Received August 1, 2017, accepted September 12, 2017, date of publication September 26, 2017,
date of current version October 25, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2756069

Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing

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This work was supported in part by the National Natural Science Foundation of China under Grant 51522501, in part by the National Key Research and Development Program of China under Grant 2016YFB1101700, and in part by the Beijing Nova Program in China under Grant Z161100004916063.

ABSTRACT With the developments and applications of the new information technologies, such as cloud computing, Internet of Things, big data, and artificial intelligence, a smart manufacturing era is coming. At the same time, various national manufacturing development strategies have been put forward, such as *Industry 4.0*, *Industrial Internet*, *manufacturing based on Cyber-Physical System*, and *Made in China 2025*. However, one of specific challenges to achieve smart manufacturing with these strategies is how to converge the manufacturing physical world and the virtual world, so as to realize a series of smart operations in the manufacturing process, including smart interconnection, smart interaction, smart control and management, etc. In this context, as a basic unit of manufacturing, shop-floor is required to reach the interaction and convergence between physical and virtual spaces, which is not only the imperative demand of smart manufacturing, but also the evolving trend of itself. Accordingly, a novel concept of digital twin shop-floor (DTS) based on digital twin is explored and its four key components are discussed, including physical shop-floor, virtual shop-floor, shop-floor service system, and shop-floor digital twin data. What is more, the operation mechanisms and implementing methods for DTS are studied and key technologies as well as challenges ahead are investigated, respectively.

INDEX TERMS Smart manufacturing, digital twin shop-floor (DTS), digital twin, virtual shop-floor (VS), shop-floor service system (SSS), shop-floor digital twin data (SDTD), convergence, cyber-physical system (CPS).

I. INTRODUCTION

With the developments and applications of new information technologies, including cloud computing, Internet of Things (IoT), big data, mobile internet and Artificial Intelligence (AI), etc., various countries proposed different manufacturing strategies (e.g. Industry 4.0, Industrial Internet, Made in China 2025, service oriented manufacturing [1], [2] and cloud manufacturing [3], [4]) to prepare for the next industrial revolution. Although these strategies are nominated under different environments, their common objective is to achieve smart manufacturing that satisfies the demands of socialization, personalization, servitization, intelligence and greenization. It puts forward requirements in reaching smart interconnection and interoperability between the physical space and the virtual space. To meet these requirements, realizing the convergence of the two spaces is the key. Since shop-floor is the basic unit of manufacturing, achieving convergence of physical and virtual spaces for shop-floor becomes imperative.

Meanwhile, from the perspective of evolution, convergence is also the inevitable trend for shop-floor itself. As shown in Fig. 1, four stages are illustrated to show the process. At the first one, due to the lack of effective information means, production in shop-floor depends on physical space completely, leading to low efficiency, accuracy and transparency. Then with the developments of information technologies, computer aided systems begin to be applied in production, but as the interaction methods are weak, virtual space is out of step of the physical one. At the third stage, benefited from communication technologies, sensors, IoT, etc., interaction between the two spaces exists. In the future, with the continuous developments of new information technologies, virtual space will gradually play the equally important role with the physical one and the two-way connection will also be enhanced, which supports the further convergence.

Nowadays, shop-floor can be considered in the third stage. Current researches, regarding the interaction between the physical space and the virtual space, are briefly reviewed as

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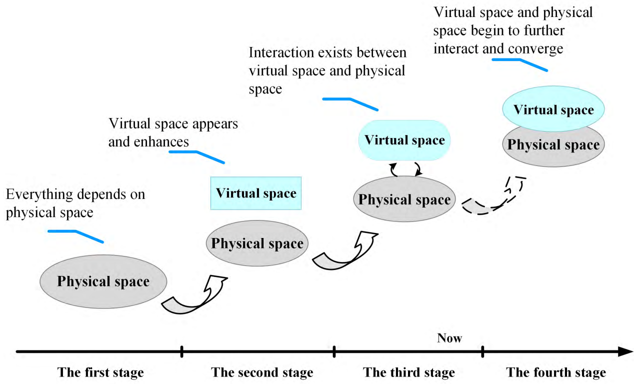

