Toward a Web-Based Digital Twin Thermal Power Plant

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***Abstract*—As a crucial part of cyber-physical systems, a digital twin can process data, visualize processes, and send commands to the control system, which can be used for the research on thermal power plants that are vital for providing energy for manufacturing and industry, and also daily consumptions. This article introduces the methodologies and techniques toward a web-based digital twin thermal power plant. To implement a web-based digital twin thermal power plant, the architecture, modeling, control algorithm, rule model, and physical-digital twin control are explored. The potential functionalities of the web-based digital twin including real-time monitoring, visualization and interactions, and provided services for physical thermal plants and universities are also presented. A case study has been provided to illustrate the web-based digital twin power plant. The research in this article can provide potential solutions for web-based digital twin research and education.**

***Index Terms*—Cyber-physical system, digital twin, thermal power plant, web application.**

I. Introduction

ENERGY is indispensable for industry and manufacturing, buildings, and transport, which contributes to the development of the economy and society, thus, energy can be regarded as the most important asset in the universe [1]. Although great efforts have been devoted to the research on renewable energy such as solar and wind, which are intermittent energy sources that have strong randomness and instability, thermal power plants that can generate electricity from coal, natural gas, etc., have been playing an important role in the past decades, and are still essential for power generation with environment-friendly, economic, and pollution-reducing schemes [2], [3].

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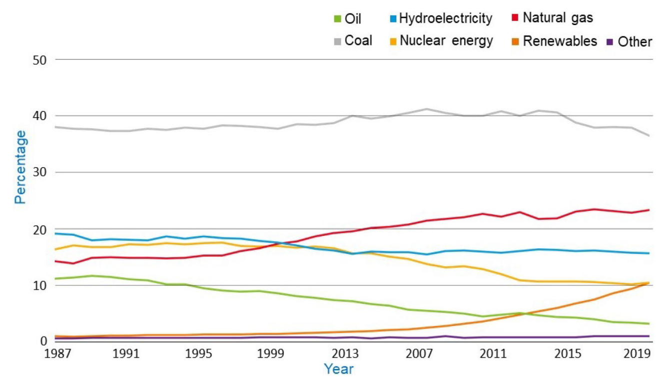


Fig. 1. Share of global electricity generation by fuel. Coal takes the most share.

With the development of the super-critical and ultrasuper-critical (USC) generation technologies, power generation efficiency has been improved and carbon dioxide emissions per unit of electrical energy generated have been reduced. Especially, the coal fired plants with leading USC technology, which provide stable and high-quality electricity have energy efficiency up to 46%, around 10% above the efficiency of the current subcritical coal fired power plants [4], [5].

According to the BP statistical review of world energy in 2020 [6], the share of global electricity generation by fuel can be depicted as Fig. 1. It can be seen that coal power plants are still dominated over other fuels, thus, in this article, coal fired power plants are chosen as an example to illustrate the situation of thermal power plants.

Thermal power plants include critical infrastructures, and power generation in thermal power plants involves massive complicated equipment, processes, and control techniques. Thus, thermal power plants are concerned with various disciplines and cover multidiscipline and interdiscipline research scopes.

The research works on thermal power plants cover several engineering fields such as control engineering, materials engineering, and energy and power engineering, as shown in Fig. 2 (reproduced based on [4], [7]), and the related components of the thermal power plant are listed in Table I. The requirements for different engineering fields are different, for example, for control engineering, typically precise, economical, and robust control are needed; while for energy and power engineering, the purpose is to achieve high efficiency and economy.

