various wireless protocols such as Wi-Fi, Bluetooth, ZigBee, 3G / 4G / 5G, RFID, Z-Wave, IPV6 over personal area networks with low power (6LoWPAN) and Near Field Communication (NFC) are available [20].

Devices are linked over the network to detect, monitor, and act on physical components in the real world. To simplify and optimize this large-scale integration, proprietary protocols and new evolving communication protocols must converge on a prevalent protocol platform [21]. One of the present existing protocols for industrial communication is OPC-UA, a protocol that has been standardized in the IEC 62541 series. OPC UA is an open and secure platform that allows vendor-neutral programmable logic controllers (PLCs) to communicate with each other and up to the manufacturing level and into the production planning or ERP system [22].

Material handling and transportation plays a fundamental role in logistics success and these workflows are needed to be turbo-charged with Autonomous Mobile Robots (AMRs). There are already few AMR solutions developed by companies like Kiva (which was acquired by the Amazon in 2012), Seegrid, Swisslog, Grenzebach and few startups like: Iam Robotics, Locus Robotics, 6River Systems, Fetch Robotics, Magazino, Grey Orange and InVia Robotics. Most

of this AMR are using laser scanning or 3d cameras to navigate and assist the workers and barcode scanning or radio frequency identification (RFID) tags to read the packages content or to identify the shelves. The AMR have also integrated GPS and accelerometers to send in real time their position, speed, and accelerations. Some of the producers, like Seegrid are providing complete fleet management software to maximize the operational efficiency of the fleet.

This tremendous amount of data generated from sensors, actuators, camera enabled devices, machines, processes, RFID's, AMR's, industrial robots, and humans, need to be accumulated in order to be processed, and this led to the concept of Big Data.

Chan (2013) identifies the nature, characteristics and potential applications of Big Data and proposed an architecture for Big Data analytics, based on a client-server protocol. In the client side, Chan proposes an architecture that consists of NoSQL databases, distributed file systems and a distributed processing framework. The NoSQL database is a non-relational data base, but it stores records in key-value pairs and work very efficiently with unrelated data. NoSQL databases are highly scalable that makes these databases ideal for Big Data applications. The server architecture consists of multiple parallel computing platforms that can handle large volume of data to be processed at an extremely fast rate. Hadoop architecture includes client machines and a cluster of loosely coupled servers that serve as HDFS and MapReduce data processing core. The client machines load input data into the cluster, submit MapReduce processing jobs, and retrieve the processed output from the server cluster when the processing is complete.

Another challenge is made by the Big Data visualization. There are few cloud-based platforms that allows historical and real time data visualization, but using tabular data or graphs is not all the time the best way of seeing how a digital twin is performing.

In their research: "The Factory of the Future Production" Milan Gregor and all, have imagined a virtual platform called ZIMS (Zilina Intelligent Manufacturing System) where the processes and simulations can be visualized using Virtual Reality.

II. THE 8 AGORA PLATFORM

The present paper proposes a Virtual Reality platform for collaborative working which is able to collect, process and display in real time how a Smart Factory perform, by creating a Digital Twin of it and synchronize all the machines, AMR's, robots, production lines and warehouses created in 3D with the real ones. Using this approach become possible by using HMD's (head mounted displays) to be immersed with other remote users in a virtual factory and see all the processes, how the machines are performing, to see real time telemetry data, information about maintenance, access a large library of technical documentation and even be able to remotely access the machines, configure the parameters and start / stop the processes.