FIGURE 1. **The evolution process of shop-floor [5].**

follows. Some researches study the interaction from the perspective of framework. For example, Monostori [6] applies the concept of Cyber-Physical Production System (CPPS), which has the potential to achieve a more decentralized way of functioning and interacting. Mourtzis *et al.* [7] explore a cloud-based approach to provide maintenance for the equipment. It builds the interaction between the software services and the physical entities by the cloud infrastructure. Zhu *et al.* [8] present a five-layer web-based structure to support the interaction between the physical resources and the application softwares. To implement the interaction from framework to practice, researches also focus on the specific aspects. (1) Data collection and orders transmission at the field level are studied. Fieldbus and Industrial Ethernet are traditionally employed in the shop-floor for the connection of sensors, actuators and controllers and the related researches mainly cover the real-time communication mechanism [9], [10], protocol standardization [11], integration in intranet [12], [13], etc. With the development of IoT, Wireless Sensor Network (WSN) and Radio Frequency Identification (RFID) are applied in shop-floor, collecting real-time states of equipment [14], [15], work-in-process [16], materials [17], etc., which increases flexibility for data acquisition. Meanwhile, standardized technologies and devices are studied to shield the heterogeneity of protocols and interfaces, such as MTConnect [18], middleware technology [19], coherent and semantic encapsulation for field data [20], [21]. (2) As the field data are collected, various data processing methods are studied to transform them into valuable information to support the further analysis and decision in the virtual space, including data cleaning [22], data mining [23], data fusion [24], etc. (3) In virtual space, information systems are built to optimize the production process. For instance, Zhong *et al.* build an RFID-enabled real-time manufacturing execution system, which provides more practical planning and scheduling decisions for shop-floor [25]. Luo and Kuo build a robot arm system to realize the proper grasp of target object in physical space [26]. Fang et al. propose an event-driven shop-floor work-in-progress management platform to monitor and control the dynamic production [27]. (4) Meanwhile, with the development of virtual manufacturing, a virtual environment, in which models replace physical entities for evaluation, verification and optimization, is established. After that, layout optimization [28], production planning [29], [30] and fault diagnosis [31], etc. are analyzed and verified in virtual space. (5) To normalize the interaction between the physical and virtual spaces, technology standards on smart connection, data to information conversion, cyber computation, etc. are researched [32]. (6) Security is another focused field. For example, studies that assess and guarantee the security of sensors [33], wireless communications [34], function blocks [35], etc. against malicious attacks are carried out.

From the review, current researches contribute largely to the interaction between physical and virtual spaces. However, to realize the further convergence, improving the status of virtual space and converging its models, data and mechanisms with the physical one are critical. To implement the aim, the following three issues are inevitable, including (1) how to build a high-fidelity virtual companion, which exists parallel and plays the same important role with the shop-floor; (2) how to make the shop-floor and its companion keep consistency and synchronism with each other and realize dual optimization; (3) how to converge data from both physical assets and digital models to generate valuable information for the production.

To solve the above issues, digital twin, a reference model to realize the convergence between physical and virtual spaces, has gained wide attentions recently. It was proposed by Grieves in 2003 at his executive course on product lifecycle management in University of Michigan and defined as three parts, i.e. physical product in real space, virtual product in virtual space and the connection of data and information that ties the two spaces together [36]. It combines the physical entity with high-fidelity virtual counterpart and the two parts company with each other during the lifecycle. The virtual part not only records the history performances of the physical one, but also carries out optimization and prediction for it. Meanwhile, the physical part provides its properties, behaviors and rules for the virtual mirror to make it calibrated and evolved continuously. Difference appearing between the two parts can be wisely used to eliminate the disturbances and uncertainties and realize the dual optimization. Digital twin also integrates and converges data from multiple sources, like sensor data, model data and domain knowledge to generate more accurate and comprehensive information. Nowadays, digital twin has been applied in aerospace for aircraft real-time monitoring, diagnosis and prognosis, maintenance, etc. [37], [38]. Some enterprises (e.g. Siemens, Dassault, PTC) also use digital twin to support their services for customers [39].

Based on digital twin, the concept of Digital Twin Shop-floor (DTS) [5] is proposed, providing an effective way to reach the physical-virtual convergence. DTS presents the shop-floor in dual visions, the physical and the virtual. It makes these two parts keep in consistency and optimized by each other. Data from both physical and virtual sides as well as the fused data are provided to drive the production. In this paper, the conceptual model and specific operation mechanism for DTS are discussed. Then the implementing methods of its four components, namely Physical Shop-floor (PS), Virtual Shop-floor (VS), Shop-floor Service System (SSS) and Shop-floor Digital Twin Data (SDTD), are studied respectively, which provides a deeper insight into DTS as well as a reference for the further realization. At last, key technologies and challenges for DTS are explored as guidelines for the future studies.

The remainder of this paper is organized as follows. In Section II, the traditional production process and its future trend are proposed. Section III introduces the concept of DTS as well as its operation mechanism. The implementing methods for PS, VS, SSS and SDTD are illustrated in Section IV. Section V discusses the key technologies and challenges of DTS and section VI concludes this study and points out the future work.

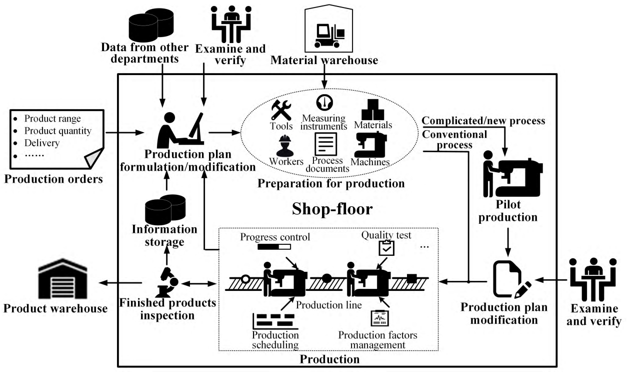

FIGURE 2. Traditional production process of shop-floor.

