DOI 10.15302/J-SSCAE-2018.04.014

# Foundation of Aeronautical Intelligent Manufacturing—Software Definition to Innovate Industrial Paradigms

**Ning Zhenbo**

AVIC Information Technology Co., Ltd., Beijing 100028, China

**Abstract:** Based on the latest Perspective article *Toward New-Generation Intelligent Manufacturing* from *Engineering*, a journal of the Chinese Academy of Engineering, combined with the evolutionary path of intelligent manufacturing in the aviation industry, this paper reviews the traditional human–physical systems (HPS), analyzes the transition of the aircraft manufacturing industry from digital to intelligent development, and expounds the transition of aircraft from model-based digital definition to digital definition based on cyber–physical systems (CPS). New-generation intelligent manufacturing relies on new-generation information technologies such as cloud technology, Internet of Things, mobile communication, big data, and artificial intelligence to achieve deep integration with humans, equipment, and materials. Furthermore, the typical feature of new-generation intelligent manufacturing is a digital twin enabled by the digital thread.

**Keywords:** new-generation intelligent manufacturing; digital product definition; digital product assembly; integrated product team; model-based definition; human–cyber–physical systems

## 1 Introduction

The Chinese Academy of Engineering has published its latest findings in an article titled *Toward the New Generation of Intelligent Manufacturing* in its journal, *Engineering*. This article introduces three basic paradigms of intelligent manufacturing: digital manufacturing, smart manufacturing, and new-generation intelligent manufacturing. The article states that intelligent manufacturing is a general concept that evolves from traditional "human–physical systems (HPS)" to "human–cyber–physical systems (HCPS)," focusing on the integration of the information system between traditional human and physical systems. With continuous enhancement of the perception, calculation, analysis, and control ability of information systems, the ideal information systems of the future will have the ability of upgrading themselves based on learning and knowledge generation capabilities [1].

As information systems are developed, software is the basic support required to strengthen the integration of information and industrial technologies. The *Guidelines on Deepening the Integration of Manufacturing and the Internet* issued by the State Council also emphasizes the accelerated industrialization of industrial software, such as computer-aided design and simulation, manufacturing execution system, and product lifecycle management with the purpose of strengthening software support and the fundamental role of defining manufacturing [2]. The new generation of intelligent manufacturing is a giant system integrated with industrial technology, comprising three intelligent systems—intelligent products, intelligent production, and intelligent services—and two supportive intelligent systems—the industrial intelligence networking system and the intelligent manufacturing cloud system. At the methodology level, the system promotes R&D virtualization and generates various professional tools based on physical technology. At the process level, the system promotes management informationization and generates various kinds of business systems with process management

**Received date:** July 20, 2018; **Revised date:** August 1, 2018
**Corresponding author:** Ning Zhenbo, AVIC Information Technology Co., Ltd., Researcher. Major research field is digital design and manufacturing of aircrafts. E-mail: ningzhenbo@163.com
**Funding program:** CAE Advisory Project "Research on Intelligent Manufacturing Led by New-Generation Artificial Intelligence" (2017-ZD-08-03)
**Chinese version:** Strategic Study of CAE 2018, 20 (4): 085–089
**Cited item:** Ning Zhenbo. Foundation of Aeronautical Intelligent Manufacturing—Software Definition to Innovate Industrial Paradigms. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2018.04.014

as the cores. At the device level, the system promotes the automation of production equipment and product intelligence, generating various kinds of embedded software. Therefore, in the development process of intelligent manufacturing, the essence of the new industrial revolution is the enhanced application of software definitions in the innovation of industrial paradigms (including defining products, enterprise processes, production methods, new types of enterprise capabilities, and the ecology of industries) and the realization of production mode revolution with software definition as the core.