Was developed a Virtual Reality server-client multi-user platform as an immersive interface that allows development by exposing a large API through JavaScript and QML (QT modelling language). The 3D environment can be created by importing 3D models with PBR (physically based rendering)

materials in FBX open format. The 3D objects can have all the textures embedded, or externally linked and could include animations which are easily triggered by scripting. The frame rate of the animations can be changed accordingly with the speed of real machines.
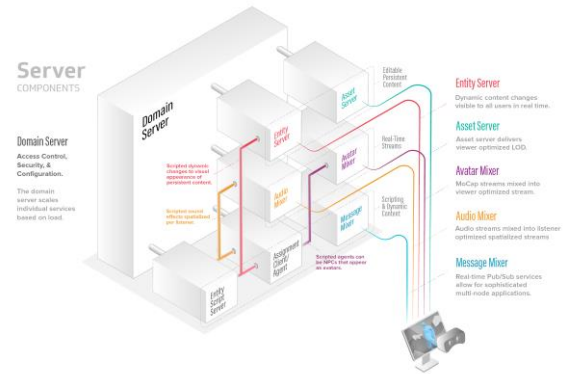

Fig. 1. 8 agora server components.

8agora engine provide live audio communication and include a server-side (Fig. 1) audio mixer that compute the attenuation based on the distance between user's avatars and spatial surround panning based on angular position of the user user avatar, providing a very realistic and immersive communication between users. The engine also allows the use of customizable 3D avatars and includes a powerful physics simulation system for avatar movement and object interaction. Based on HTC Vive or Oculus Rift trackers, or by using a Leap Motion controller, all the joints motions of the user are reflected in real time to the avatar and are also broadcasted to the other users, using an avatar mixer server-side process. In this way all the user movements are shown in real time by all the participants of the simulation.

To enhance the nonverbal communication and body language, the engine includes an advanced automated animation system and a gesture interface for the users which are using the platform without HMD and hand controllers, in desktop mode. By shaking hands, users can exchange contact information, all contacts being displayed in a contact list application. Using this contact list application, all your contacts and friends can be displayed with their status, online or offline and by a simple click on their names you can see their location and have the option to follow them.

8agora engine also allows the access of web content inside a web entity, which is a chromium-based web browser. Using this option, to display web content in 3D environment, can be developed a wide array of applications to extend the functionality of the platform.

The implementation of Digital Twin based on this platform consists of the following modules: data acquisition, data storage, animation driver, remote control, and digital library.

1) The data acquisition module is based on few OPC UA client applications that will read all the values from the OPC UA servers, on timed cycles with a predefined frequency (each second for example) and use a novel method for encoding and encrypting of data and automatic uploading in the cloud.

The method consists in creating full-color images (16 million colors) whose pixels are generated based on numerical or alphanumeric values to be stored.

The color of each pixel can be defined by the

three-component R, G, and B with values between 0 and 255, respectively 0 and FF in hexadecimal. The image size can be defined according to the number of values to be archived and their type. Each variable type has a predefined encoding method, being easy to store Booleans, integers, floats, or varchars. On the generation process is used a symmetric key consisting in a random generated image, and the color pixels are augmented based on corresponded pixel in the image key. Without the encryption key it is impossible to decode the stored values. Also, the LZW nondestructive compression of the PNG (portable network graphics) format used to save the images ensure a good data storage, the resulted PNG images being 10-15 times smaller than the widely used JSON (JavaScript open notation) format. This compression of the data assures an increased speed on data transmission and a small traffic over the network [29], [30]. The generated files are named using this model:

deviceUniqueID_timestampInMiliseconds.png
example: a1a5_1495270124340.png

The Data Storage module is based on the same method used for data transmission (PNG images). The images are stored on the cloud on an arborescent folder structure, generated based on timestamp by exploding the first 7 characters and store the images inside the last subfolder (t7).

/deviceUniqueID/t1/t2/t3/t4/t5/t6/t7/deviceUniqueID_timestampInMiliseconds.png
example:

/a115/1/4/9/4/2/7/0/ k137_1495270124340.png

The reading speed of data for the historian application is not dependent on the volume of stored data. Each time when a timestamp snapshot is called, the application will read the correspondent PNG image, based on the timestamp value, and will decode using the image key the variable values. To read a specific variable is not needed to decode the entire image, but only the correspondent pixels (x, y) from that image.

The animation driver module was created to synchronize the motion of all machines, robots, AMR's, production lines products and materials (figure 2). In a factory there are a really big number of real time data that need to be captured, transmitted, analyzed, and processed in order to create the Digital Twin.