II. PRODUCTION PROCESS IN SHOP-FLOOR AND NEW INFORMATION TECHNOLOGIES

The traditional production process of shop-floor is shown in Fig. 2. Before production, the production plan is generated based on the orders, advice from other departments and history production data, etc. It illustrates specific tasks for groups, workstations and individuals. With the plan passing the examination and verification, preparation for production is carried out, such as worker training and allocation, equipment maintenance and material collection. It is necessary to organize pilot production for complicated or new process. However, in conventional process, this procedure can be omitted. The formal production is organized according to the plan and during it, scheduling, congress control, quality test and management of production factors, etc. ensure the normal operation. If some conflicts appear, the plan is modified to adapt to the actual situations. After production, finished products are inspected to ensure whether the indicators like size, shape and performance meet requirements. Then qualified products are transported into the warehouse, while the unqualified need repairing. Information generated during production such as process documents, fault records and standard specifications are kept in files for the next round.

However, for the above traditional process, the function of virtual space is limited and it tends to rely on the physical world, but lacks of autonomy and evolution. The consistency and synchronism between the physical and virtual spaces are difficult to warrant. What is more, this process usually focuses on the collection, storage, test, process and control of data obtained from entities, but ignores data of simulation, optimization, prediction and verification generated by models and information systems, especially the fused data converging both the physical and virtual sides. In this situation, a series of problems usually exist, for examples, the inconsistence between the plan and the actual production, the unreasonable resource allocation and the inaccuracy in production control.

Nowadays, new information technologies are developed considerably and applied widely. IoT provides ubiquitous sensing ability to collect data from different factors, businesses and processes of shop-floor. Cyber-Physical System (CPS) integrates the computational and physical capabilities, which makes physical resources be capable of computing, communicating and controlling. Since cloud computing provides powerful computing capability, it lays the foundation for building and operating sophisticated models. By big data and AI, intelligence can be given to entities, models and systems, which supports the autonomous negotiation and cooperation between physical and virtual spaces. These technologies enable digital twin to be applied in the shop-floor. Embracing digital twin to converge the physical and virtual spaces, so as to solve the existing problems and realize smart production and management will be the inevitable trend.

III. CONCEPT AND OPERATION OF DTS

A. CONCEPT OF DTS

As shown in Fig. 3, DTS consists of four components, PS, VS, SSS and SDTD. PS includes a series of entities, such as human, machines and materials, existing objectively in physical space. Strictly following the predefined orders from both VS and SSS, PS organizes production meeting the requirements of delivery, cost and quality, etc. VS consists of models built in multiple dimensions, including geometry, physics, behavior and rule. VS evolves with PS, providing control orders for PS and optimization strategies for SSS. SSS is an integrated service platform, which encapsulates the functions of Enterprise Information System (EIS), computer-aided tools, models and algorithms, etc. into sub-services, then combines them to form composite services for specific demands from PS and VS. SDTD includes PS data, VS data and SSS data, the fused data of the three parts, as well as the existing methods for modeling, optimizing and predicting, etc. Data in SDTD are integrated, which eliminates the information isolated island. What is more, the fused data converge those from both physical and virtual spaces, providing more comprehensive and consistent information.

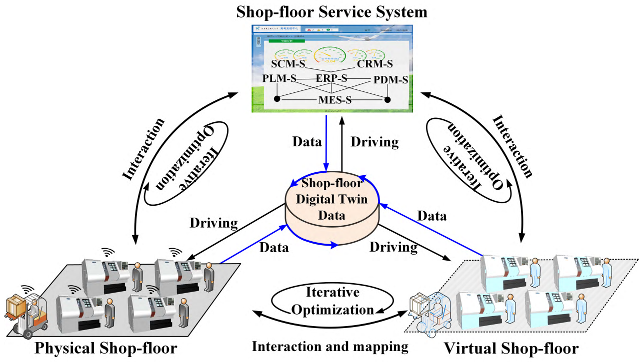

FIGURE 3. **Conceptual model of DTS [5].**

In Fig. 3, SDTD works as the "driver" for the other three parts. For PS, data in SDTD make the entities be aware of the states of themselves and others as well as the global production target. If necessary, the entities make allowable adjustments driven by SDTD to better implement cooperation. For VS, the models and their operation mechanisms are built and updated based on the relations, constrains and rules mined from SDTD. Towards the specific demand, SDTD provides SSS the corresponding data, algorithms and models, etc., which are encapsulated into sub-services to drive the service composition and the subsequent service process.

Interactions between PS and VS, VS and SSS, SSS and PS are interpreted respectively as follows. (1) PS generates actual states to update the models in VS and evaluate their accuracy, while VS feedbacks control orders to make PS achieve synchronism with the predefined process. (2) On one hand, SSS provides services to support normal operation and evolution of VS. On the other hand, the services provided for PS are transmitted to VS first for verification and VS feedbacks modification advice to SSS. (3) Actual states monitored in PS are transmitted to SSS. After the demand analysis, SSS provides services for PS, which have been verified in VS, to optimize the production.

With PS, VS and SSS evolving with time, continuous interactions make them keep in consistency with each other and optimized iteratively.

B. OPERATION MECHANISM OF DTS

As shown in Fig. 4, the operation mechanism of DTS is illustrated in three stages, including before production, during production and after production. In this figure, yellow block, blue block and purple block represent PS, VS and SSS respectively, and their operations and interactions are supported by data, namely SDTD.

