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Development of Systems, Instrumentation, and Control Technologies for Steel Manufacturing Processes and Future Prospects

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Abstract

Systems, instrumentation, and control technologies using computers are indispensable for the efficient manufacture of high-quality steel products. Based on the knowledge accumulated through computer use for more than half a century, Nippon Steel & Sumitomo Metal Corporation has developed a wide variety of technologies in this field. The application of computers to systems, instrumentation, and control technologies for steel manufacturing is closely related to the advance in computer technology. This paper reviews the history of computer application to the control of steel manufacturing processes in various aspects, and speculates on future prospects in consideration of the latest advances in computer technology.

1. Introduction

As the world economy grows, new steel manufacturing facilities are being constructed in many countries. The equipment of the Japanese steel industry was built mostly during the period of high economic growth in the 1960s and 70s, and most of it has operated for more than 40 years. The industry, however, now has to establish competitiveness in all aspects of productivity, product quality, delivery time, etc. against new facilities in other countries. In this situation, the industry has developed, fostered, and refined effective tools for this purpose, namely systems and control engineering to operate steel manufacturing processes, instrumentation engineering to quantitatively monitor product quality and process conditions, and control technology to support the appropriate functioning of these two.

The major steelmakers of Japan began to use computers actively in the 1960s in consideration of the rapid development of modern management practice,[1] and soon after that, through the combination of electric and instrumentation control devices, the prototype of a three-hierarchical production control system was constructed (see **Fig. 1**). In 1968, Kimitsu Works was inaugurated as the first computerized integrated works operating on the basis of an overall, on-line, real-time production control.[2] As a result of the remarkable growth in the computer processing performance, communication rate, and the capacity of memory devices, along with the digitalizing of design and engineering of related devices and the advance in software engineering thereafter, it is possible to entrust computers with a wide variety of functions. The process control of the steel industry, in this way, has been brought to its present high functionality.

This paper reviews the past trends of the systems, instrumentation, and control technologies that Nippon Steel & Sumitomo Metal Corporation has developed, fostered and commercially used, and delineates prospects for the future era of "Industry 4.0"[*1].

2. Development of Systems and Control Engineering for Steel Manufacturing

2.1 Expanded use of computers for process control

The steel industry is characterized by mass production by massive equipment, and in consideration of the complicated operation of various types of equipment and the huge amount of materials handled, the Japanese steel industry has aggressively introduced new technologies to optimize its production structure and raise operation efficiency. In the 1970s when the technology of process computers, which have to work in the plants in real time and around the clock, firmly took root, they automatically calculated operating parameters for the production facilities and collected data for product quality control based on the production schedule prescribed by

[*1] The concept of a new stage of industrial development proposed by the government of Germany in 2011; also called the 4th industrial revolution.

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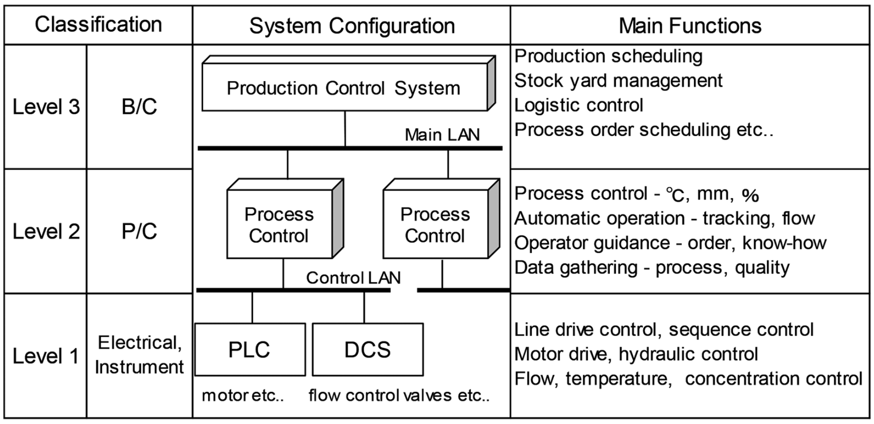

Fig. 1 Control system architecture of steel production process
B/C: Business computers, P/C: Process computers