From each machine we can collect from the sensors: pressure, temperature, rotation, accelerations, vibrations, operating state, statuses, alarms, errors.

Form the AMR's accelerometers the acceleration values on X,Y,Z, GPS positioning, battery level, current task, from automated production lines even more data need to be read. This led to the impossibility to create a reliable real time animated model for the factory.

Taking this in consideration, was developed a simplified model based on triggers, and the telemetry data were used only for selective component status real time visualization. For each machine was created an accurate 3D model with different animations for each working process. The speed of animations can be adjusted to be in sync with the real machine movement.

For machines are collected this status messages:

NM – need raw material.

In this case the animation of machine is stopped.

SP.t.n - Starting process type (t), followed by the counted process execution time (n) (e.g. SP.16.20 - the machine start the process 16 with estimated execution time of 20 seconds); In this case we will load animation number 16 and we will adjust the animation frame rate so the total animation will have 20 seconds in length.

PR - have processed material and need raw material.

The animation of the machine is stopped.

EM – emergency stop

The machine animation is paused.

RM – resuming the task

In this case the animation is un-paused and continue until the last frame of that specific task sequence.

For the AMR's are collected this status messages:

AV - Idle and available to task

The AMR is stopped in the last known position.

ST.p.m.s – Starting a task to deliver raw material or product (p) to the machine (m) with estimated speed of 5 km/h (s)

BL – battery level (it is just an augmentation value)

BS – battery swap

The AMR will go from the current position to the Battery exchange stand.

ES – emergency stop

The AMR animation is paused.

RT – resuming the task

The animation is un-paused and the animation of movement of the AMR continue until it reaches his target.

For the AMR's were created animations for each individual task (serving a specific machine number), these animations and their frame rate being triggered and adjusted based on the status messages (Fig. 2).

Fig. 2. View from the virtual factory.

For the warehouse twin was used a connection to the ERP database and the current stocks and position of each component, product or raw material is read in real time.
Using an extensible library of 3D models and reading the position of each individual inventory piece, we are able to populate the shelves in the 3D simulation to be the same as in the real factory.

Were implemented in the ERP few supplemental columns for positioning: *warehouseID, shelveID, packaging, positionXY, sizeX, sizeY and sizeZ* for each inventory piece.

warehouseID – [integer] represent the ID of the warehouse, based on this the object are placed in a speciffic warehouse
shelveID – [integer] each Shelve have his own ID
packaging – [integer] for the small entities (screws, bolts etc.) we have the number of items in a container (e.g. 1000)

positionXY- [array] – relative position on the shelve (each shelve is sliced in zones on x and y, the relative position being defined by the zone number (e.g. positionXY=[3,7], means that the object will be placed on the 7 shelf starting with the third zone.

sizeX – size of the entity on x

sizeY – size of the entity on y

sizeZ – size of the entity on z

For small and packaged entities (with *packaging >1*), the *sizeX, sizeY* and sizeZ represent the container size, not the individual size. For example, in the case of a container with 100 bolts, we will keep the container on the shelf until these 100 bolts are all consumed (Fig. 3).
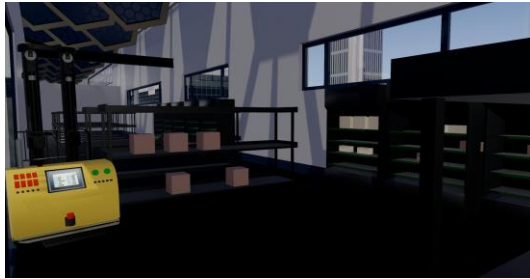

Fig. 3. Warehouse view.

Fig. 4. Outside view of the factory.

The Remote-Control module was implemented to facilitate the control of machines from the VR environment and to allow a real time view of machines, access to the control panel of machine to adjust the parameters and trigger commands.

The Remote-Control module contains these components:
- User Authentication
- Remote desktop connection to the machine
- Low latency live streaming

The user authentication module based on username / password allows the user to commute from visualization mode to command mode on the Remote panel. Each user can have remote commands access only on specific machines or processes.