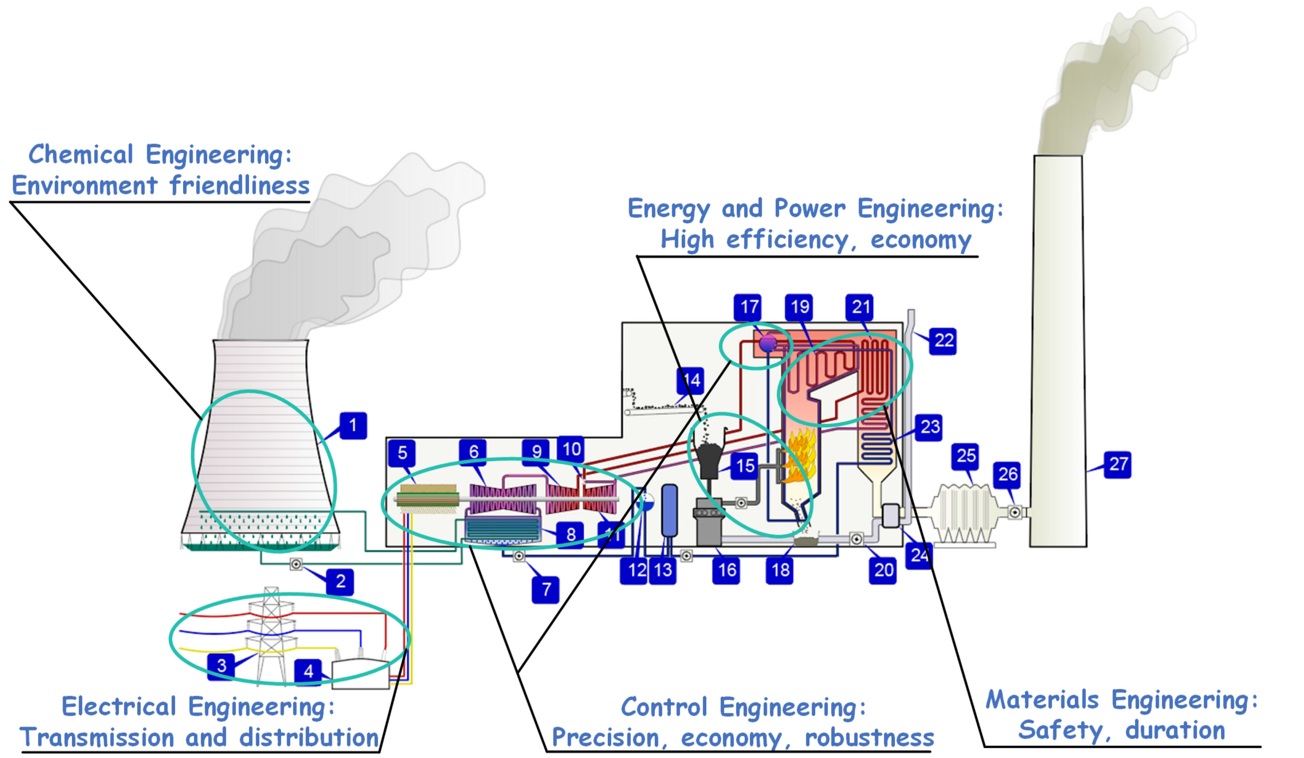


Fig. 2. Schematic of thermal power plant covering different fields of engineering (reproduced based on [4], [7]).

TABLE I
COMPONENTS OF THE THERMAL POWER PLANT IN FIG. 2

ID	Name	ID	Name	ID	Name
1	Cooling tower	10	Steam governor	19	Superheater
2	Cooling water pump	11	High-pressure turbine	20	Forced draught fan
3	Pylon (termination tower)	12	Deaerator	21	Reheater
4	Unit transformer	13	Feed heater	22	Air intake
5	Generator	14	Coal conveyor	23	Economizer
6	Low pressure turbine	15	Coal hopper	24	Air preheater
7	Boiler feed pump	16	Pulverized fuel mill	25	Precipitator
8	Condenser	17	Boiler drum	26	Induced draught fan
9	Intermediate pressure turbine	18	Ash hopper	27	Chimney stack

From coal which can be regarded as the input of the thermal power plant, to electricity, which can be regarded as the output, the working process of a thermal power plant can be simply described as follows:

1) *Coal ->[transport][milling] Boiler*: Coal is transported to the power plant via trains or ships, and is stored in a coal yard. Through a conveyor belt, coal is transported to the coal hopper, then it is milled and sent into the boiler.
2) *Water ->[Coal Buring][Purification] Steam Turbine*: The feed water is purified (deoxygenation, softening, etc.) and heated, and then turned into steam to drive the steam turbine.
3) *Steam Generator ->[transforming voltage] Substation*: The steam turbine drives the generator and produces a three-phase ac output, which is transformed from low to high voltage by transformers at the substation.

During the process, the energy flow from coal to electricity is as follows:

$$\text{chemical energy (coal)} \xrightarrow{\text{Boiler}} \text{heat energy} \xrightarrow{\text{SteamTurbine}}$$

$$\text{mechanical energy} \xrightarrow{\text{Generator}} \text{electrical energy (electricity)}.$$

It can be seen that complex equipment, procedures, and change of states of matter are involved in the thermal power plant. As a dangerous (high temperature, high pressure), complicated (involving multi discipline), expensive (industrial equipment), and vital (providing energy) research object, it is necessary to understand how the thermal power plant works and keep the power plant running safely and efficiently.

A thermal power plant involves computation, communication, and control, thus, it is a cyber-physical system (CPS), which is a new generation of systems that integrates physical processes and computation [8], [9]. As an exact cyber copy of a physical system that can represent all the functionalities, a digital twin which is a transformative technology has expanded the CPSs in which digital twin is the computation module and can even visualize physical processes [10], [11].

Due to the fact that a thermal power plant is such a huge, complex, and critical infrastructure, and it is impossible to shut down a power plant for a closer look and understanding, a digital twin thermal power plant is a feasible solution for the study of thermal power plants, which can provide visualized information, interactive operations, and ensure the security of equipment and the safety of humans.

The rest of this article is organized as follows. Section II presents related works of digital twins and their applications in thermal power plants. Section III investigates the implementation framework of the digital twin power plant, including 3-D modeling, mathematical modeling, rendering, and interactions and motion control. In Section IV, the functionalities and provided services of a digital twin power plant are explored, followed by a case study with a web-based thermal power plant in Section V. Finally, Section VI concludes this article.

II. Related Works

Currently, digital twins have become a more and more popular research topic mainly focusing on smart manufacturing and industry 4.0 [11]–[13], smart cities [14], [15], and driver assistance systems [10], [16], etc. Digitized laboratory [17], which is a kind of digital twin for laboratory setups, is also toward a kind of digital twin online laboratories in recent years [18].