## 2 The paper-based symbolic definition

The definition of the traditional manufacturing industry is regarded as the paper-based symbolic definition. Tradition is, of course, distinct from modernity. The distinction criteria are based mainly on technology. The modern manufacturing is characterized by its sophistication, such as new aircraft, micro-nano, laser, semiconductors, CNC lathes, and a series of other industries supported by modern high-end technology. On the contrary, those that still use old manufacturing technology belong to the traditional manufacturing industry. The traditional manufacturing system consists of two parts: human and physical systems, through human control of machine operation for the completion of various tasks. The Industrial Revolution consisted of two milestones: the first and second industrial revolutions. The applications of steam engines, internal combustion engines, and electric engines (including electric generators and electric motors) are based on human−physical systems. According to the book *Three-Body Intelligence Revolution*, a perfect intelligent system must have the features of "state perception, real-time analysis, independent decision-making, accurate execution, and learning-based upgrading," and it should evolve in this cycle [3]. In human−physical systems, human beings perform state perception, real-time analysis, autonomous decision-making, and learning-based upgrading, while machines merely perform accurate executions under human control.

The paper-based symbolic definition states that the industrial paradigm of the traditional manufacturing industry works in the serial mode of design−manufacturing−experiment, which has been termed Edison's "trial and error method" in the past. First, the symbolic definition based on the paper can be seen in the blueprints of manual designs (blueprints for parts and assembly), process cards, various forms, production plans, and paper documents. It is based on the manual definition of all kinds of design documents so that the follow-up work, such as process design, can be carried out. Thereafter, various parts can be trial-produced using machines and then assembled into prototype products. Experiments are performed to test the design function and performance of the products, followed by batch production after the design targets are met. Failure to meet the design targets necessitates the modification of the design and process until the design targets are eventually met. Under this industrial paradigm, the application scope and depth of manual drafting for the past 200 years and early computer-aided design (CAD) software have been limited. These primarily focus on the consistency and standardization of the expression of engineering intention. An example is the large scale use of CAD software in the 1980s and 1990s. The improvement of industrial efficiency still depends mainly on machines (materials, equipment, tooling, tools, and testing instruments) used for processing, which are a result of the invention of steam, internal combustion, and electric engines, tremendously enhancing the production efficiency and quality of physical systems (machines). Machines replace a considerable amount of human physical labor. In the traditional manufacturing system, people are required to complete many tasks such as state perception, real-time analysis, autonomous decision-making, operation execution, and learning-based upgrading. Apart from the high demand on humans, the labor intensity is also still high, but the efficiency, quality, and ability to complete complex tasks are also limited.

## 3 Model-based digital definition

Compared with the traditional manufacturing system, the industrial paradigm of first- and second-generation intelligent manufacturing has changed substantially, which is exemplified by the breakthrough of the digital product definition (DPD), digital product pre-assembly (DPA), integrated product development team (IPT) of Boeing 777, and model-based definition (MBD) of Boeing 787. By introducing information systems between people and physical systems, it replicates and migrates a significant portion of human perception, analysis, and decision-making functions to information systems, with local information systems carrying out the mental work in place of human beings and extensive control of the physical system moved to the information system for the purposes of completing more manual labor in place of human beings.

The Boeing 777 is the first product in the world that uses software to define the manufacturing process of the aircraft. Three techniques are used: 100% DPD, 100% DPA, and 327 IPTs in parallel. The computer software and hardware used in the development are as follows: 8 IBM mainframe computers, 3200 UNIX workstations used in 3D design that are all connected to the network, approximately 20 000 PC computers, and 800 types of independent software. The MBD technology is fully applied to the design of Boeing 787 aircraft. MBD technology is responsible for the change in tradition of describing geometric shape information with two-dimensional graph documentation, and expresses the complete product definition information with an integrated 3D digital solid model, which becomes the only basis in the manufacturing process [4].

As a result of the technological progress of digitization and management reform adopting concurrent engineering, the development cycle duration of the Boeing 777 has been reduced from 12 to 4.5 years compared with its equivalent; the Boeing 767. The first Boeing 777 being built was of better quality compared with the 400th Boeing 747, which had been manufactured for 24 years. What is more significant is that the model-based digital definition overturns the traditional industrial paradigm of design–manufacturing–experiment and realizes the transformation of the industrial paradigm to design–virtual synthesis–digital manufacturing–physical manufacturing.

