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REGULAR PAPER

Process Modelling of an Analytic Control Machine in Virtual Reality Platform

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Abstract

While the combination of virtual reality (VR), industrial internet of things (IIoT) and digital twin (DT) can promote the integration of the physical world (real) and the digital world (virtual), one of the most important challenges that companies face is the choice of architecture. This study intends to utilize VR, IIoT, DT advantages and to reduce some adverse effects the constituent processes produce when they are individually applied. This bridges the existing gap between the physical and digital machines to enable near real-time monitoring control of the manufacturing process. In the realization of this paradigm shift, we use of IIoT infrastructures by adopting a bi-directional communication protocol for conveyance of data and information between the physical and virtual models in hardware in the loop or software in loop configuration. This study takes into account user case industrial application for the formation of silica scale and methods of reducing its production. In systems operating above pH 8.5, magnesium silicate is very likely to form due to the presence of magnesium hydroxide $Mg(OH)_2$ and silicate $(SiO_4)^{4-}$ ions. In this research work, the developed platform (VR, IIoT and DT) is used to remotely monitor and control the process that prevents silica scale formation by maintaining an acidic solution (pH < 6.7). A supervisory control is achieved using VR whereby instructions and commands sent to the physical station for execution. The data collected is stored in a data lake and is used to find the PID controller trends for pH 4 dosing and gain actionable insights. Analysis of the data is done by utilization of visualization schemes, diagrams and infographics. Results show the achievement of near real-time control (correlation coefficient at 99.92%) of a cyber-physical machine using VR by the adoption of bi-directional communication between the physical and virtual models in an immersive environment.

Keywords Digital world · Physical world · Digital twin · IIoT · VR · Manufacturing industries

1 Introduction

Cyber-physical systems (CPS) involve merging the physical machines and machines in virtual spaces by the integration of sensors, actuators and high-fidelity communication to ensure that both machines are running in near real-time. Currently, the main challenge in the realization of Industry 4.0 is bridging the gap between the physical world and the digital world [1].

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Digital twin (DT) is projected as a key pillar in the realization of cyber-physical systems [2, 3]. As defined by [4] DT integrates Multiphysics, multiscale probabilistic simulation of a complex product, which functions to mirror the life of its corresponding twin. The application of the DT allows the virtual representation of a physical product/process to obtain insights and predict the physical counterpart's performance characteristics. The DT get data from installed sensors on the physical objects to determine the objects' real-time performance, operating conditions and changes over time. This kind of connection creates a kind of a closed loop of feedback in a virtual environment [5, 6] as depicted in Fig. 1 where there is a constant exchange of data between the virtual and the physical domain.

The ever-growing use of interconnected systems with sensors and networked machines has resulted in the continuous generation of a high volume of data and has prompted the adoption of CPS for managing such data by leveraging the

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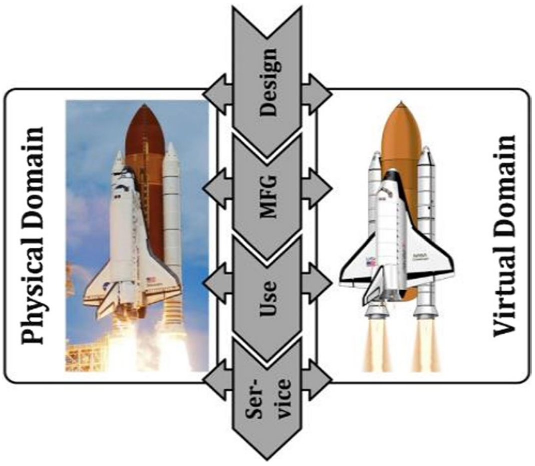

Fig. 1 Digital twin realization as envisioned by NASA[7]

interconnectivity of machines to achieve intelligent and self-adaptable machines [8]. The use of these technologies and Industry 4.0 proposals have opened the way for real-time monitoring and synchronization of real-world activities to the virtual space. The has been possible by the progress in research in Physical–virtual connection and networking of the CPS elements and architecture [1, 9–11].

This study seeks to utilize virtual reality (VR) technology in the sphere of Industry 4.0. VR in this context provides a platform that enhances visualization and contextualization of digital content by allowing intuitive user interactions in a highly immersive virtual environment.