In terms of the design of a digital twin, the mathematical model is a foundation to realize a digital twin. A digital twin-driven joint optimization model was proposed in [19], which can quickly optimize the stacked packing and storage assignment of a warehouse. In [20], a configuration, motion, control, and optimization model driven by digital twins was discussed, which can avoid potential design errors and inefficiency through hardware-in-the-loop simulation.

For the implementation of a digital twin, the hardware reconfigurability of the system is an important aspect for parallel controlling. For instance, in [21], an open architecture model was proposed for rapid reconfiguration of manufacturing systems based on digital twins. The proposed model allows the integration of personalized modules for catering to process planning. For a smart workshop under the mass individualization paradigm, parallel controlling is useful for continuous improvement and strategic adaptability [22].

For digital twins which work as a vital part of CPSs, the information architecture and the security issues in the digital twin are crucial. To provide reliability and security, a six layer digital twin architecture was proposed in [23], which used OPC UA servers and cloud-based database services that are readily available technologies and services. Using an analyzing engine, security analysis can be conducted directly on the digital twin to detect harmful state transition [12]. The incorporation of blockchain and smart contract into digital twins can potentially address security issues, especially data integrity, confidentiality, and availability [24].

Regarding web-based digital twins, a remote control approach has been achieved for web-based digital twin production systems in [25]. Web services are used to retrieve information to visualize a digital twin together with augmented reality in [26]. The March 2021 edition of the Journal of Innovation of the Industrial Internet Consortium focuses on ongoing research under the theme "Innovations in Digital Twins," in which a web-based digital twin was discussed and a laser plotter has been chosen as a demonstrator.[1]

As a physical thermal power plant involves high temperature and high pressure, mis-operations may cause damage to the expensive equipment or to the operator. Moreover, control techniques in a real thermal power plant cannot be easily changed since a thermal power plant tend to adopt traditional control techniques to ensure security and economy without accidents and incidents. Thus, a thermal power plant is a perfect candidate for digital twin research, which can provide more details that cannot be achieved by a physical system with limited sensors providing limited information, and also address the safety issues. For example, digital twins can simulate the behaviors and use in real time. The autistic steel used in superheater and reheater is supposed to be creep and oxidation-resistant at high temperature during the long-term aging service. The digital twin can be potentially applied to the simulation of the materials testing, for example, finite-element analysis for testing Super304H [27] and Sanicro25 [28] for superheater and reheater.

As for digital twin research in thermal power plant, currently several research works have been conducted, for example, steam turbine control stage for online performance monitoring [29], digital twin based power plant condenser maintenance [30], and the use of digital twins to reduce auxiliary power and improve boiler efficiency [31]. In [32], a numerical model of a digital twin coal fired thermal power plant is explored, which employed the digital twin for the analysis of the plant-operating performance and the exploration of optimization solutions.

The abovementioned literature conducted research on the design, architecture, or implementation of digital twins. Only a few research efforts have been devoted to web-based digital twins, which are focused on industrial systems concerning manufacturing and production. Considering the research on thermal power plants, which involve process control that continuously monitors and controls digital and analog measurements, a full picture on the design and implementation of a digital twin thermal power plant regarding the implementation, modeling, control, and rule models is to be explored, which is outlined in this article.

III. Digital Twin Implementation

A digital twin is a virtual representation, also called a mirror, a sibling, or simply a twin of a physical system. A digital twin can be decoupled as the 3-D model, the mathematical model, and the rule model, where the 3-D model looks exactly like the physical system with 3-D modeling technologies, the mathematical model is related to the mechanisms, kinetics and data of the physical system, and rule model defines interactions from users and motion control of a digital twin and the corresponding physical system.

In the following sections, the detailed design and implementation of a digital twin thermal power plant will be investigated.