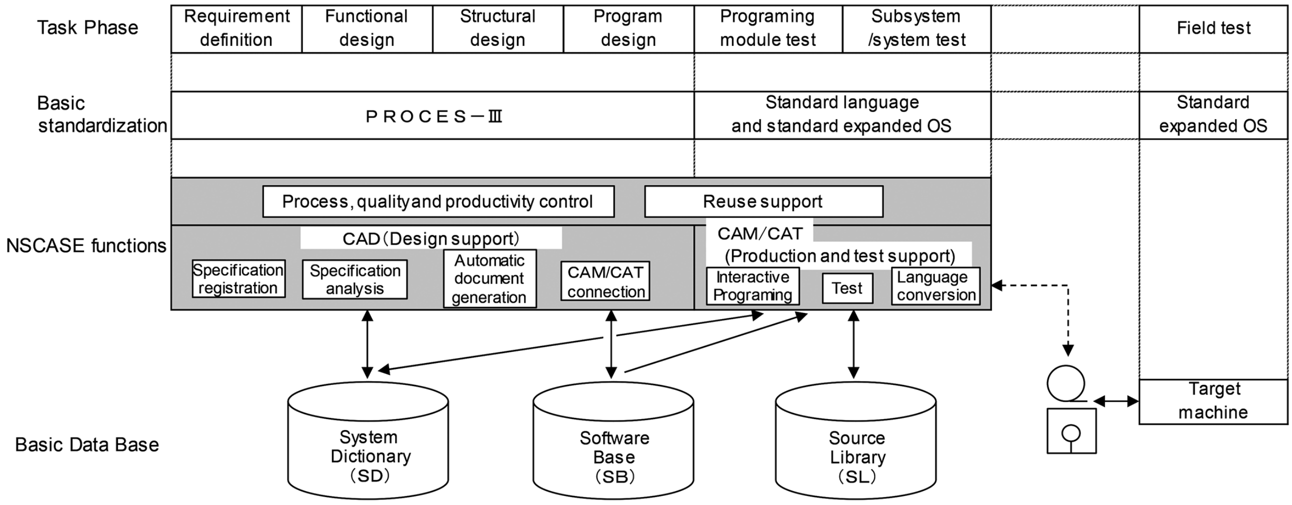

Fig. 2 Functional configuration of NSCASE

upper-level computers. The concepts of factory automation (FA) and computer-integrated manufacturing (CIM) were already part of daily practice, and the number and size of the software for process computers that supported the functioning of manufacturing processes grew day by day.

In this situation, understanding that the keystone of the product quality, which is the very basis of the competitive edge, was the software for the computers that controlled manufacturing processes, the company developed a support tool for software engineering, the Nippon Steel computer-aided software engineering system (NSCASE, see **Fig. 2**), in the 1980s,[3] and with this, a framework for efficient in-house software production was established. Further, in the second half of the 1980s, based on technical knowledge in computer use accumulated so far, the company developed a new type of computer for industrial use characterized by the unique concept of expandability, ease of integration, compatibility, open structure, etc.[4] It was widely used at the company's works, and in addition, it was combined with NSCASE and launched onto the market as a system product of the company's electronics, information and communication business (then EI Division[*2]) (see **Photo 1**). In the 1990s, when the company became capable of manufacturing both hard- and software autonomously, a wide variety of control application software was produced and applied to steel manufacturing processes at all of its works.

Photo 1 FA computer system products released by Nippon Steel Corporation in 1980s

2.2 Wider use of process computers

In the 1970s, the basic functions of process computers (Level 2

[*2] Now part of NS Solutions Corporation.

in Fig. 1), positioned between business computers for production control (Level 3) and control devices for production line facilities (Level 1), were to set the control devices automatically based on the instructions of the production control and accumulate the data of the lower-level processes for the upper level. As the processing performance of computers increased, expectations increased to apply such computers to the area of dynamic control of manufacturing processes instead of the once-dominant analog amplifiers. In the 1980s to 90s, when modern control theories were actively studied, digital control technology came to be widely practiced based on the brand-new theories. Some of the remarkable outcomes were the precise strip temperature control, which was critical to enable innovative processes such as continuous annealing and processing lines (C.A.P.L.), the optimum control of converters and hot strip mills, and the fuzzy control of tandem cold mills.[5–7] During the second boom years of artificial intelligence (AI) in the latter 1980s and thereafter, various types of operator assistance systems became part of daily practice by the contribution of new technology concepts such as expert systems based on knowledge engineering, anomaly anticipation applying neural networks, and so on.[8–10]