Before production, orders (e.g. delivery, quantity, cost and quality) are transmitted to the production plan service in SSS. To support the formulation of production plan, related data are collected, including sensor data (e.g. material stock, human workload and equipment capacity), simulation data (e.g. prediction of equipment fault, assessment of human physical power and analysis on material performance) and EIS data (e.g. product lifecycle data, process document and market data). Since these data come from PS as well as VS and SSS, data fusion service is provided to fuse them and generate consistent interpretation for the certain object. Driven by the fused data, production plan service produces production plan, which is then given to VS for verification. VS finds potential conflicts in the plan before actual production and feedbacks modification strategies to the service. After revision, the plan is transmitted to resource allocation service which guides the preparation for production in PS. If the real-time states of resources change, modification advice can still be given back to production plan service.

During production, the verified plan is transmitted to VS to predefine the production in virtual space. Then control orders from VS are given to PS to start the actual process and keep it synchronize with the predefined one. On one hand, real-time data generated by PS are recorded in VS and, on the other hand, simulation, evaluation and optimization, etc. based on models are carried out in real time and generate orders to regulate the production in PS whenever necessary. During this process, the predefined data from VS are compared with real-time data from PS continuously. If the two parts are not consistent, the evaluation service driven by fused data will be given. It judges whether the inconsistence is caused by the disturbances in PS (e.g. equipment failure, material shortage and emergency order) or by the inaccuracy of models in VS (e.g. unreasonable setting on boundary and initial condition). If disturbances exist in PS, corresponding services, such as scheduling service, quality service and congress service, will eliminate or reduce them. These services are given to VS first for verification, then transformed into control orders to regulate PS. Otherwise, the inconsistency may be caused by VS. In this condition, services for model calibration are scheduled and implemented on VS. The production plan verified by the previous models should be regulated based on the calibrated ones, while the production process will be adjusted accordingly.

After production, the finished products are outputted and transported to warehouses. At the same time, the history production data are achieved from the records in models. Based on these data, data mining service extracts new knowledge for model building and calibration. With the adjustable timeline, VS can playback the historical situations, which is an effective way to find out the defects in previous productions as well as the corresponding solutions.

From the perspective of DTS, it is a constant evolution process along with different rounds of productions.

IV. IMPLEMENTING OF DTS

A. PHYSICAL SHOP-FLOOR (PS)

As shown in Fig. 5, except traditional production abilities, PS in DTS is also able to realize the interconnection and interaction. It means that from the vertical perspective, production factors (i.e. human, equipment, materials, environment) convey data to virtual space and receive control orders from it, while from the horizontal, they sense other production factors