VR is a concept that has been widely used in the gaming industry, where players interact with virtual items in the virtual environment [12]. Therefore, VR allows intuition and interaction with digital contents, as users are able to freely move around the scene, interact with objects, and perform experiments thus contributing to mastery and comprehension of the subject at hand. VR provides realistic simulations just like the physical environment. Therefore, the application of VR, in this case, ensures active learning by encouraging learning by doing [13, 14].

Researches have been done by different authors to explore other potential applications of VR in engineering, medical fields and how VR can be incorporated as a learning tool [15]. The application of VR in education has also been tested in training medical students and its application led to an increase in self-confidence and knowledge in performing procedures among novice medical students as discussed by [16]. VR in education not only allows imagination, creative thinking but also allows observations within a controlled environment.

After the outbreak of the COVID-19, laboratory experiments that require users' contacts with physical machines are greatly affected. This is due to guidelines that imposed social distancing thus institutions are compelled to adopt e-learning platform as an alternative to augment teaching and training [17]. Unfortunately, the conventional e-learning platforms do not enable learners to make realistic observations and interact with machine parts in a virtual environment. These coupled with the global competition and rapidly changing customer needs have necessitated significant changes in manufacturing enterprise production styles and configuration. Traditional centralized manufacturing systems cannot meet these new demands, therefore, internet-based solutions for information processing for distribution, heterogeneity, autonomy and cooperation must be developed and deployed [18].

VR application in the design field is gaining acceptance among design engineers. VR is utilized in design reviews where CAD models are verified for compliance with previously defined requirements and also aims to reveal potential deviations so that they may be corrected at an early stage [19]. This technology provides also simulation and support that will enhance industrial processes prior to adoption in a production environment by offering training and guidance for semi-skilled workers [20]. The rapid adoption of information technology tools is poised to enhance the learning experience among students [21]. Sensors can be integrated to the DT to provide field information that can be used to build virtual machines for cyber-physical manufacturing [22]. CPS are an emerging discipline that involves engineered computing and communicating systems interfacing the physical world. Industrial Internet of Things (IIoT) is driving the fourth phase of the Industrial Revolution [23].

IIoT is driving strong demand for more data acquisition, communication, real-time analytics and data-driven decisions across a wide range of industrial verticals. While, the combination of VR, IIoT and DT can promote the integration of the physical world (real) and the digital world (virtual), one of the most important challenges that companies face is the choice of architecture.

Looking into the future, there is a need to build robust systems that will prevail during uncertain times as witnessed during COVID-19 pandemic and solutions such DT, VR and internet-based manufacturing will sustain the endeavour with minimum disruption to normal manufacturing, teaching and training routines [24]. This study therefore intends to mainly make use of the combination of VR, IIoT, DT advantages and to reduce some adverse effects the constituent processes produce when they are individually applied. This bridges the existing gap between the physical and digital machines to enable almost real-time monitoring control of the manufacturing process.

This article considers a user case of an industrial application by examining a silica scale instance and suggests strategies for reducing its production. At pH less than 8.5, polymerization of silica is favoured which eventually forms amorphous silica (SiO_2) scale, while at pH larger than 8.5, the mixed solution may experience magnesium silica ($MgSiO_2$) formation [25]. In this research work, the developed platform (VR, IIoT and DT) is used to remotely monitor and control the process that prevents silica scale formation by maintaining an acidic solution (pH < 6.7).

2 Methodology

To realize the control of the analytic process station in VR, a physical machine, a cyber-model of the machine and a communication interface for data and information exchange between the two is necessary. A data log feature is also included to keep track of changes in process parameters after every 1 s within the physical and the virtual model.

2.1 Solution Preparations

To carry out the study, solutions of pH 4.0, pH 7.23 (Water) and pH 10.0 shown in Fig. 2 are procured and used in the experimental procedure. The experiments are conducted in the following steps:

First step: Mixing a solution of pH 10 and pH 7.23 to attain pH of 8.5.
Second step: Attaining a solution of pH 6.5 by using solutions of pH 4.0 and pH 8.5. As per the design of experiment (DOE) in Table 1, it take a minimum of 4 min and a maximum of 20 min.
Third step: Controlling dosing of pH 4.0 while maintaining constant dosing of pH 7.23 and pH 10.0 to achieve pH 6.0. This particular process imitates the industrial scenario where chemical substances (pH. 8–14) and natural water (pH 6.7–7.4) are mixed with a non-linear dosing while an inhibitor (pH 1–6) is heuristically dosed to reduce silica scale formation. Figure 3 summarizes the steps undertaken in solutions preparations.