Digitalization of electric and instrumentation controllers was motivated initially by maintenance and management requirements such as to lower costs and errors through reduction of the number of electrical parts such as relays and wires, and to improve control accuracy against drifts and noises caused by analog amplifiers. After that, with the increase in the data processing performance and memory capacity of computers, new control methods and languages were devised.[11] As a result, the control functions of electric (E) and instrumentation (I) controllers and process computers (C) began to overlap with each other. After the concept of combined EIC systems was conceived in the mid 1980s, combined single-vendor EIC systems became a reality in the very latter part of the decade, and multivendor EIC in the early 1990s.[6, 12] The actual use of the combined systems ironically made it clear that the functions of E, I, and C should be separated from each other according to their respective languages and computation methods to suit each control function, rather than existing as three different control systems in one package. In the 2000s, E, I, and C developed in directions distinct from each other, and evolved into separate systems, but were easily intercommunicable through the Ethernet and other generalized communication networks that spread during the Internet age.

2.3 Permeation of general-purpose devices into systems and control engineering field

The evolution of computers used to focus on the enhancement of processing performance, but the focus gradually shifted to downsizing and price reduction, and high-performance personal computers (PCs) became household commodities in the late 1990s. At that time, when Windows®[*3] and Linux®[*4] made their appearance as the basic software or the operating system (OS) for PCs, Nippon Steel & Sumitomo Metal changed its computer business policy from the in-house manufacture of computer hardware to the use of open-system devices. NSCASE was expanded to deal with the requirements for 24-h uninterrupted operation, response within the order of seconds, and compatibility independence from the difference of hardware and OS among vendors of such general-purpose open PCs. Accordingly a new process control middleware called NS SEMI SYSTEM™[*5] was developed,[13] a Windows-NT PC server was ap-

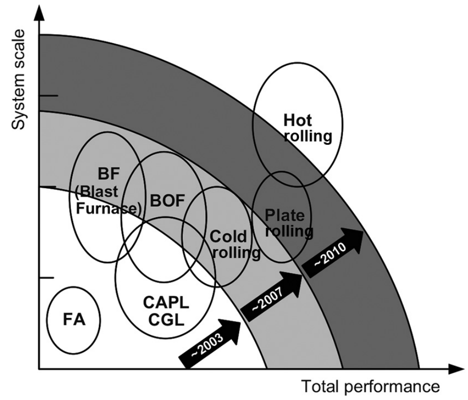

Fig. 3 Expanded use of open-system hardware for process control

plied as the first case to the process control of a continuous caster at Kimitsu Works in 1997, and a Linux server to that of a blast furnace of Kimitsu in 2001. Use of open-system devices such as the above expanded steadily, and currently, it is applicable to practically all process control systems of the company (see **Fig. 3**).[14]

The use of general-purpose devices occurred also in the field of electric and instrumentation control devices. Programmable logic controllers (PLCs), initially developed mainly for the control of the steel industry's complicated electrical equipment and specialized in mathematical processing, and general-purpose sequencers for general industrial use became close in terms of data processing performance and memory capacity in the 2000s, and the only practical differences of them were software productivity and maintainability. E-CASE,[15] a tool for software engineering for electrical PLCs based on the IEC61131-3 language developed by Nippon Steel & Sumitomo Metal, solved the problem. The line-up of software function blocks was expanded, and a new capability to create a virtual test run scene in open PCs was launched.[16] Thanks to them, electrical control systems using general-purpose sequencers were introduced to steel manufacturing processes in many works. Furthermore, by applying computer-aided software engineering (CASE) designed for the instrumentation engineering field to the general-purpose sequencers having instrumentation control functions, the use of general-purpose devices in the field of instrumentation controllers in the steel industry is also expanding.

As for the control of electric drive motors, general-purpose devices for variable-speed control of pumps and blowers began to include functions of high-performance AC variable-speed control[12, 17] adequate for rolling mills and sheet processing lines. As a result, general-purpose devices are used for sheet processing lines and temper- and skin-pass rolling mills. A continuous hot-dip galvanizing line (CGL) commissioned lately at Yawata Works now has electric drive motors controlled entirely by general-purpose devices.[18]

2.4 Period of new technology application

Smartphones and other devices of advanced information technology (IT) became everyday items in the 2000s, and high-speed processing units and open software technology appeared as a result of the popular use of PC games and expansion of web markets. In those years, solution technology was actively developed, in which new values were created by applying such new technologies to steel manufacturing practice.