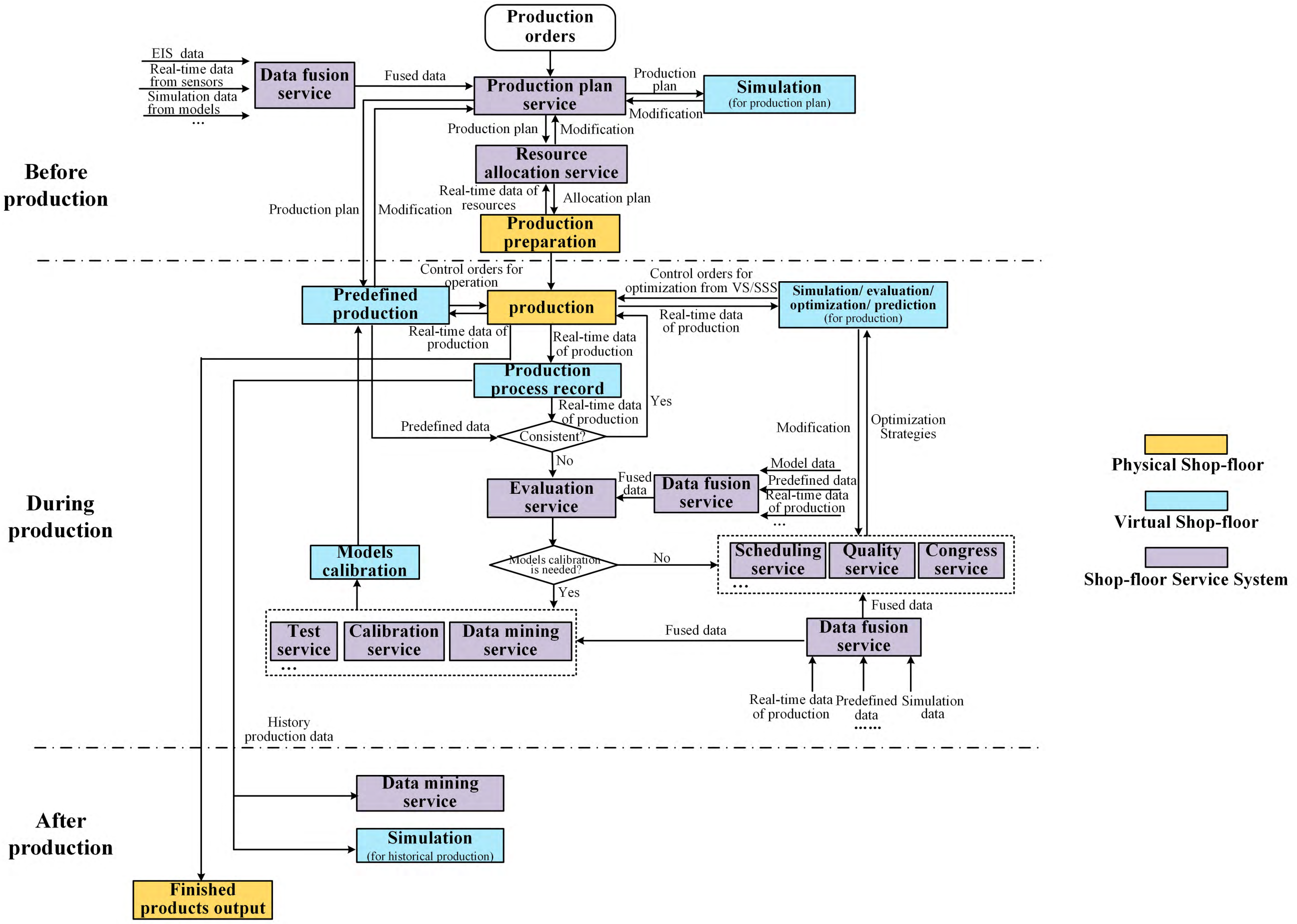

FIGURE 4. Operation mechanism of DTS.

and regulate the behaviors of themselves or others on a global target.

Data of production factors should be retrieved in real time. Considering the heterogeneity, different sensors are applied. For human, portable devices collect physical power, motion and work congress, etc. Wired or wireless sensors can be deployed on equipment to achieve the states such as machine speed, energy consumption and tool wear and, for equipment with high degree of automation, these data can be read from embedded modules of its own. RFID can be used for lifecycle tracking of materials and environmental sensors detect the real-time changes of the environment.

However, these data are usually transmitted with different interfaces (e.g. RS232, CAN and ZigBee) and communication protocols (e.g. Profibus, TCP/IP and Modbus), which makes it difficult to implement unified data access to virtual space. Hence, it is necessary to deploy customized access modules, through which data from different sources are transformed into uniformed interface and protocol. In addition, since accessed data always have different formats, types and information models, data integration including cleaning, format conversion, association, etc. should be carried out.

Based on the integrated data, collaborative network, describing the production factors and their relations, is built for the common and compatible goals during the production. In the network, production factors are represented by nodes which have the abilities to sense, compute and interact, while their relations are expressed by edges. According to the orders from virtual space, the node asks others to cooperate with it and also responds to requests propagated by others, which makes PS own stronger adaptability, flexibility and robustness.

Orders from collaborative network are transmitted to customized access modules for interface and protocol conversion to adapt to different communication modes of actuators in PS. Finally, the orders are performed to control and coordinate the production.

B. VIRTUAL SHOP-FLOOR (VS)

As the digital mirror, to simulate the physical counterpart with high fidelity, VS is built in four levels, i.e. geometry, physics, behavior and rule. As shown in Fig.6, the modeling process of CNC machine is taken as an example. Firstly, three-dimensional geometric models are built to describe shapes, sizes, positions and assembly relations of machine components. The common tools for these models include

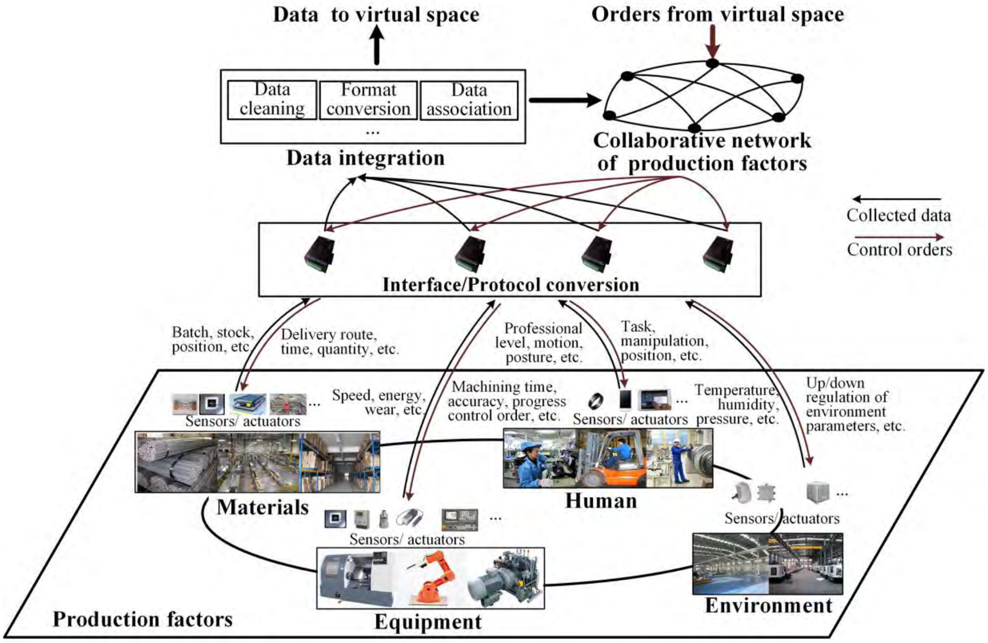

FIGURE 5. Interconnection and interaction in PS.