Fig. 2 Chemical solutions used (pH 4.0 and pH 10.0)

A design of experiment (DOE) is undertaken to measure the time taken to achieve an acidic solution in the reactor tank by varying the volume, pH and the flow rates. Using Minitab (version 19), 15 runs are generated and performed as tabulated in Table 1.

An analysis of the collected data from the experiment shows non-linearity, unpredictability of the data samples and

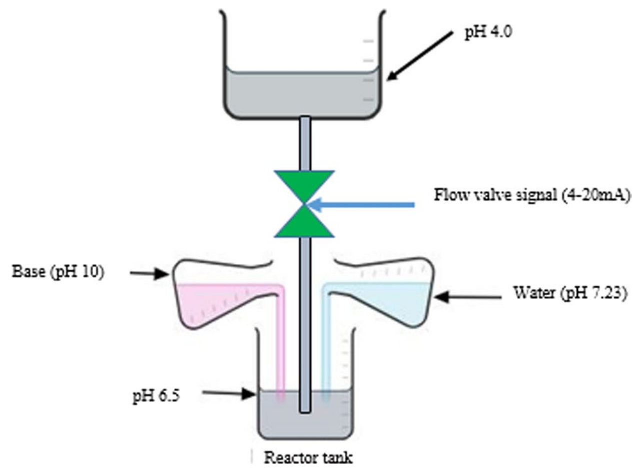

Fig. 3 Solutions preparations

Table 1 Design of experiments for pH monitoring

Run	Basic pH (7–9)	Amount of fluid in reactor tank (l)	Flow rate of pH 4 (litres per minute–LPM)	Time (s) to achieve a pH of 6.0
1	9	8.0	3.6	754.07
2	9	5.0	3.6	316.01
3	7	8.0	3.6	289.10
4	8	5.0	2.4	336.06
5	8	5.0	4.8	381.10
6	8	6.5	3.6	242.06
7	9	6.5	2.4	1178.07
8	9	6.5	4.8	408.10
9	8	8.0	2.4	417.08
10	7	6.5	2.4	634.07
11	8	6.5	3.6	241.05
12	8	6.5	3.6	237.03
13	8	8.0	4.8	238.05
14	7	6.5	4.8	222.01
15	7	5.0	3.6	359.01

S	R-sq	R-sq(adj)	R-sq(pred)
185.640	81.70%	48.77%	0.00%

Fig. 4 Model summary

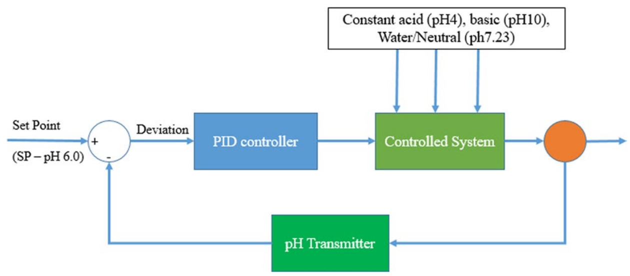

Fig. 5 Process control

Fig. 6 Amatrol Analytic process control system

therefore, a challenge in generating a mathematical model of the system. A summary of the model is as shown in Fig. 4.

To continuously monitor and control the pH of the solutions in the reactor tank, a PID is deployed to control the induction rate of the acid solution (pH 4.0). Basic (pH 10.0) and water (pH 7.23) solutions are added to the reactor tank at a constant rate. These three substances create a disturbance to the system and therefore the need of monitoring and control of the inhibitor dosing (pH 4.0) to maintain the set point of pH 6.0. The control process is depicted in Fig. 5.