The remote desktop connection module stream live the screen of the machine control panel and capture (in control mode state after authentication) the actions of the remote user on the remote screen and execute this actions on the machine control panel.

This component is developed in Node.js, using web sockets, and allows remote desktop sessions from Linux and Windows operating systems. The remote-control window is displayed in a web browser entity inside the VR platform.

This approach, using Remote Desktop connection allows an easy implementation of remote sessions for all types of machines, having a low latency (40-100 ms) (Fig. 5), much

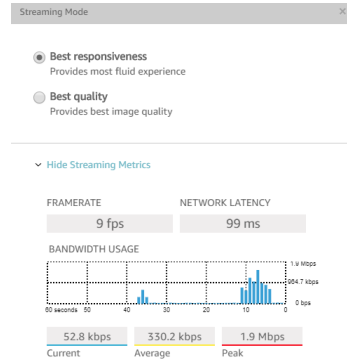better than using web services (800 ms) or CyberOPC (400 ms) [31].

Fig. 5. Streaming details for the remote desktop.

The Low Latency live streaming component use video cameras and based on a WebRTC implementation assure a remote view of the machine. This real time view from the machine is mandatory for controlling it remotely (Fig. 6).

Fig. 6. Control and live view screens.

On the 3D models of machines were implemented some hot spots, at machine component level and when an user clicks with his controller on one of this spots, he can show the telemetry data from sensors, information regarding the maintenance (can be implemented also a cloud application for predictive maintenance to see the remaining working hours for each component) (Fig. 7).

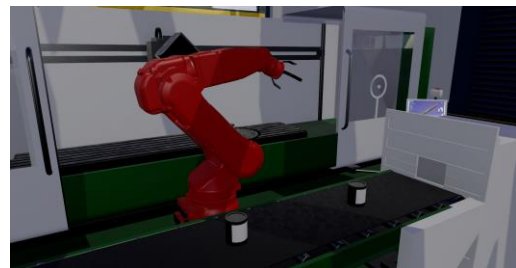Fig. 7. Assembly line on the factory.

Fig. 8. CNC machine with robotic arm.

Also, was included a technical library and all the users can have access in real time to technical information regarding the machines and processes by clicking on machine brand

logo.

Fig. 9. Training simulation machines.

Fig. 10. Training zone with interactive screens.

The platform can be used also for training on machines, different scenarios for working conditions, hazard and simulations being easy to be implemented using the physics engine in combination with the fbx baked animations triggered by scripting (Fig. 9).

In this way the new employees can be trained to proper use the machines without stopping the production process and affecting expensive machine. After completing the training in VR they can easily use the knowledge to operate the real machines and processes (Fig. 9, 10, 11).

Fig. 11. Hydraulic press.

III. CONCLUSION AND FUTURE WORK

In this research we have tried to find an easy way to create a Digital Twin of a smart factory, which can display in 3D in real time the processes, the machine status, the AMR's positions and movement, the Warehouse stock. We didn't use the telemetry data to create the simulations, these values being used for visualization only. To create a Digital Twin simulation for each machine, for each process and for AMR's based on telemetry data, tremendous hardware resources are needed and the results, from the user point of view could be worse, because of the lagging in getting the data, the latency caused by processing the data and physical simulations. The Remote-control using web-based access, created with web sockets, seems to be a good solution, the latency being really small (under 100 ms) and the controls very responsive. The WebRTC live streaming solution also assure a small latency, the remote operator being able to visualize from VR the machine tools and the effect of the parameter changing and commands triggered remotely from VR. As a result of applications implemented in this paper, we can conclude that Virtual Reality is an emerging technology that can be used with success for visualization of industrial processes. Future research will be done in order to optimize the animation driver and to include supplemental status messages, in this way the representation accuracy being higher. We are trying to find partners to implement this platform for multiple real-life scenarios, and we are confident that this platform can become a valuable support for collaborative work at a distance.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors had equal contributions in: the literature review, analyzing the data, writing the paper and approving the final version.

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