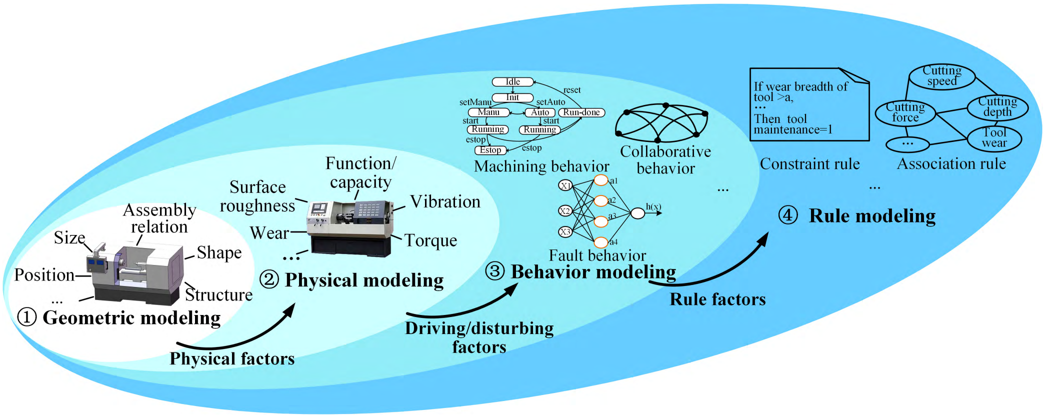

FIGURE 6. Four steps of modeling for CNC machine in VS.

SolidWorks, 3D MAX, AutoCAD, CATIA, etc. Secondly, physical properties (e.g. function/capacity, cutting force, torque and wear) and loads (e.g. stress, resistance and temperature) are given to the geometric models to form the physical models, which analyze physical phenomena, such as deformation, cracking and corrosion. Finite Element Model (FEM) can be used for simulation in this level. Then the behavior models are built to describe the machine responsive mechanisms under driving factors such as NC programs and disturbing factors such as human interferences. Finite state machine, neural network and complex network, etc. can be applied to describe the responsive processes. At last, rules of associations, constraints and deductions are modeled to describe the domain knowledge and make the above three kinds of models be capable of evaluating, reasoning and predicting. To build the rule models, data mining algorithms, such as apriori, support vector machine and K-means can be used.

After modeling, models in four levels are integrated in both function and structure to form a complete virtual CNC machine. For other entities in PS, the modeling processes are similar.

To ensure the accuracy of models, Verification Validation and Accreditation (VV&A) tests the transformations from models to program codes, compares the inputs and outputs of models with entities and estimates the models sensitivity. In addition, with Virtual Reality (VR) and Augmented Reality (AR), VS presents vivid three-dimensional images and overlaps virtual models on physical entities, providing an immersive environment for users.

As shown in Fig.7, models operation and evolution are parallel processes. During operation, models run synchronously with the physical counterparts. Calibration strategies are generated through comparing the models with entities to support models evolution, which means a higher fidelity to PS. At the same time, the evolved models support more accurate estimation, verification, optimization and prediction for the operation process.

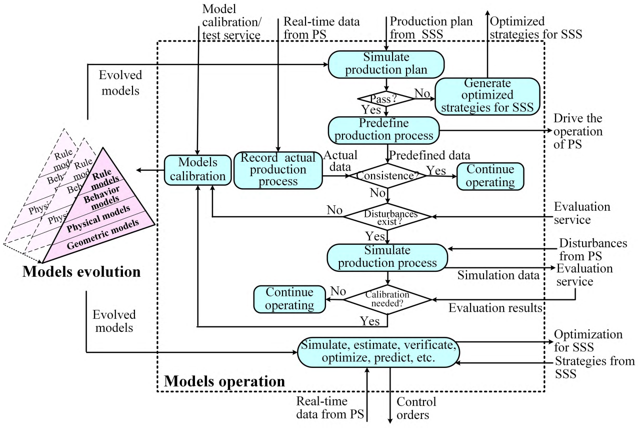

FIGURE 7. The operation and evolution of models in VS.

Firstly, the production plan from SSS is transmitted to VS for verification. Based on the verified plan, predefined virtual production process will form and drive the actual production in PS. As entities start to work, real-time data generated by them are recorded and compared with data from predefined process to evaluate the consistence. If the two kinds of data are aligned, the accuracy of models is confirmed, otherwise, evaluation service will be scheduled to estimate the reason of inconsistence. In this process, if disturbances do not exist in PS, it can be considered that the inconsistence is caused by the defects of models and calibrations are needed. If disturbances indeed exist in PS, they will be captured and provided for models. Simulation is carried out again under the disturbances which are unknown to VS before. If the simulation results still cannot reach an agreement with the actual states, calibrations are needed, otherwise, it can be considered that the models are accurate. With models evolving to approach entities continuously, the simulations for PS and SSS will be more accurate.