2.2 Physical System

The machine used for this study is an Amatrol Analytic process control system Model T5554 as shown in the Fig. 6. The machine controls, monitors and modifies the chemical properties of solutions. Analytic control systems are ubiquitous especially in geothermal Industries, food and beverage Industries as well as pharmaceutical Industries. The station features a metering pump, eductor pump, an agitator, ISFET pH sensor, two reagent tanks, a flow valve, and a reactor tank.

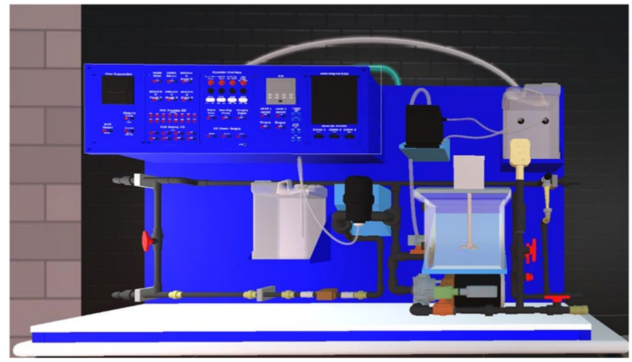

Fig. 7 CAD model of the analytic machine in Unity

The existing Honeywell UDC 2500 PID controller is upgraded using a Siemens S7 1214 DC/DC/DC programmable logic controller (PLC) as hardware and TIA portal (TIA version 16) migration tools to make the transition from legacy to contemporary systems easier and allow for proactive monitoring and control of silica formation data.

The PID controller feature in the PLC S7 1214 is tuned to attain a set point of pH 6.0 while IIoT allows remote input of the set point, pH 4.0 flow rate setting and transmit data to the VR platform through DT.

2.3 Virtual System Development

The 3D CAD model of the analytic machine is designed using Siemens NX and blender software. The 3D CAD model is then imported into the Unity software (version 2019) for physics assignment and visual development for the components as shown in Fig. 7. This aims at replicating components behavioural characteristics in the physical environment.

For the creation of the immersive virtual world and the incorporation of wearable virtual reality devices, the Unity game engine is used. The software features a rendering, physics engine and a scripting interface for development of interactive scenes. The game engine relies heavily on scripting; therefore, it offers greater freedom and flexibility in undertaking this study compared to Siemens NX software. In addition, based on its interoperability, the software allows creation of DTs and virtual commissioning platform.

Process parameters are also scripted to match the normal machine operations i.e., flow rate, pH trends. The physics assignment is achieved using a C-sharp script. The physics addition is important in this aspect as it helps in the creation of the digital twin of the analytic process machine. User interface (UI) panel and a graphing output are developed for user interaction and monitoring of process parameters in the immersive environment.

2.4 Digital Twin Creation

The realization of virtual commissioning and DT using Unity software first involves emulation of the PLC controller by writing control logic operation of the analytic process machine. The totally integrated automation portal (TIA) software is used to develop the control logic of the machine using ladder diagrams and functions. TIA portal provides an engineering framework for implementing automation solutions. The developed software is then validated using simulations before deployment to the physical machine.

The second phase is the use of IIoT and the adoption of a bi-directional communication protocol for the conveyance of data and information between the physical and virtual models. The PLC S7 1214 is selected as a gateway that provides connectivity and allows communication through a ProfiNET IP based network connection. Verification of communication is performed with hardware in the loop (HiL) or software in loop (SiL) configuration. Simulation of sensors, actuators connected to the controller as well as system behaviour in Unity software requires modelling and scripting. The dynamic response of the actuators is done to describe the actual response of the system. This is necessary for testing and validation of the machine control logic.

In the third phase, modelling of the visualization interface is included. The UI window allows the VR user to interact and engage with the analytic machine. The UI also includes a graph window that displays the pH trends of the virtual machine in the immersive environment. The virtual reality Oculus Rift S VR head-mount displays (HMDs) and hand controllers are incorporated to enable real-time visualization of the machine in an artificial immersive environment and navigation and interaction with objects within the scene, respectively.

The fourth process in Unity software is kinematic modelling of inputs and actuators. The dynamic response when interacting with UI buttons within the immersive environment is key in ensuring replication of what a user in the physical environment does. The kinematic modelling is also performed for rotation of the agitator shaft to mimic the agitator present in the analytic machine. The process of modelling these graphical representations requires high-end graphical processing units (GPUs) for seamless rendering and smooth operation in the virtual environment.

