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Technical Trends in the Field of System and Its Control for Iron- and Steelmaking

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Abstract:

Owing to the great progress of computer technology, motor drives, sensors, and control techniques have been greatly evolved, to form the basis of improvements in the quality and yield of steel products. With regard to the driving system, the DC drive has been substituted by the AC drive with a high function, and recently both the GTO inverter and the IGBT inverter of a high power-supply quality have been applied extensively. Various detectors have been also fully arranged, giving priority over the detections of profile, surface defects, internal defects, and surface flaws. With regard to the control technique, humanistic controls such as H^{∞}, μ synthesis, fuzzy, GA and so have been put to practical use. Further, with regard to the system for generally controlling over these systems, such a system as utilizing personal computers on the basis of the development of computer technology has been already operating actually. It is considered that the system control technology will be innovated much further henceforth, and thereupon we are ready for applying novel techniques without delay to the actual steel manufacturing equipments to make a contribution to improvements in the quality of steel products and in the labor productivity.

1. Introduction

The conditions surrounding the industry have dramatically changed in recent years. The progress of applied electronic technologies, especially computers and their associated technologies, is eye-opening.

This technological progress has greatly changed system control technology in the steel industry and has improved the quality and yield of steel products. This special issue of the Nippon Steel Technical Report introduces some of the results achieved in the system control area in recent years.

Before specific discussions, let me touch upon the roles played by system control technology in the steel industry. An overview of the structure of process control is given in **Fig. 1**. Ironmaking and steelmaking processes work and modify their materials into products. Energy, such as gas or electric power, is inputted into each process. The quality and shape of products are measured by instru-

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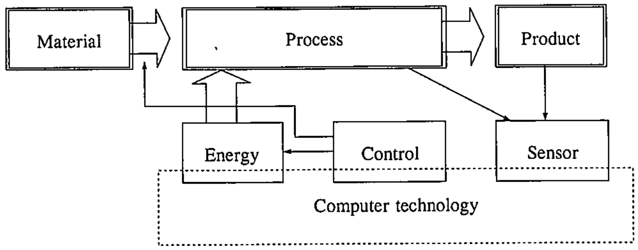


Fig. 1 Structure of process control

ments, and the amounts of energy, alloying elements, and other materials to be inputted to the processes are adjusted to meet product quality requirements, and the processes are automatically or manually controlled to satisfy the desired product specifications. The material charging position, speed, and other details are also controlled to manufacture products of the desired quality. Such energy input devices are represented by rolling mill drive motors.

Mill motors run at highly speed responce when operated motors only, but run at a couple of tenths of speed responce at motors only when used in combination with rolls and shafts. Shaft vibration control can bring the performance of mill motors close to that achieved on a stand-alone basis. Formerly, as-rolled steel strip was visually inspected for shape in a free-tension condition in a subsequent process. Poorly shaped strip was corrected in the subsequent process or portions of poor shape were cut off to obtain products of prime quality. These procedures increased the production cost and decreased the production yield.

The tension distribution of strip in the width direction is simultaneously measured at a few dozen points, introduced into a computer, fitted to an orthogonal function, and used to approximately represent the shape of the strip. The shape of strip being rolled is measured on-line and fed back to change the amount by which intermediate rolls are to be shifted and to correct the shape of the strip accordingly. The screwdown position was formerly set by the mill operator according to the steel grade or finished thickness of the strip, but is now automatically set by computer. In this way, system control technology helps mechanical equipment to make the most of their potential performance, and serves to reduce the production cost by automation and labor saving. The motors, sensors, and automatic operation systems owe all of their performance improvement to advancements in computers.

2. Practical Application of System Control Technology to Ironmaking and Steelmaking Processes

The practical applications in the past 10 years by Nippon Steel of the system control technology that has made rapid progress as supported by the above-mentioned development of computers are shown in **Fig. 2**. System control technology is divided into four elements; measurement technology, control technology, electric energy application technology, and computer system technology common to the first three.