In Fig. 1, for ease of understanding, aircraft development is divided into four phases that are described below. The first stage is the conceptual design phase (including requirements engineering, conceptual design, and blueprint design) with focus on the aerodynamic and general layout of the aircraft. In the trial and error method, the flight sectional view is calculated according to the tactical and technical indexes, based on the drawn outline sketch followed by the processing of the scale model, which is tested in a wind tunnel to determine the aerodynamic configuration. The process is repeated until satisfactory results are obtained. As it takes several months to process an airplane scale model and it is costly to carry out a test in a wind tunnel, it takes many years and extensive planning to obtain a satisfactory plan with repeated comparisons (see the upper left picture of the wind tunnel in Fig. 1). The method described in this paper is the first of its kind, capable of constructing a virtual airplane aerodynamic outline on a computer with software (see the lower left picture of an airplane in Fig. 1) based on the results of the aerodynamic mathematical calculation method. Repeated optimization of the computational fluid dynamics calculation is performed until the best option is obtained, followed by the processing of a scale model suitable for testing in a wind tunnel. These technologies have already being applied at a large scale in the aeronautics and astronautics fields.

Consider the Boeing 787: Mike Bayer, Senior Vice President of the Boeing 787 Program stated that "We have tested more than 50 different wing configurations in the 767 project, while in the 787 project, we have only performed approximately 10 tests." With fewer wind tunnel tests and better aircraft quality, the software defines the aerodynamic layout of the aircraft during the conceptual design phase.

The second phase is engineering development. When the aerodynamic and overall layouts of the aircraft have been determined, structural design can begin. Almost all CAD software can accomplish the structural design. In the Boeing 777 project of 1991, the utilized CAD software was only capable of defining geometric shapes. However, in 2004 when the Boeing 787 was being developed, the CAD software was not only capable of defining geometric shapes but also of generating the material, process, standard, production definition, and testing data related to the mechanical structure, and all the data related to the manufacturing process expressed in the 3D model; realizing the software definition of the part being designed, and then that of the product, i.e., the MBD. In other words, the representation of all of the data on a 3D model means that paper-based symbolic definitions, such as traditional blueprints and process cards, can be eliminated. This is the digital revolution. With a complete digital mockup (DMU), virtual reality can be used to realistically simulate many types of applications. The manufacturing process then merely translates into conformance with the design, that is, the physical realization of the digital prototype. The full digital and physical prototypes are shown in the lower middle and upper middle panels of Fig. 1, respectively. It should be noted that