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*3 Windows is a registered trademark of Microsoft Corporation.
*4 Linux is a registered trademark of Linus Torvalds.

*5 NS SEMI SYSTEM is a trademark of Nippon Steel & Sumitomo Metal Corporation registered in Japan.

Easy information handling at production sites led to the wider use of things such as the following: operation navigation[14] whereby all detailed operation orders and instructions, which had been given on paper, were computerized, stored as know-how information, and displayed when necessary (see **Fig. 4**); device technology to automatically recognize and store measured values and oral information;[19] identification and recognition using two-dimensional barcodes and images; display technology to show massive numerical data three-dimensionally on large screens (see **Fig. 5**);[20] a data-driven process control approach whereby trend and causal relations are extracted from large-scale data of operation conditions and fed back in real time; and measurement technologies by real-time processing of ultra-high-resolution digital images. Thus, the advances in computer hard- and software have significantly changed the systems and control engineering of steel manufacturing processes.

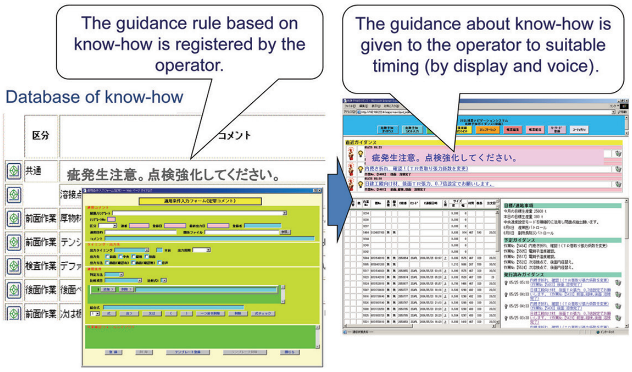

Fig. 4 Outline of the navigation system for steel plant operation

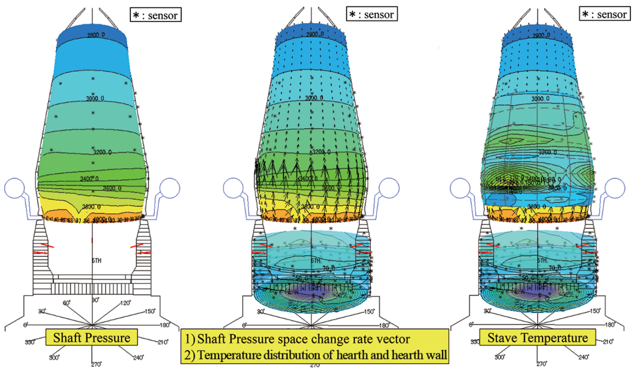

Fig. 5 3D visualizing of blast furnace condition

More recently, thanks to the use of general-purpose graphics processing units (GPGPUs), which are general-purpose parallel computing processors that had evolved for game use, real-time control involving ultra-large-scale computation has been made practicable, yielding optimum solutions through the processing of a massive amount of data under various conditions.[21] Moreover, real-time process control using high-precision models is expanding due to some general-purpose control devices equipped with high-level language units and combined use of high-function PCs with control facilities.

3. Advances in Measurement and Control Technology for Steel Manufacturing Processes

3.1 Historical trend in measurement and control technology

Physical, chemical, thermodynamic, and metallurgical changes are mixed in different ways and evolve through mutual interactions in steel manufacturing processes. As a result, the processes involve highly complicated dynamics, and it is necessary to measure and control the process phenomena with high accuracy in hot, pressurized, and dusty environments. In order to produce varieties of steel products stably in quantities based on the accurate measurement of processed objects that change from moment to moment in harsh environments, Nippon Steel & Sumitomo Metal has long since made efforts to develop process control technologies on the basis of accurate measurement, physical model calculation, and control theory (see **Fig. 6**).

From the 1980s to the 2000s, in response to diversifying customers' requirements, appeals for energy saving, and calls for cost cutting, the objective of measurement technology changed dimensionally from points to planes and then to 3D, its accuracy was enhanced, and the enormous amount of measurement data was made easily comprehensible thanks to visualizing techniques. The development philosophy of process control shifted from the control of individual functions to that of quality control in the products, and then to integrated automatic control and optimization control.