C. SHOP-FLOOR SERVICE SYSTEM (SSS)

SSS provides various services to support the management and control of PS as well as the operation and evolution of VS. As shown in Fig. 8, resources such as data, models, algorithms are encapsulated into sub-services and then selected to form composite services for demands from PS or VS. The operation mechanism is described as follows.

Sub-services in SSS are transformed from resources including data, models, algorithms, existing systems, visualization approaches, etc. The data consist of those from PS, VS, SSS and their fused data, while the models and algorithms are mainly existing modeling and data processing methods. Systems refer to EIS and other computer-aided tools. Virtualization approaches provide different display methods to present information in a vivid way. To realize the mirrors from resources to sub-services, processes like service description, virtualization, encapsulation and register are needed.

Demands from PS mainly include production planning and scheduling, quality test, congress control, etc., which ask for solving the existing problems quickly and preventing the possible faults during the production. Meanwhile, demands from VS mainly require calibration and test, data mining, etc. to support the model operation and evolution. These demands can be decomposed into sub-demands which usually focus on problems like what data should be used, which model is the most suitable and which algorithm provides the best solution. According to these, SSS selects suitable sub-services from candidate ones, then combines them under certain rules to form composite services for PS or VS, which are monitored at runtime and will be recomposed if work unexpectedly.

For VS, composite services are transmitted to models directly and for PS, they are conveyed to VS first for verification and then to PS for execution. Also, the services can be scheduled manually through application software on computer or mobile phone if necessary.

D. SHOP-FLOOR DIGITAL TWIN DATA (SDTD)

SDTD mainly consists of PS data, VS data, SSS data, the fused data of the three parts as well as the existing modeling and data processing methods, etc. PS data mainly include production factor data, production process data and environment data. They are directly generated by entities without further processing and considered as physical data. VS data refer to model parameters and data of simulation, evaluation, optimization and prediction, while SSS data mainly involve data of various services. These two kinds of data are deduced from physical data and defined as virtual data. Fused data are the integration and convergence of physical and virtual data through data comparison, association, combination and clustering, etc. For example, wear data of machine tool from physical space can be combined with its simulation data about stress, deformation and strength as well as service data about scheduling and maintenance records from information systems to form the fused data. It presents the tool correlating both the physical and virtual information, providing more consistent, accurate and comprehensive representation compared with the data from single aspect.

The construction of SDTD is described as follows. Firstly, data conversion makes data from PS, VS and SSS with various formats, types, structures and encapsulations into the unified form. Then data cleaning detects and removes dirty data (e.g. errors, duplicate data, invalid data) and replenishes missing data to improve the data quality. Thirdly, to achieve consistent and comprehensive interpretations, data fusion is applied. As shown in Fig. 9, physical data and virtual data

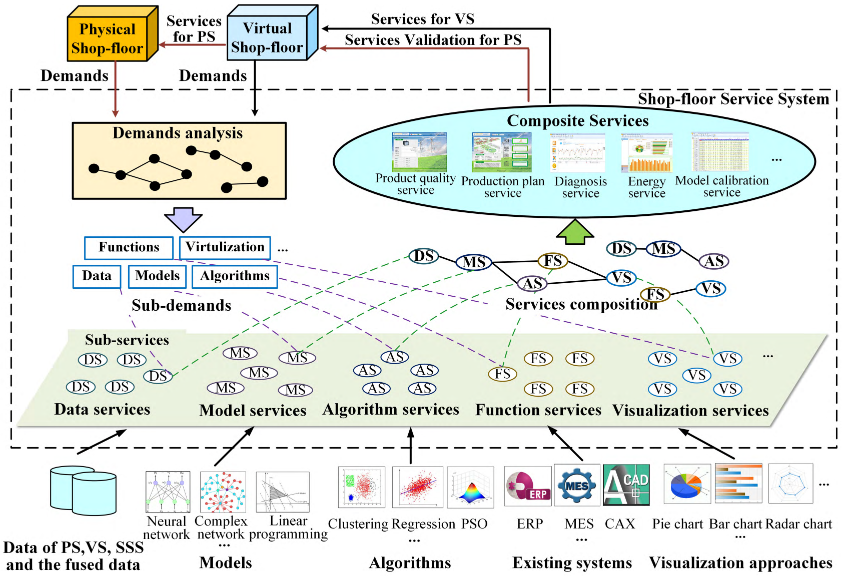

FIGURE 8. The operation mechanism of SSS.

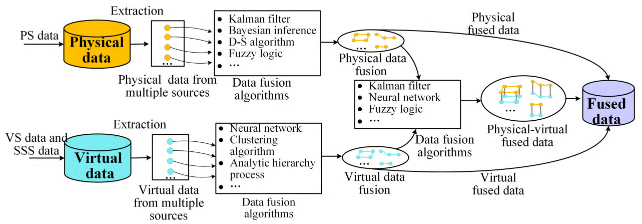

FIGURE 9. Data fusion of SDTD.

are converged to form fused data through data fusion algorithms, such as kalman filter, neural network and bayesian inference.