The final level of creation of the DT is the addition of a communication system to link the virtual and physical models to facilitate near real-time communication. Achievement of this level involves the application of information technology techniques. A successful deployment of Sharp 7 communication ensures constant exchange of information between the physical and virtual models. Sharp 7 script contains classes that can be directly incorporated into the .NET Unity project to communicate with S7 PLC. It handles Ethernet S7 protocol communication, which is the backbone of the S7 PLC communication. S7 protocol is classified as function oriented or command oriented in that each transmission contains a command or a reply.

2.5 Virtual-Physical System Integration

An appropriate communication technology that facilitates data exchange between virtual and physical models is also adopted. This particular communication system is based on LAN topology and provides a means of ensuring data transmission and exchange between the physical analytical station and the virtual model in the Unity game engine. This is achieved by using a network driver script included in the game engine to enable a kind of closed loop information exchange between the physical and virtual model. Figure 8 highlights the flow of data and information between the cyber model and the physical model in the cyber-physical architecture.

This selected approach suits the realization of the DT used to monitor the process of the analytic station. The implementation of the communication is performed inside the unity environment. A sharp 7-client script is written to allow communication with the S7 1214 PLC. The selected communication interface is easily deployed and works perfectly with ProfiNET technology and is well compatible with the Windows platform. For its usage, a correct and available IP address is selected to make communication to the S7 1214 PLC. This net driver is selected based on its merits as listed in Fig. 9.

Seamless integration between the physical and virtual systems achieved enabled near real-time control of the analytic machine. As a result, a change in the command signal altered the performance and behaviour of the inputs or output instantaneously with minimum delay. Collection of data from the controller is done using a data log feature of the PLC S7 1214. Data logging of the process parameters is done at a frequency of 1 Hz.