[1][Online]. Available: https://www.iiconsortium.org/journal-of-innovation.htm

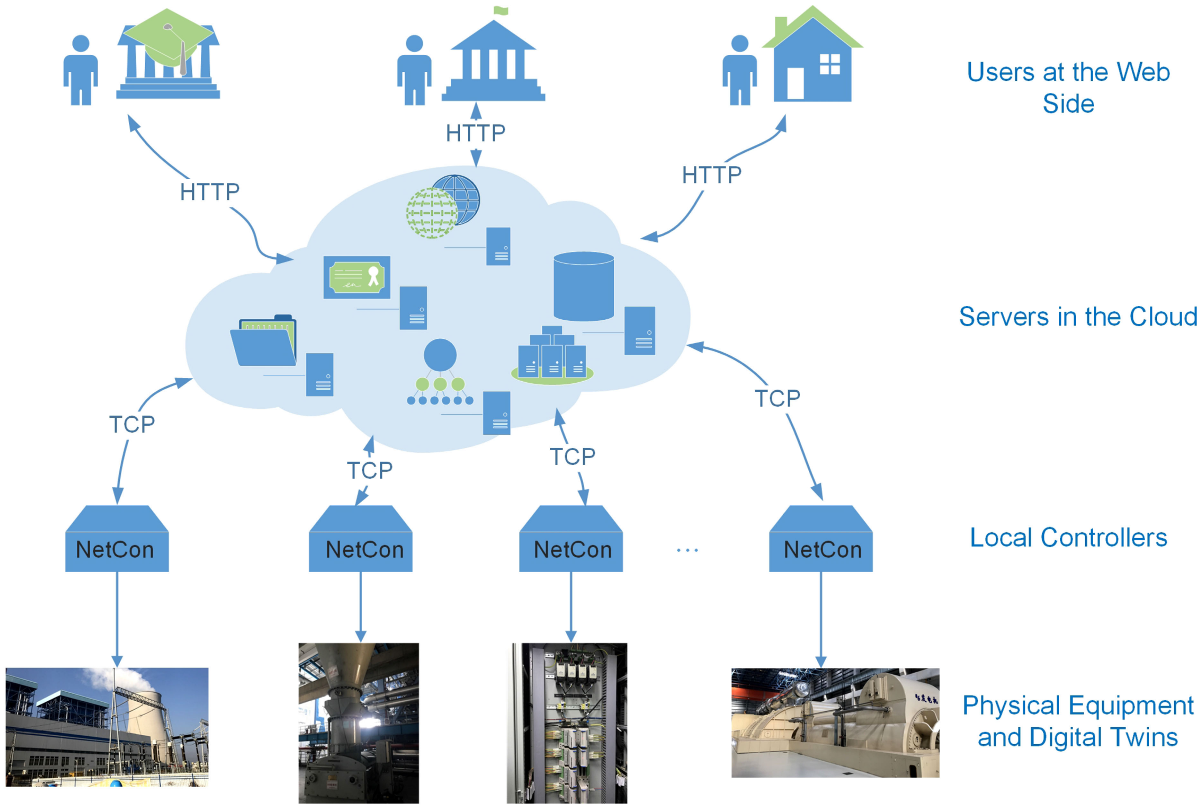


Fig. 3. Four-layer architecture of a web-based digital twin thermal power plant.

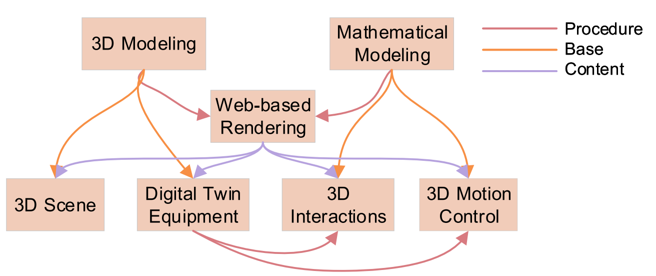


Fig. 4. Methodology for design and implementation of a web-based digital twin.

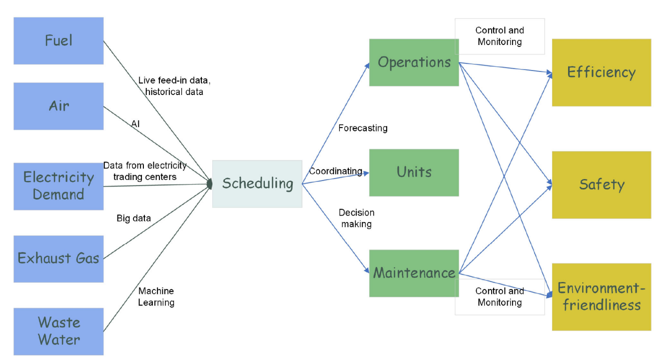


Fig. 5. Illustration of big data and AI enabled thermal power plants.

A. Architecture

To enable remote operations of the digital twin, a four-tier architecture has been proposed regarding the perspective of use, deployment, and control. From the view of users, they can experience the digital twin with mainstream web browsers. To support web access, several servers have been deployed. The networked controllers, which are based on ARM9 with the real-time performance are integrated as controllers. Fig. 3 shows the four-layer architecture of a web-based digital twin thermal power plant.

Fig. 4 illustrates the methodology for the design and implementation of a web-based digital twin. For a web-based digital twin, mainly three procedures are required, namely, 3-D modeling, mathematical modeling, and web-based rendering. 3-D modeling includes the construction of 3-D scenes and digital twin equipment, while mathematical modeling is the base for 3-D interactions and 3-D motion control. Web-based rendering includes a concrete 3-D scene and digital twin equipment, and also abstract 3-D interactions and 3-D motion control.

Fig. 5 shows the illustration of big data and artificial intelligence (AI) enabled thermal power plants. To achieve a high-efficient, safe, and environment-friendly thermal power plant, the input and output variables of the thermal power plant such as fuel, air, electricity demand, exhaust gas, and waste water are supposed to be considered. Big data including live feed-in data, historical data, and data from electricity trading centers and AI technologies such as reinforcement learning and deep

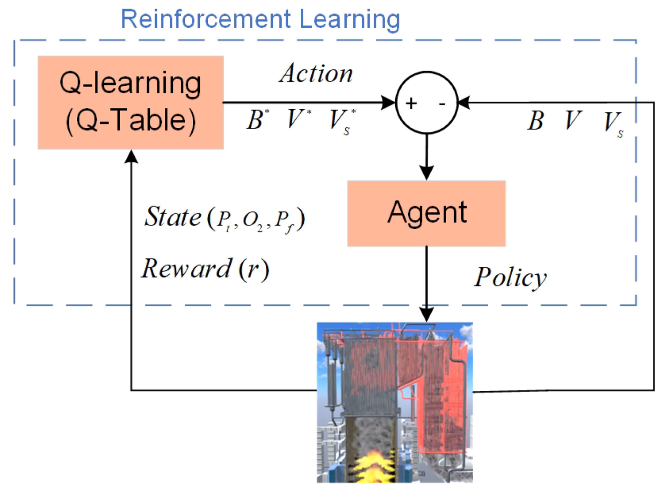


Fig. 6. Reinforcement learning for optimization of the combustion control system of the digital twin thermal power plant.