3.2 Recent advances in measurement technology

The advances in measurement technology in the 2000s and thereafter, and some development examples in this field are outlined in this subsection.

Typical process measurement techniques to deal with high-temperature objects of iron-making processes developed include the quantifying of blast furnace tuyere images,[22] whereby raceway images captured by tuyere cameras are processed into a mapping on a two-dimensional feature plane. Another example is the multiple image measurement technique for monitoring the temperature and flow rate of the mixed liquid of molten iron and slag tapped from a blast

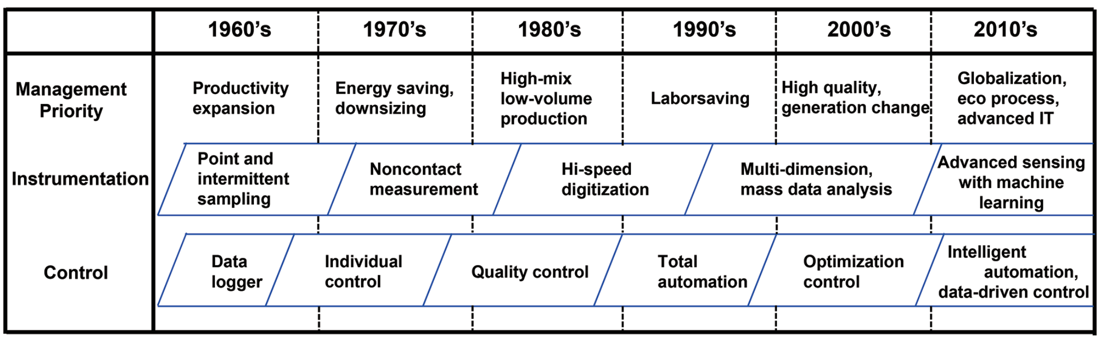

Fig. 6 Trend of instrumentation-control technology

furnace at 1500°C.[23–25] Those for downstream processes include the stereo-camera type strip walking measurement, whereby the strip position in the finishing mill train of a hot strip mill is accurately measured in the harsh environment between the finishing mill stands using 2D cameras,[26, 27] and the LED-pattern-projection type strip shape meter, whereby strip flatness is measured by analyzing a specific dot pattern projected from an LED light source onto the surface of a strip.[28]

Other noteworthy developments include the strip shape measurement employing a unique optical system composed of a modulated laser source and a time delay integration (TDI) camera, having a measurement speed ten-fold higher than that of the conventional light-section method,[29] and the slab shape measurement by the light-section method using vertical and horizontal beams to determine the amount of scarfing.[30] Another interesting development is the fountain pyrometer capable of accurately measuring strip temperature on the run-out table of a hot strip mill, where a great amount of cooling water is poured onto the strip from above and below.[31, 32]

In the field of non-destructive inspection, the high-accuracy, high-speed inspection method applying phased array flaw detection[33, 34] has been used for the on-line inspection of welded seams at UO pipe plants. Flaw detection by the synthetic aperture focusing technique has been used for the on-line inspection of round bars,[35,36] and also the quantitative evaluation of lamination defects of seamless pipes.[34, 37] Developments employing electromagnetism include omnidirectional flaw detection to which the superimposed magnetic field rotation technique (SMaRT)[34, 38, 39] is applied, and the stress measurement of thin sheets employing the material testing method by the laser ultrasonic.[40]

3.3 Recent advances in process control technology

The advances in process control technology and some development examples in the 2000s and thereafter are outlined in this subsection. The technical development in this field was actively promoted from the viewpoints of the close combination of measurement and process control, sophistication of process models, application of advanced control methods, on-line optimization, and data modeling.