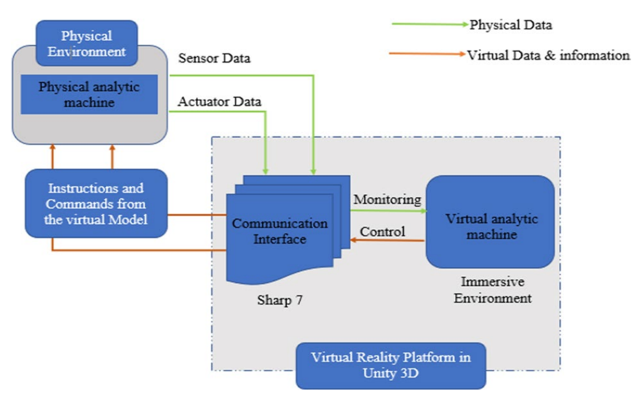

Fig. 8 The CPS control architecture

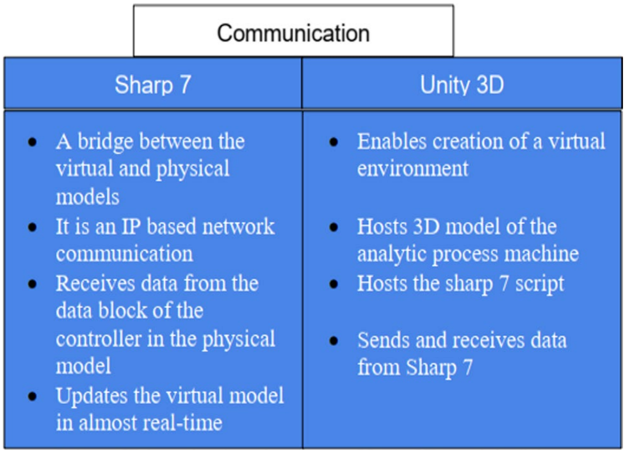

Fig. 9 Communication technique for integration

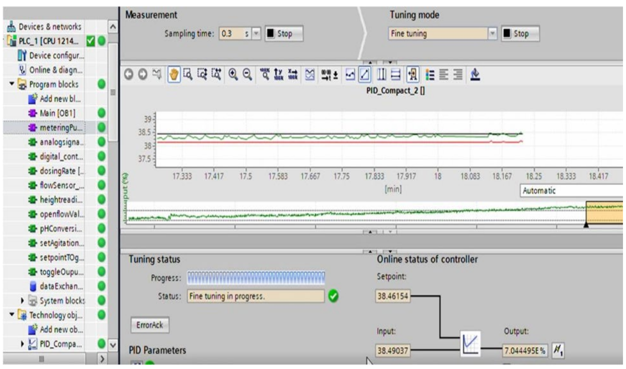

Fig. 10 PID commissioning window

3 Results and Discussions

A PLC program is developed using a ladder and functions. The incorporation of PID ensures that the process variable is maintained within a range of the set point. Figure 10. Shows the commissioning window of the PID. Using the window, fine-tuning of the controller is performed, monitoring of the controller response as well as the behaviour of the process variable (pH) in percentage. As the value of the input goes beyond the set point, the PID responds by sending an output signal to the metering pump to dose with an acid to correct the error. Properly tuned controlled ensured the system responded promptly to disturbance and achievement of the target.

setpoint.

Figure 11 shows the response of the PID controller as the process variable goes beyond the set point. From the graph, the output of the controller is maximum when the process variable is above the set point. However, as the controller takes corrective measures, the output reduces as

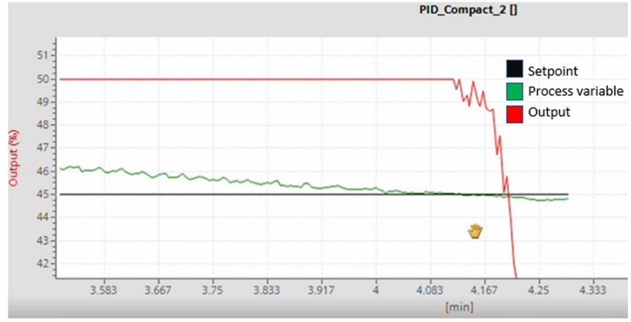

Fig. 11 Controller response

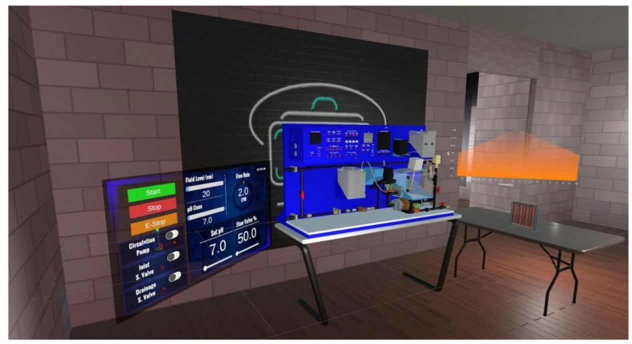

Fig. 12 Controller response

Fig. 13 VR user interface

the error margin between the set point and process variable is small. The maximum occurs until process variable (PV) almost equals set point (SP). The moment PV goes below the SP, the output of the controller goes to zero to allow the pH level to rise.

The virtual representation of the lab environment in Unity game is as shown in Fig. 12. Successful integration of the VR wearable devices allows the user to walk around the scene, interact with the objects, monitor process parameters and control the machine.

Process parameters such as flow rates, height level at the reactor tank are observed using the UI window shown in Fig. 13. Also included in the UI is control settings that enables remote control of the system. Tasks that can be done remotely include; setting process set point adjustments, flow valve opening, process start and stop as well as other operations. The pH trends of the analytic process are observed by including graphs in the virtual environment.

A communication script is deployed to merge the physical and virtual model in Unity for data exchange between the environments. The Fig. 14 shows the integration of the cyber and the remote physical station with monitoring and control through TIA and Unity.

Having integrated the physical and virtual models, there is a need to analyze data and motion in both the physical and virtual systems and to ensure synchrony. Real-time monitoring of the system showed that the update of the virtual model is instant and the sensor values displayed matched the values of the physical system.

Figure 15 shows the pH reading in the physical and virtual models. The pH values being displayed in the virtual model UI are equal to the pH values being read by the pH transmitter at the physical system thus enabling monitoring of process parameters. The slight variations of the pH values is attributed to the delay in streaming of data in the virtual model and also rounding off of the values being obtained from the sensor. The status of the actuators is likewise updated almost instantly. To allow the VR user to remotely monitor and operate the analytic system, flowrates and digital controls (Start, Stop) are included into the UI. Majority of Industries are gearing towards realizing the supervisory control and data collection architecture that this configuration offers.