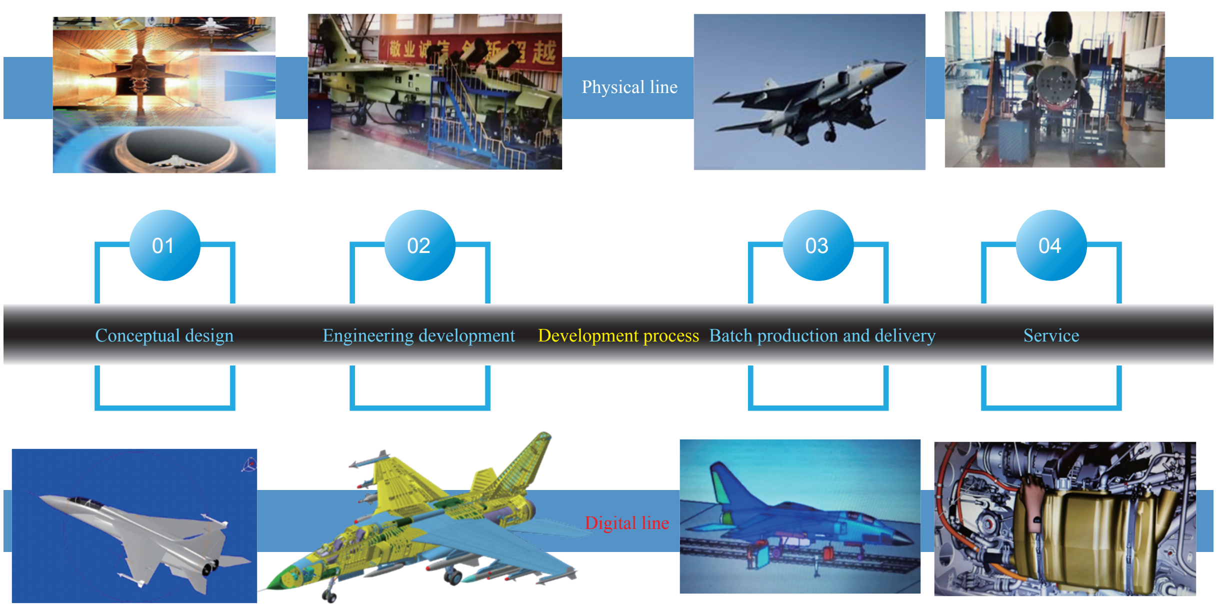


**Fig. 1.** Product development process, traditional physical production line, and digital mainline.

the fundamental concept of the model-based digital definition is still based on the multi-disciplinary simulation analysis and optimization based on the geometric model.

The third phase is comprised of batch production and delivery. The basis of manufacturing still utilizes a digital prototype of the whole aircraft. Following the digital prototype, the key to production is to enhance the production capacity and meet the needs of the customers. The construction of the production assembly line must be practical, with the digital and physical lines separated out, mixed only on demand, and focused on the improvement of quality and enhancement of efficiency.

The fourth phase is the service guarantee, and the digital prototype can be extended to this phase. The earlier aircraft training, aircrew, ground service, and maintenance manuals were all paper-based and thus voluminous. Now all these can be realized with the model. The interactive electronic technology manual can be generated based on the digital prototype coupled with mixed reality technology, which facilitates the service providers.

## 4 Digital definition based on information–physical system

The successful launch of the Falcon-9 heavy rocket heralded a new era in space history. The successes of Falcon-9 and SpaceX demonstrate the feasibility and enormous success of several technical routes, research and development ideas, and process management systems. They describe the behavior of the functional decomposition, starting with the abstract question domain (requirements/functions) by associating and transforming the requirements/functional and logical architectures into physical architecture, and the process of assigning behavior (run) to the product (structure) that specifically resolves the domain. Thus, they avoid the direct mapping from function to structure, which leads to the "leapfrog development cycle" where some researchers skip logical design and function/behavior analysis and head directly toward physical realization, upon eliciting the problem to be solved from the requirements. For example, in traditional rocket development, the separation of boosters depend on the initiation of explosive devices, such as using explosive bolts as separators. The Falcon-9 used mechanical separation, which was attempted only once in earlier development. The Xiongfeng 3 missile was used in Taiwan of China in the early days, but it failed repeatedly and ended up with pyrotechnic separation. SpaceX not only implemented the mechanical separation method but also adopted this design without a physical verification test, and its rationality and reliability depended entirely on the simulation calculations. As a result, the undefined test verification costs of SpaceX are much lower than those associated with conventional rockets. SpaceX saves considerable time and money by avoiding the use of pyrotechnics and large numbers of physical tests. It must be emphasized that although the capabilities of simulation computations have made significant progress, they are not infallible. The reliability of simulation results depend directly on the accumulation requirement, operation of basic research and level of analysts. This is the digital definition based on the information–physical system.

In the present stage of the virtual environment, we can realize top-down and bottom-up integrated designs and realize design−virtual synthesis by stages and levels (system simulation based on function performance and geometry models) to digital manufacturing–physical manufacturing verification, and finally to product transition. This is the industrial paradigm of the new generation of intelligent manufacturing innovation and ultimate pursuit of virtual synthesis (system simulation based on function performance and geometry model).

Further, the booster of the mechanical separation method of the Falcon-9 heavy rocket is not subjected to physical verification tests. Its rationality and reliability are completely realized by simulation calculations, thus avoiding the use of the initiator. The reason for eliminating the large number of physical experiments is to avoid the large number of calculations and simulations required. The application of a large number of industrial software endows the software with human knowledge and intelligence, which is the basis of the new generation of human−information−physical systems. From a theoretical point of view, the first- and second-generation intelligent manufacturing systems can significantly improve computing, analysis, precision control, and perception capabilities by integrating the respective advantages of human intervention, information systems, and physical systems. On one hand, the work efficiency, quality, and stability of the system can be improved significantly. On the other hand, the transfer of the relevant manufacturing experience and knowledge to the information system can effectively improve the transmission and utilization efficiency of human knowledge. The evolution of manufacturing systems from the traditional human−physical system to the human−information−physical system can be further abstracted: the introduction of "information system" add "human—information system" (HCS) and "information−physical system" (CPS) simultaneously to the manufacturing system. Among these, the information−physical system plays a significant role. In 2006, the United States put forward the complete theory of information–physical systems, which is regarded as the core technology of Industry 4.0 in Germany. The application of the information–physical system in engineering is to realize perfect mapping and deep fusion of the information and physical systems, and humans are the core element of realizing the information. The new generation of human−information–physical, human–information, human–physical, and information–physical systems will all achieve qualitative leaps [1].