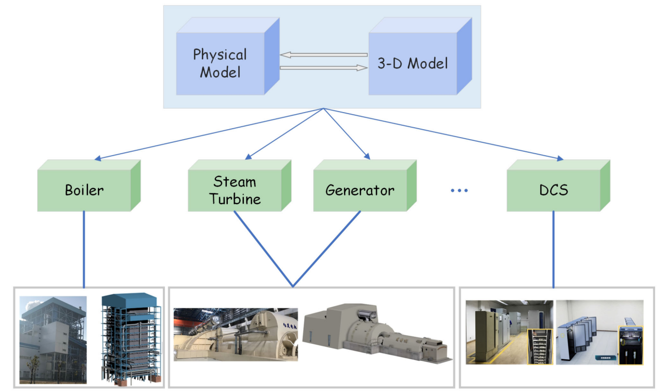


Fig. 7. Physical and 3-D models of the thermal power plant.

learning can be used for scheduling the operation and maintenance of the thermal power plant, for example, forecasting the needed resources and electrical output, coordinating among different units, and also decision making for maintenance policy selection, protection actions, and optimal control, etc. Fig. 6 is an example of reinforcement learning for optimization of the combustion control system of a digital twin thermal power plant. The states are the main steam pressure P_t, the oxygen content O_2, and the furnace negative pressure P_f, and the actions are the fuel input B^*, the air input V^*, and the air output ${V_S}^*$. Reinforcement learning is capable of interacting with the environment to generate control strategies, an optimal of which is formulated in the Q-table through Q-learning. The agent learns from its experience and forms a control strategy that can maximize predefined goals [33].

B. Modeling

For modeling, 3-D model, mathematical model, and rule model are three crucial parts.

1) 3-D Model: To implement virtual replicas of physical systems, 3-D models should be constructed as a virtual representation of physical systems as similar as possible. As for a web-based digital twin, a tradeoff between 3-D modeling precision and loading performance in the web browser should be considered. A less complex model, which mainly mimics the appearance with fewer details would result in a small size and, thus, is preferred for a better loading performance. With the 3-D modeling software or even with a 3-D scanner, 3-D models can be constructed based on the corresponding physical models. Fig. 7 shows several 3-D models of a thermal power plant, in which the physical models are also provided, it can be seen that the 3-D models mimic the physical models in appearance.

2) Mathematical Model: 3-D models only resemble the static physical models in appearance. However, to build a digital twin, the dynamic behaviors should also be considered so that the animation of 3-D models resembles the dynamic physical models. For different control plants, for example, the boiler or turbine, their mathematical models are different. For each specific control plant considering constraints, several methods can be employed for mathematical modeling. For example, process knowledge/mechanism modeling using kinetics and data with some system assumptions, data-driven modeling, and online learning methods for mathematical model design and implementation [34], and data-based modeling considering system law and characteristics. Machine learning and data mining can also be used for mathematical optimization to build complex models [35], [36].

C. Control Algorithm

Mathematical models reflect the characteristics of specific control plants. To control a digital twin control plant, a control algorithm involving control methods is vital to achieving security, high efficiency, economy, and environment-friendliness for the thermal power plant.

Although a great many advanced control techniques such as affine nonlinear control [37], hierarchical model predictive control [5], and active disturbance rejection control [38] have been proposed, currently, in most thermal power plants, proportional-integral-derivative control, which is simple and easy-to-use is still dominant over other control techniques for security and other considerations. Fig. 8 illustrates the control algorithm diagram for a digital twin thermal power plant, in which different mathematical modeling methods are included.

D. Rule Model (Animations)

The rule model is to combine the control algorithm and the 3-D model for a dynamic digital twin, including motion control and 3-D interactions. The combination of a 3-D model with a control algorithm can activate the virtual replica working as a digital twin of the physical system whose dynamic behaviors can be animated based on data. The digital twin also generates information and process data, which will be sent to the physical system. Fig. 9 shows the rule model for a digital twin.

Fig. 10 shows several interaction examples for a digital twin thermal power plant, which takes the valve, knob, and button as examples. The corresponding valve, knob, and button in a

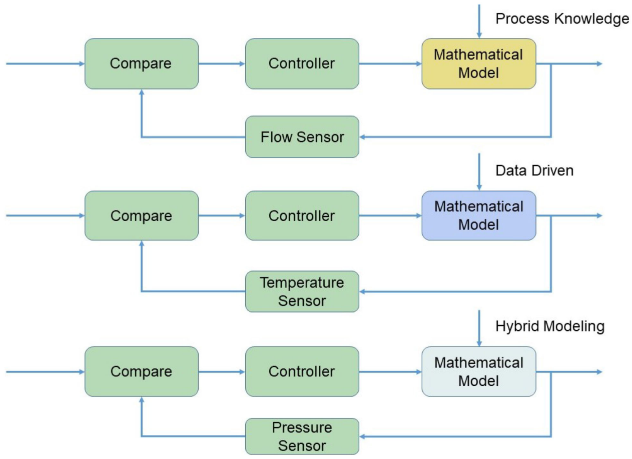


Fig. 8. Control algorithm diagram for the digital twin thermal power plant.