4 Data Analysis

A supervisory control is achieved using VR whereby, instructions and commands sent to the physical station for execution. Figure 16. Illustrates the VR view of the pH readings from the graph. The graph shows the changes in the process variable as the controller stabilizes to maintain the set point.

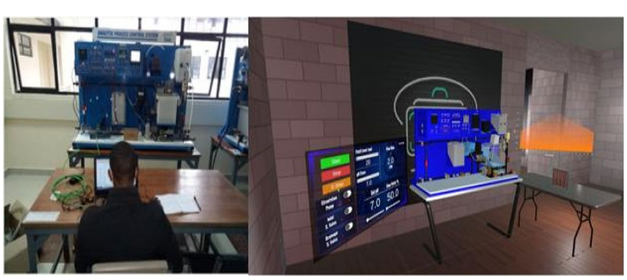

Fig. 14 Physical–virtual system integration

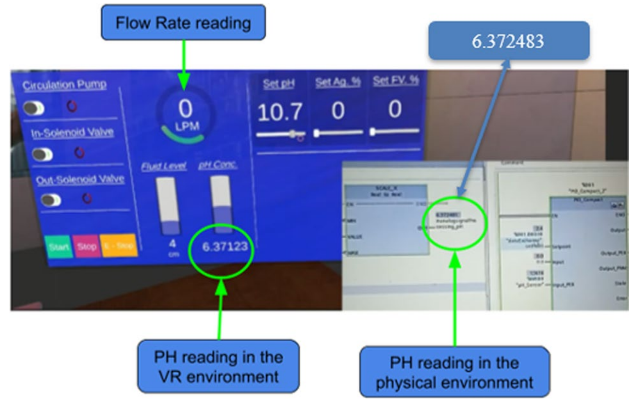

Fig. 15 pH sensor value reading in VR environment

The data collected is stored in a data lake and is used to find the PID controller trends for pH 4 dosing and gain actionable insights. Analysis of the data can be done by utilization of visualization schemes, diagrams and infographics. As observed in Table 1, it takes 4–20 min to achieve a pH of 6.5. In the final sample result in Table 2, we capture the behaviour of the PID controller during dosing of pH 6.7 to 6.0.

Observation of the physical by using the combination of VR, IIoT and DT helped in identification of inefficiency of the system and informed possibility of integrating machine learning (ML) algorithms to improve the silica scale inhibition model.

A sample of the data collected to compare the virtual model and the physical analytic station are presented in the Table 2 below.

Figure 17 shows the comparisons between the pH readings of the physical machine, the readings on the virtual user interface and the set point (SP = 6.0). Results show the achievement of near real-time control of a cyber-physical machine using VR by the adoption of bi-directional communication between the physical and virtual models in an immersive environment.