Figure 7 shows the recent control technologies for hot strip mills using the advanced sensors described earlier as the examples of the combination of measurement and process control. For the strip walking control in the finishing mill train, a strip position sensor using stereo cameras between mill stands is combined with model predictive control (given in **Fig. 8**)[26, 27]. A method of strip flatness control has been developed,[41] wherein symmetric and asymmetric components are extracted from the strip flatness data obtained by an LED-pattern-projection type strip shape meter at the delivery side of the finishing mill and fed back to the work roll bending and levelling of the finishing mill stands. For the strip cooling on the run-out table, a strip cooling control system using fountain pyrometers has been devised.[32, 42] The method consists of measuring the strip temperature at prescribed sampling points (control points) of the strip being cooled, predicting the coiling temperature of those points, and adjusting the cooling water flow by feed forward control so that the coiling temperature becomes equal to the target value at each of the control points. In addition to the coiling temperature control, the fountain pyrometers are used also for dynamic cooling pattern control by which rapid-cooling-end temperature and intermediate air-cooling time are controlled for the respective target figures.[32, 43, 44]

Since the set-up control plays an important role in process control to improve productivity and product quality, the precision of set-up control models has been improved in several ways. For the hot strip mill, a high-accuracy, on-line strip profile prediction mod-

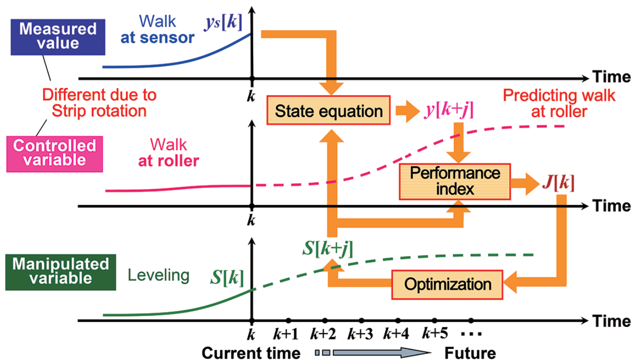

Fig. 8 Walking control by using model predictive control

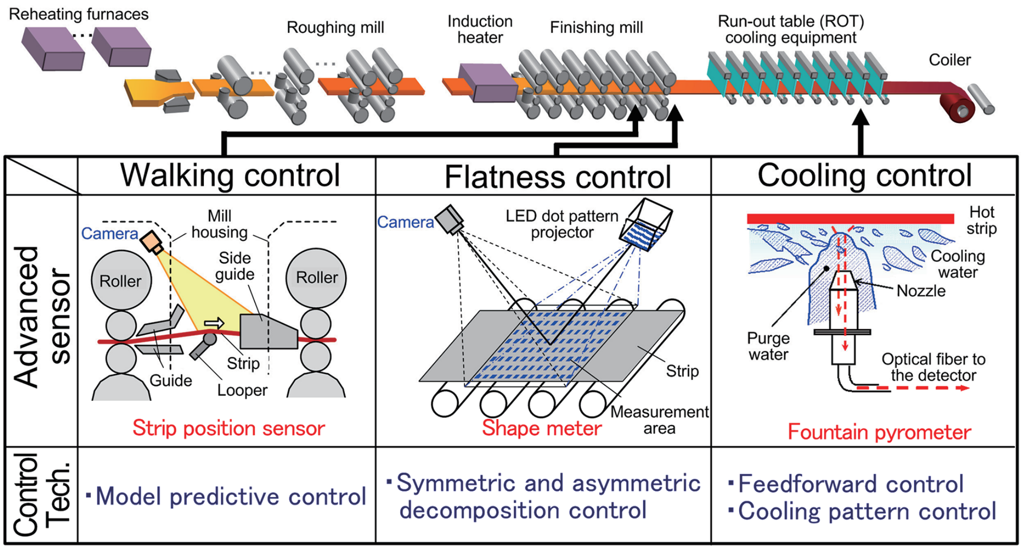

Fig. 7 Development of advanced sensors and control technologies

el[45–47] in the finishing mill train incorporating a matrix model has been developed and proved effective for improving production techniques for high-strength hot strips. For plate rolling, furthermore, a roll pass schedule model has been up-graded[21] taking advantage of graphic processing units (GPUs). For accelerated cooling of plates, a high-accuracy cooling control system[48, 49] has been developed based on a water-cooling heat transfer model[48–50] for water jets from nozzles, which was developed based on numerical fluid analysis and experimental results.