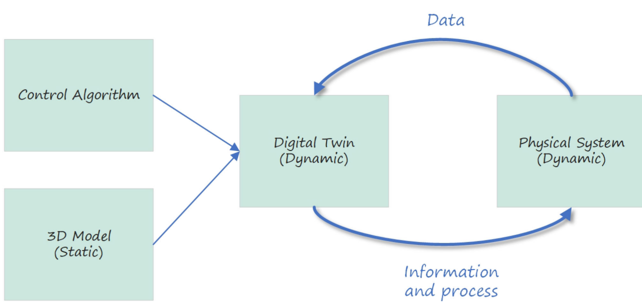


Fig. 9. Rule model for a digital twin.

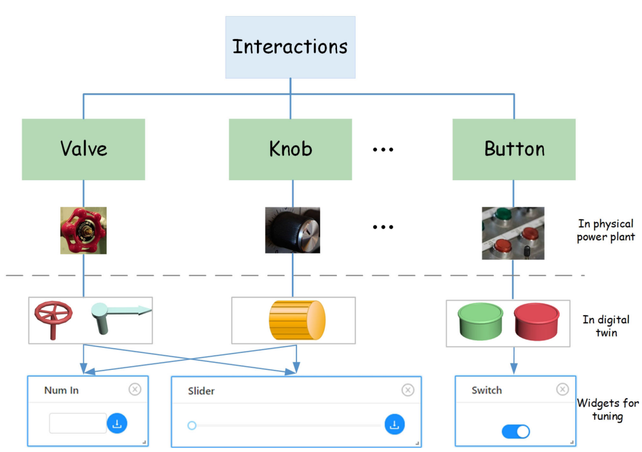


Fig. 10. Interactions for the digital twin thermal power plant.

physical power plant are also given. When users interact with different actuators, different action responses to corresponding input signals will be executed. The interactions can be implemented through 3-D models in the digital twin, where users can directly interact with the implemented 3-D valve, knob, or button. Moreover, textbox, slide, and switch widgets can also be used for interactions. For example, if a textbox is linked with the parameter for valve tuning, then the input of a number in

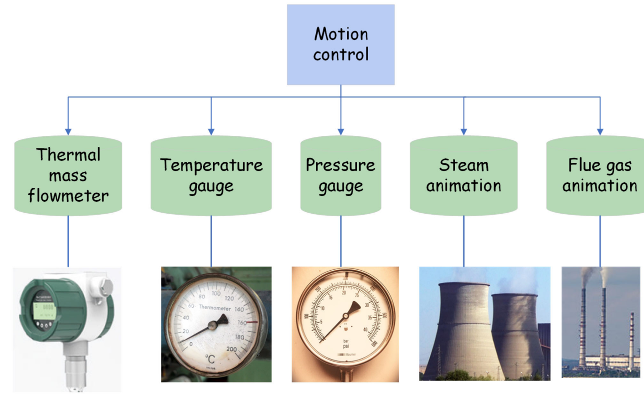


Fig. 11. Motion control for the digital twin thermal power plant.

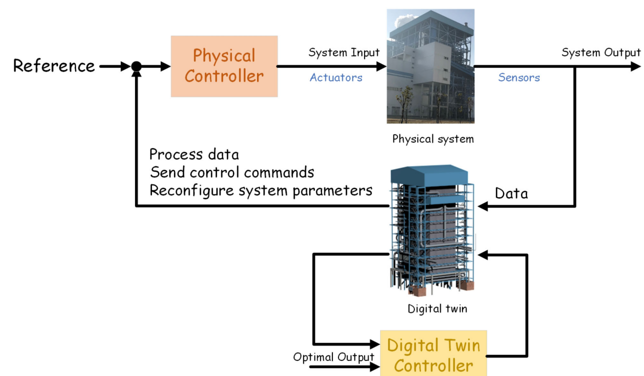


Fig. 12. Control block diagram of the physical-digital twin thermal power plant.

the textbox can change the valve position. Fig. 11 illustrates the motion control for a digital twin thermal power plant. When interactions are conducted, the motion control can reflect the real-time responses, for example, the flowmeter, temperature gauge, pressure gauge, and animations can all be employed for demonstration. All these motions are supposed to be collected and depicted on the web for real-time monitoring and control.