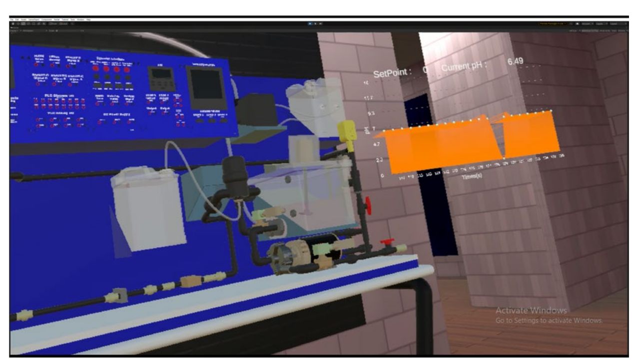

Fig. 16 pH trends of the virtual model

Table 2 Physical and Virtual sampled pH readings

Record (s)	Date	Time	pH values in VR	pH value from physical system
1	08/12/2021	19:13:27	6.677458	6.68
2	08/12/2021	19:13:28	6.679502	6.68
3	08/12/2021	19:13:30	6.677458	6.67
4	08/12/2021	19:13:32	6.67848	6.67
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
99	08/12/2021	19:16:42	6.540467	6.55
100	08/12/2021	19:16:44	6.542	6.54
101	08/12/2021	19:16:46	6.531266	6.53
102	08/12/2021	19:16:48	6.54609	6.55
103	08/12/2021	19:16:50	6.553246	6.56
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
199	08/12/2021	19:20:02	5.964389	6.00
200	08/12/2021	19:20:04	5.968989	5.98
201	08/12/2021	19:20:06	5.969501	5.97
202	08/12/2021	19:20:08	5.961833	5.96
203	08/12/2021	19:20:10	5.976657	5.98
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
300	08/12/2021	19:23:24	6.037485	6.02
301	08/12/2021	19:23:26	6.024195	6.02
302	08/12/2021	19:23:30	6.043619	6.03
303	08/12/2021	19:23:32	6.036974	6.04
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
352	08/12/2021	19:25:08	6.050264	6.05
353	08/12/2021	19:25:10	6.03544	6.04
354	08/12/2021	19:25:12	6.054864	6.05
355	08/12/2021	19:25:14	6.055887	6.05
356	08/12/2021	19:25:16	6.04822	6.05

The utilization of this approach introduces a data driven DT of a control process in a virtual and interactive environment.

A summary of the correlation between the pH values on physical machine and in VR is shown on Table 3 below. Results show a positive correlation and an achievement of near real-time data exchange between the virtual and physical systems.

5 Conclusion

This study aimed at making use of the combination of VR, IIoT, DT advantages and to reduce some adverse effects the constituent processes produce when they are individually

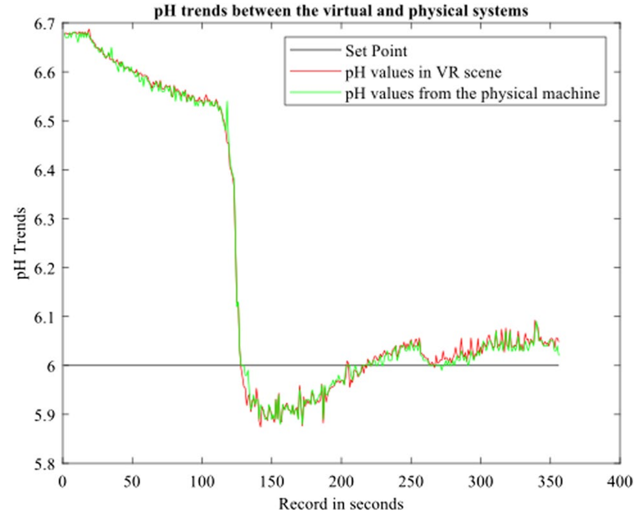

Fig. 17 Process parameter readings between the virtual and physical analytic system

Table 3 Correlation between VR and physical pH values

Correlation coefficient		
pH values on physical	1	0.9992
pH values In VR	0.9992	1

applied. This bridges the existing gap between the physical and digital machines to enable almost real-time monitoring control of the manufacturing process. In this research work, the developed platform (VR, IIoT and DT) is used to remotely monitor and control the process that prevents silica scale formation by maintaining an acidic solution ($pH < 6.7$).The data collected is stored in a data lake and is used to show the PID controller trends for pH 4 dosing and gain actionable insights. Analysis of the data can be done by utilization of visualization schemes, diagrams and infographics. Results show the achievement of near real-time control of a cyber-physical machine using VR by the adoption of bi-directional communication between the physical and virtual models in an immersive environment. The utilization of this approach introduces a data driven DT of a control process in a virtual and interactive environment.

Observation of the physical by using the combination of VR, IIoT and DT helped in identification of inefficiency of the system and informed possibility of integrating machine learning (ML) algorithms to improve the silica scale inhibition model.

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Declarations

Competing interests The authors declare that they have no competing interests.

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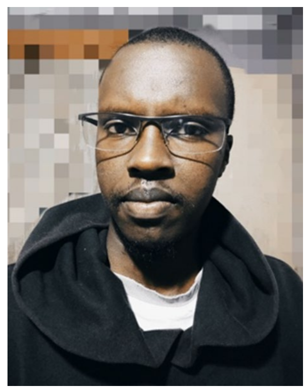

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