As an example of advanced control application, molten steel level control in the mold of a continuous caster[51] has been developed based on the Q-parameter approach. The approach consists of providing existing control devices with a filter including a free parameter system Q, which makes it possible to apply a desired frequency weighting to the sensitivity function of the system. With this, it is possible to minimize the fluctuations of the molten steel level at the frequency by designing the free parameter Q such that the frequency characteristics are close to that of the notch filter having the center frequency equal to that of disturbance. A strip shape feedback control method[52] based on generalized predictive control has been developed for a tandem cold strip mill, and proved effective at enhancing the strip shape control capacity of the mill. New control techniques developed for a reversing cold strip mill include a method for identifying the response characteristics of thickness control[53] applying the identification method of the auto regressive moving average model with exogenous input (ARMAX model) by the expanded least squares method, and a feedforward control of deformation resistance[54] to minimize the thickness fluctuation caused by the change in deformation resistance at each lap of a material coil. These new methods have proved instrumental for improving the control accuracy of strip thickness. For the mandrel mill making seamless pipes, a technique has been developed to identify a mill stand where eccentricity is occurring and define its amount by inverse calculation based on complex Fourier analysis. It has been applied to an actual mill in combination with an eccentricity prevention method based on individual control of screw-down cylinders and an on-line, feedback eccentricity control method using a wall-thickness gauge; this improved the homogeneity of wall thickness.[55]

As for the process control incorporating on-line optimization technology, a hot stove combustion control technology has been developed to optimize the combustion pattern of hot stoves of a blast furnace. Employing a combination of plant simulator and genetic algorithm (GA), it enables maximization of the heat efficiency while satisfying constrained conditions[56] (see **Fig. 9**). For the continuous reheating furnaces of plate mills, based on a simplified 3D slab temperature calculation model, an automatic combustion control model has been developed[57, 58] to determine the temperature setting of the furnace zones by linear programming.

In the field of data modeling, a wide variety of new techniques have been developed for different applications; these include large-scale, database-based on-line modeling (LOM)[59], case-based modeling[60], a control model construction method based on automatic partitioning[61], principal component analysis-linear discriminant analysis (PCA-LDA)[62], data-driven quality improvement (DDQI)[63], and a generalized linear model (GLM)[64].

For example, the case-based modeling is a technique to compose local condition prediction models based on relevant data (neighboring data) resembling the manufacturing condition extracted from huge operation data in the database (see **Fig. 10**). The approach of the case-based modeling is applicable to estimate the prediction er-

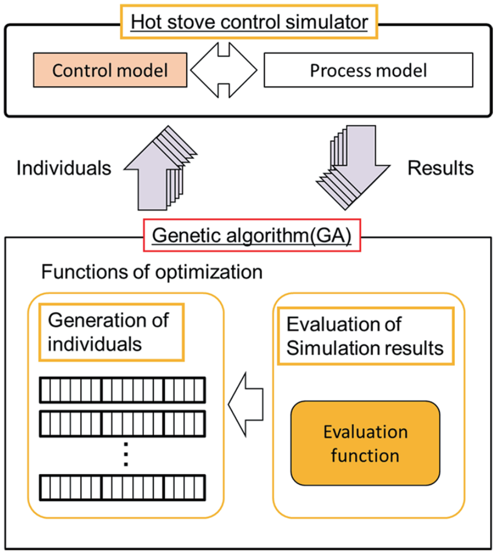

Fig. 9 Optimization control by combining process simulator and GA

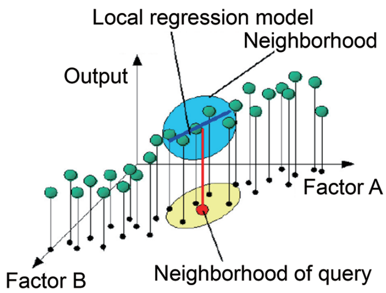

Fig. 10 Case-based modeling

rors of the prediction models as well.

The use of a vast amount of operation data collected from manufacturing processes will not be limited to data modeling, and it is expected to become more active and developed to produce data-driven control and intelligent control of manufacturing processes.

4. In the Epoch of "Industry 4.0"

The concept of "Industry 4.0" was proposed in Germany in 2011, and together with the news of a professional go player being defeated by a software program of the game applying deep learning in 2015, it rapidly became widely known. With the propagation of the Internet of things (IoT), whereby a variety of information is exchanged through the Internet, the expectation for industrial application of artificial intelligence (AI) has quickly grown. Although people's understanding of the words AI, IoT, etc. is somewhat different from what they really are, the advances in computer and information network technology will surely strengthen the progress of the systems, instrumentation, and control technologies in the steel industry. We attempt to predict in this section how such advances will be utilized for the control of steel manufacturing processes.