E. Physical-Digital Twin Control

Taking the boiler as an example, the control block diagram of the thermal power plant is illustrated in Fig. 12, which forms a closed-loop control system [39]. The physical system provides data for the digital twin system, the latter of which then processes data, sends control commands, and even reconfigures system parameters if necessary. As can be seen in Fig. 12, the output of the physical system serves as one of the two inputs of the digital twin, and the generated output of the digital twin controller acts as another input. Once the output of the digital twin converges to the optimal output, the optimal configuration between the digital twin and the physical system can be achieved. For example, for the control of the oxygen content, which is a vital part of the boiler combustion control process, under a constant main steam pressure, the fuel input, and the air input are two main factors. To achieve a good burning efficiency, thus, leading to the reduction

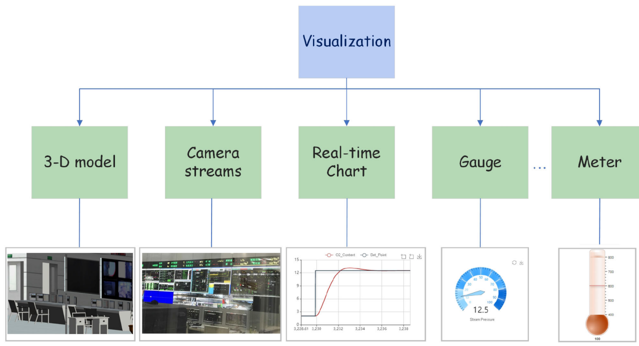


Fig. 13. Visualization for the digital twin thermal power plant.

of fuel consumption and minimization of costs, fuel input and the air input are supposed to be controlled to achieve a proper air/fuel ratio. Through changes in the fuel input, which is the output of the physical system, the error between the output of the digital twin (air input) and the optimal output (desired air input) are minimized in an iterative way. Once the error is acceptable, the output of the digital twin converges to the optimal output, thus, the desired fuel/air ratio can be achieved, which ensures a proper oxygen content.

IV. Functionalities and Provided Service

On-site visiting and watching in a physical thermal power plant is definitely intuitive and impressive for understanding the structure and function of a thermal power plant. However, the safety (both the users' and also the equipment'), cost and scale limitations are the main considerations.

As the physical thermal power plant is complex and dangerous, the research on digital twins is necessary and helpful. To achieve a web-based accessible, available (24/7), and secure power plant, the digital twin power plant can be designed and implemented with the following functionalities.

1) *Real-time monitoring:* To avoid dangerous on-site visiting and watching (which is also impossible for operating boiler units), a web-based thermal power plant that provides real-time images or video streams can be an option. However, cameras installed at the physical power plant can only provide a fixed angle of the physical power plant, and sometimes cameras installed in harsh environments can provide limited information. Moreover, the number of sensors at the physical power plant is limited. A digital twin can provide real-time monitoring of the power plant without limitation of cameras and sensors, and can provide details of the power plant from all angles.
2) *Visualization:* There are different types of signals, for example, temperature and pressure, in the thermal power plant. To ensure a full-functioning thermal power plant, these signals should be collected and processed for real-time monitoring and control. For different signals, various widgets can be developed for monitoring and control. Fig. 13 shows the illustration of visualization for a digital twin power plant, in which the 3-D model, camera stream, real-time chart, gauge, and meter can all be used for visualization of different purposes from different perspectives.
3) *Real-time interactions:* Through the implementation of digital twins, users can interact with the physical thermal power plant through a digital twin and vice versa, for example, the tuning of a valve or a knob, the response of which can be observed from both the digital twin system and the physical system in real time.
4) *Virtual reality (VR) and augmented reality (AR):* VR and AR can enhance digital twins to provide immersive environment and interactions, thus, enhance user experience and sense of presence.
5) *Algorithm design:* A thermal power plant is a complex system containing several different subsystems with different characteristics, for example, the boiler combustion process can be regarded as a multiple input and multiple output system, to which the design and implementation of different control schemes can be applied. Through the algorithm design process, users can control the process and validate their ideas.

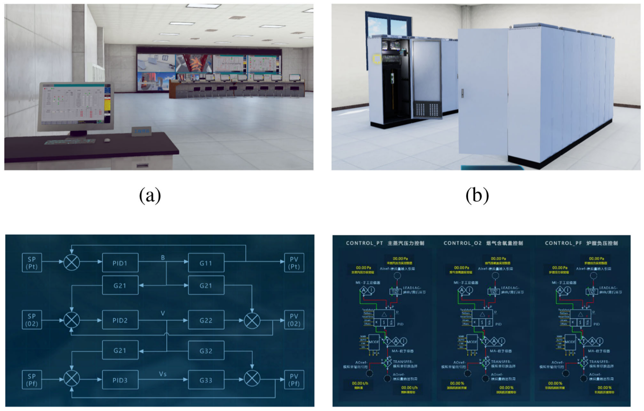
As for provided services, various scenarios in which a digital twin thermal power plant can be useful are summarized. Typically, the scenarios can be cataloged into the following two categories.

1) *For physical power plants:* Compared with the physical thermal power plant, a digital twin power plant can ensure the safety of workers as well as the equipment. Operations that are not allowed in the physical system can be simulated and possible consequences can be previewed, thus, feasible solutions to prevent accidents/incidents can be worked out. If well designed, a digital twin power plant can even be applied for fault/failure diagnosis and prognoses, for example, based on big data and AI, the failure of superheater tubes may be predicted.
2) *For universities:* A digital twin power plant can be used for training and education. Compared with traditional descriptive training, a digital twin power plant is intuitive and provides a full picture of a thermal power plant for students, which is impossible in a physical power plant. Moreover, students are allowed us to conduct operations without considering the consequences. In this way, they can see what happens if operations are wrongly conducted.