## 5 Industrial paradigm innovated by the new generation of intelligent manufacturing

In 2002, the former Commission of Science, Technology, and

Industry for National Defense launched the appraisal and evaluation of the project "Digital Engineering in Aircraft Manufacturing Industry," with the participation of 18 domestic aircraft development units. The clear development goals were to establish digital production lines in the aircraft manufacturing industry; form a digital aircraft R&D system; and to reform management, production, organization flow, and technical standards. In other words, in the aircraft manufacturing industry, the digitized model in the design phase is evolving through continuous improvement spanning the life cycle of engineering development, batch production, maintenance and repair, and scrap recovery. In retrospect, this appears to be the digital thread. Today, China's industrial system has been developed and has become the world's most complete industrial system, which is proof of our own theoretical self-confidence.

The concept of the digital thread has been included in the objective of digital engineering in the aircraft manufacturing industry, which has been consistently followed. The physical line depicted at the top of Fig. 1 is the definition of traditional manufacturing: the paper-based symbolic definition. The middle line in Fig. 1 shows the aircraft development process and the line below corresponds to the digital line based on the software definition. Fig. 1 demonstrates the system of the system in CPS, and the physical and digital systems in each phase of development in each column of Fig. 1, constituting multiple pairs of digital twins. Of course, digital twinning does not only occur for each column, but also between phases.

There is no doubt that the predecessor of intelligent manufacturing is digital manufacturing, and the success of digital manufacturing is based on the foundation of physical manufacturing laid down by the traditional manufacturing industry over hundreds of years. The innovation of the industrial paradigm is realized by applying the digital model defined by software; therefore, the software definition of the digital model as well as all other definitions must be based on the solidified foundation of the physical entity. As the old Chinese saying goes, "If the skin does not exist, the hair has nowhere to cling to;" the physical entity is the skin and the digital model is the hair. The fusion of the two forms the basis of intelligent manufacturing. In the intelligent manufacturing system, industrial software is not only the core but also the new mode of human thinking. Therefore, in light of the experiences of developed foreign countries, the development of industrial software in China urgently requires promotion to the national strategic level. Software awareness and talent must be inculcated and encouraged right from childhood. There must be national consensus to place importance on the knowledge of the industry, understanding of the software, talent, and protection of property rights.

With the establishment of digital technology, represented by big data, cloud computing, and the Internet of Things, we are in an era of digital economy. The development of software definition and CPS technologies with the support of the new generation of information technology (cloud computing, Internet of Things, mobile communications, big data, and intelligent manufacturing) will realize an industrial paradigm innovated by a new generation of intelligent manufacturing in the future, providing a fusion of people, equipment, and materials with the typical characteristic of digital twinning enabled by the digital thread.

China is the largest manufacturing country in the world. Under the condition that industrialization has not yet been completed, China views the arrival of the digital wave as a dual historical task and a difficult challenge; to catch up with the industrialization process and synchronize the digitization opportunity. The report of the 19th National Congress of the Communist Party of China calls for the promotion of the deep integration of the Internet, big data, artificial intelligence, and real economy, geared toward cultivating new growth points and providing new impetus. The new generation of intelligent manufacturing provides a significant policy and path for promoting the digital transformation of Chinese traditional industries, giving birth to new business models, reshaping the innovation chain, reconstructing the industrial chain, and expanding a new space for economic development. We must provide complete flexibility to the leading role of artificial intelligence in technological innovation; speed up the construction of a powerful manufacturing country; accelerate the development of advanced manufacturing; promote the deep integration of the Internet, big data, artificial intelligence, and real economy; and upgrade China's industry to the middle and high end of the global value chain.

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