Various technologies for smart factories were suggested and presented at the latest international exhibitions such as the Hanover Messe in 2016 and the CeBIT in 2017. Application of the digital twin (a simulation model to create a product in a virtual space in a computer), cyber physical systems (CPS), etc., for example, may allow effective use of information produced and applied in every part of the production processes. Other new technologies presented include quantum computers, deep learning, display devices for virtual and augmented realities, and high-speed 5th-generation (5G) communication. These advanced technologies are expected to come into industrial practice shortly, and current development cases such as automatic driving and advanced robotics are widely publicized. Such presentations at the exhibitions, however, are mostly messages from the supplier side emphasizing the possibility of advanced systems being economically introduced to markedly wider fields of activities as a new opportunity for industry in general.

Since the steel industry is a seasoned pioneer of computer users, we may well view "Industry 4.0" from a somewhat different viewpoint. It can be said that the concept of digital twin is that of the reference model in process control, CPSs are nothing but an extension of the application of CIM commonly used, deep learning is a method of machine learning, statistical analysis, and the like; all these have long been familiar to the process control of the steel industry.

Nevertheless, for further development of the systems, instrumentation, and control technologies for steel production processes, we have to make the most of the facts that new solution possibilities have been made available for our technical development, and that new tools and mechanisms for remarkably enhancing software production efficiency have been offered as the fruits of the technical advances in this field. Now it has been made possible to compose software programs for research and development, which were conventionally constructed one by one through studies in detail, by combined application of general-purpose open program sources available in the market. Sooner or later, the hardware for process control will also evolve from current devices in individual panels to those in virtual spaces. Fundamental technologies will be developed for information systems and software that can handle the reality after such changes.

In the field of measurement and process control for steel manufacturing, the requirement for higher precision and reliability will grow stronger, and numerical/mathematical methods, which engineers can use based on causal understanding, should continue to be the main approach. Sophistication and efficiency improvement in the system design for measurement and process control will advance through the application of the theories of data-driven design, sparse modeling, compressed sensing, etc. enhanced by computers. This will bring about things such as simultaneous measurement of multiple variables using cameras and other common input devices and feedback control by complex control systems covering a plurality of processes to realize steel manufacture of higher precision, product quality, and added value.

AI using further advanced deep learning, on the other hand, will be applied, albeit on a limited scale, to the control of steel manufacturing processes. Learning from big data of past plant conditions operated, AI is likely to become capable of automatic operation in place of human operators to a certain extent. The steel industry accumulated a wide variety of experiences during the second AI boom period in the 1980s, and those experiences should be effectively used for developing such new practical methods of higher efficiency for prognostic diagnosis, operator assistance, etc. in the current third AI period.

New wireless technology deserves attention. Information from a great number of widely scattered, ultra-high-speed wireless sensors will replace a good part of conventional information collection expending human toil and time. By the effective use of chronological data, it will be possible to predict the future from the present, which will lead to technologies of automatic correction, in the aspects of equipment healthiness, plant operation condition, or product quality, before anomalies actually take place. The Nippon Steel & Sumitomo Metal group has already begun to study the possibility of systems for safety monitoring, remote assistance, and operational analysis by collecting information of workers' positioning data and vital condition data.[20] Based on these, an algorithm will be developed that can optimally control the operation of plant facilities and the motions of personnel in an integrated manner.

While effective utilization of AI and big-data for steel manufacturing processes is actively being pursued in and outside Japan, Nippon Steel & Sumitomo Metal established a company-wide big-data analysis platform in 2016 as a basis for enhancing production efficiency, product quality, and the cost structure, and the number of its users has already exceeded 300. In addition, the Intelligent Algorithm Research Center was organized as part of R & D Laboratories in April 2018 to accelerate the research and development in the fields of data engineering from fundamental studies to field application of the fruits of such studies.

5. Conclusion

The history of technical development and the latest approaches of Nippon Steel & Sumitomo Metal in the field of systems, instrumentation, and control technologies have been presented herein. The technical advance in this field is inseparably linked with the evolution of computer technology. As was the case in the past, the appearance of new devices and advance in software algorithms resulting from the evolution of computer technology will undoubtedly increase the importance of systems, instrumentation, and control technologies in steel manufacturing.

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