V. Case Study

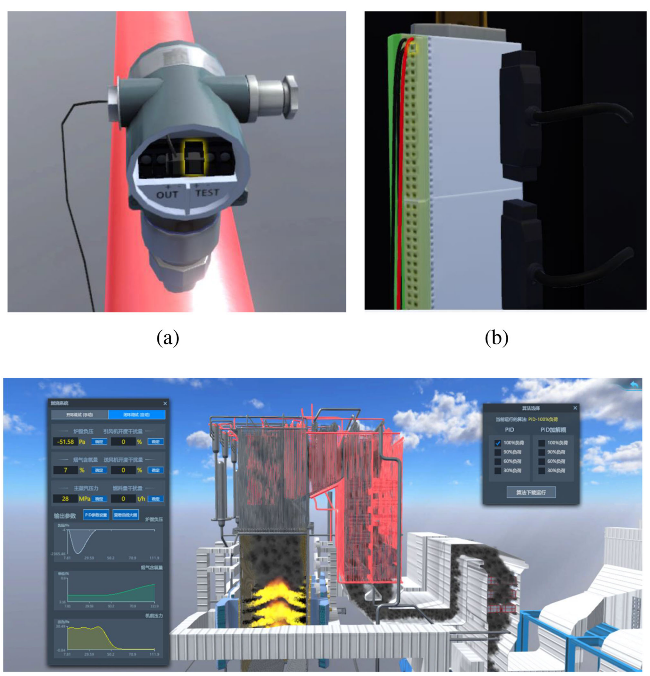
Without loss of generality, within the context of this article, the digital twin focuses on the control perspective of a 1000 MW USC unit, where the combustion process, air and flue gas system, and the distributed control system (DCS) have been designed and implemented. Control algorithms have been designed and applied into the control process.

As the Scientific Apparatus Makers Association (SAMA) diagram is typical and widely used in thermal power plants, it is also included in the web-based digital twin power plant. To ensure that the SAMA diagram control logic works, the SAMA



(a) (b) (c) (d)

Fig. 14. Web-based digital twin thermal power plant. (a) Central control room from the perspective of engineer station. (b) DCS process control room. (c) Control algorithm. (d) SAMA diagram.



(a) (b) (c)

Fig. 15. Functionalities of the proposed web-based digital twin thermal power plant. (a) Meter for the measurement of main steam pressure. (b) DCS module with wiring functionality. (c) Control of boiler combustion process.

diagram is linked to the control block diagrams designed with MATLAB/Simulink, where signals/parameters in the control block diagram can be parsed. Once parameters in the control block are linked with the designed widgets such as the textbox, virtual slider, and switch as shown in Fig. 10, they can be tuned in the web directly and corresponding signals can be monitored through the real-time chart, gauge, meter, and also through a 3-D model in the digital twin.

Fig. 14 shows a web-based digital twin thermal power plant, in which the central control room from the perspective of the engineer station [see Fig. 14(a)], and the DCS process control room [see Fig. 14(b)] are included. Moreover, control algorithms [see Fig. 14(c)] are also provided to users who can also customize their own control algorithms through the web interface, and the SAMA diagram is also provided for control [see Fig. 14(d)].

The web-based digital twin thermal power plant can be used for research and education purposes. With a mainstream web browser, users can control the power plant and then monitor the processes through digital twins and provided widgets. Fig. 15 demonstrates two examples of the functionalities of the proposed digital twin thermal power plant. Fig. 15(a) and (b) illustrates the wiring process of the meter for the measurement of main steam pressure with the corresponding DCS module, in which a click action on the meter would result in a wiring connection with the DCS module. Through wiring, the meter for the measurement of the main steam pressure can be activated. In Fig. 15(c), the control of the boiler combustion process is demonstrated. Control algorithms can be downloaded to the remote controllers and then the control process can proceed. The fuel input B^*, the air input V^*, and the air output $V_S{}^*$ can be tuned, and the corresponding states of the main steam pressure P_t, the oxygen content O_2, and the furnace negative pressure P_f can be depicted in real time.

VI. Conclusion

In this article, the methodologies to achieve toward a digital twin thermal power plant were explored. Digital twin which is a transformative technology is a crucial part of the thermal power plants as a CPS. The detailed implementation of the digital twin was explored regarding five different aspects, which provided a feasible and practicable route for monitoring and control of the digital twin via web browsers. The functionalities of a digital twin thermal power plant can be concluded as real-time monitoring, visualization, interactions, algorithm design, etc. As for provided services, the digital twin thermal power plant can be applied in different scenarios such as physical power plants and universities for training and education, and potential fault/failure diagnosis and prognoses. The case study showed an example of a working web-based digital twin thermal power plant, which could provide potential insights for other researchers regarding digital twin research and education.

There are remained issues such as cyber-attacks and communication constraints in the web-based digital twin thermal power plants, which can potentially be addressed using approaches introduced in networked control systems.

In the future, for such a huge and complicated system, multidiscipline, and interdiscipline collaboration is required for a fully functional digital twin thermal power plant.

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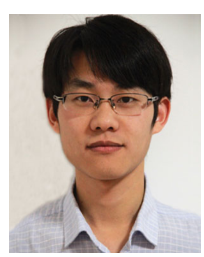

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