SDTD is optimized iteratively through the interaction between different kinds of data. On one aspect, the history data are updated and expanded with the real-time data joining, while the real-time data can be tested and corrected according to the knowledge accumulated in the historical. On the other aspect, the physical data can be evaluated and simulated by the virtual data, while the virtual can be compared with the physical to confirm the accuracy.

V. KEY TECHNOLOGIES AND CHALLENGES FOR DTS

A. KEY TECHNOLOGIES

As shown in Fig. 10, key technologies for implementing DTS are concluded in five aspects and the specifications in each aspect are given as well.

1) Interconnection and interaction in PS

Related technologies include the perception and access, communication protocol analysis, data encapsulation and publication, multi-agent technology, etc.

2) Modeling, operation and verification of VS

Technologies including multi-dimension modeling, model integration and model verification, etc. need to be addressed.

3) Construction and management of SDTD

Technologies involve data cleaning, data integration, data fusion, two-way mirrors between physical and virtual data, shop-floor big data [40], etc.

4) Operation and evolution of DTS

Technologies including iterative optimization, self-learning, self- organization and self-adaption mechanisms, standardization, etc. need to be explored.

5) Smart production and precious services based on SDTD

Services encapsulation, composition and publication, demand decomposition, precious service-demand matching, energy consumption management [41], etc. should be studied.

B. CHALLENGES AHEAD

Challenges exist when it comes to the fully realization of DTS. Firstly, it is necessary to keep adequate two-way connection between physical and virtual spaces to support the real-time interaction. It mainly addresses challenges on technologies of sensors, communication, database and data processing, etc. Secondly, due to the variability, uncertainty and fuzziness of physical space, building models in virtual space to mirror entities with high fidelity is a fundamental issue. In addition, when inconsistences between models and entities appear, how to identify and utilize them wisely is also difficult. Thirdly, as the continuous physical space and discrete virtual space are in different scales, how to transcend the divergence to realize the seamless integration of the two sides is challenging. With virtual space evolving with the physical one along the lifecycle, data from entities, models and systems are generated continuously. In this situation, how to integrate and converge the increasing data is a challenge. Also, security is another focus that ensures the normal operation of physical and virtual spaces against the malicious

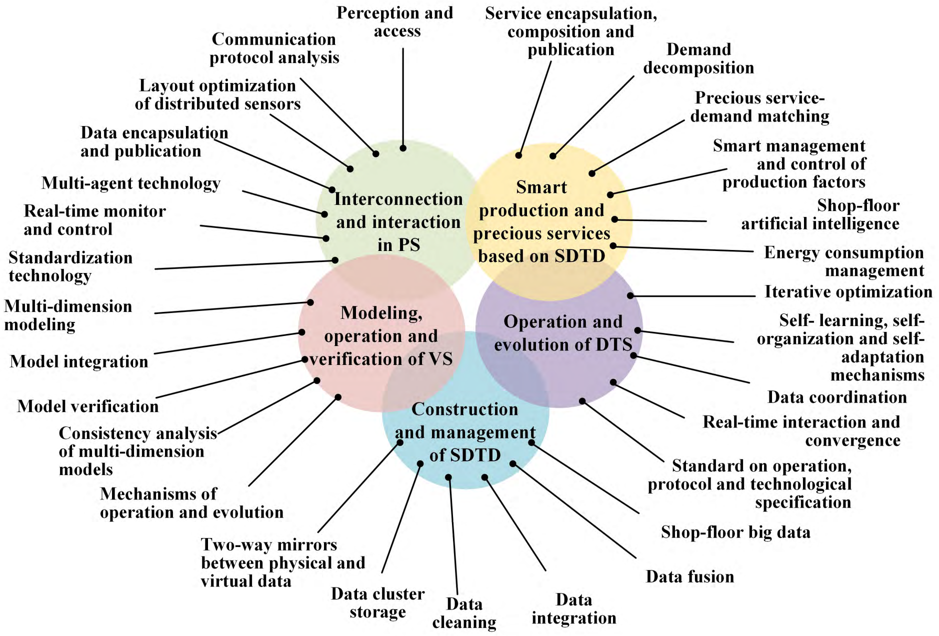

FIGURE 10. Key technologies for DTS [5].

attacks. By the way, to guarantee the interests of enterprises, how to realize the equilibrium between costs and interests of DTS should be considered.

VI. CONCLUSIONS AND FUTURE WORK

With new information technologies developed and applied continuously, developing DTS to start new paradigm of shop-floor becomes imperative. To support the further convergence in shop-floor, DTS provides evolved models with high fidelity, continuous interactions between physical and virtual spaces and fused data converging those two spaces. This paper provides an insight into DTS and a guideline for the future work. The main contributions are concluded as follows: 1) The concept and operation mechanism of DTS are explored. 2) The implementing methods for four components of DTS are illustrated. 3) The key technologies and challenges ahead are discussed. At present, the research is in an initial stage and still needs a lot of work. Future work will focus on the following aspects: 1) smart interconnection and interaction in PS, 2) two-way connection between physical and virtual spaces, 3) high-fidelity models for VS, 4) service management and precious service-demand matching, 5) applications of DTS in smart manufacturing.

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