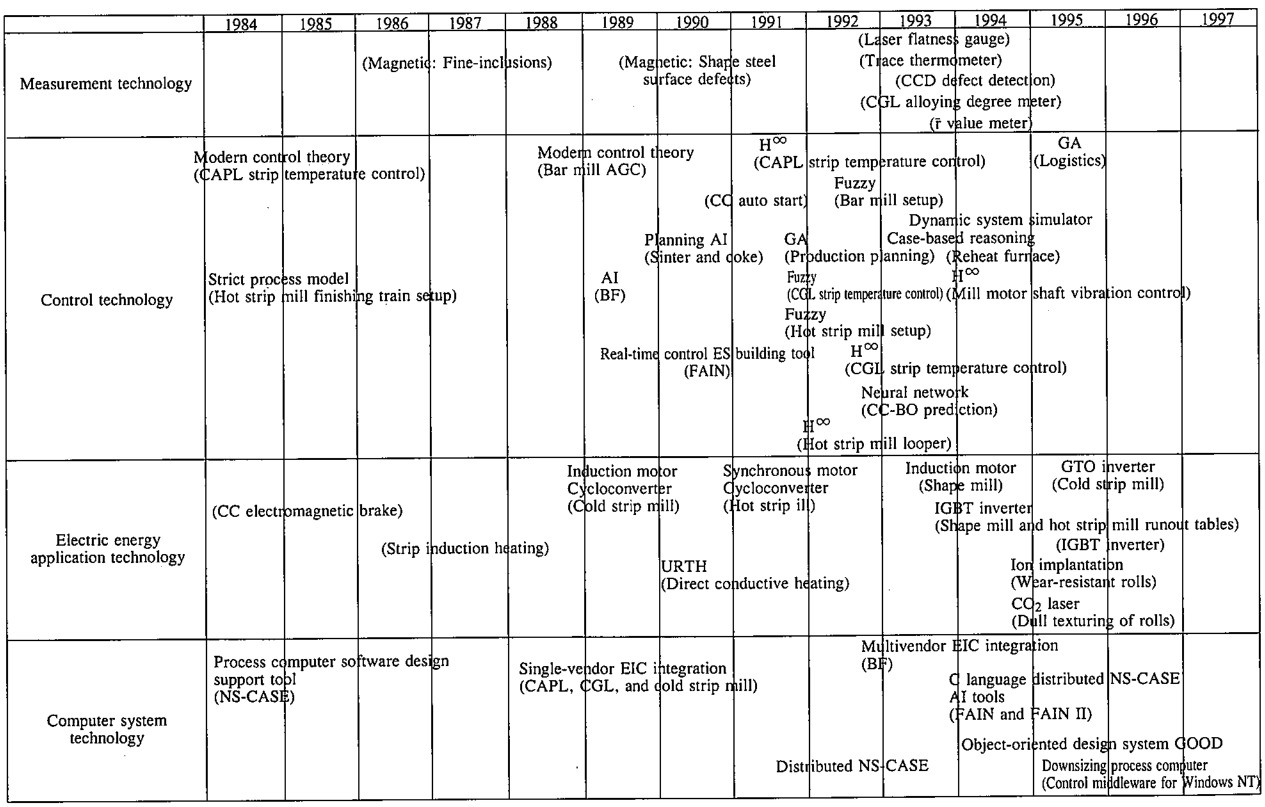


Fig. 2 Applications of system control technology

Measurement technology is changing from the traditional detection of material shape and surface defects to the measurement of mechanical properties (plastic strain ratio or $\bar{r}$ value in particular) and to the detection of finer surface defects. This is because product quality control requirements are made more demanding by improvements in manufacturing technology in the steelmaking stage and the introduction of more detailed manufacturing control technology.

Control technology advanced from conventional PID control to modern control theory requiring matrix computation in the 1980s, and modeling improved in exactness. As a recent trend, phenomena are too complex to be represented by mathematical equations, so phenomena that cannot be completely described by mathematical equations are regulated by fuzzy control involving judgment close to human intuition. Where physical images are difficult to grasp directly by modern control theory, H^{∞} control is used, which is easy for humans to intuitively understand and which can evaluate the stability of control in a frequency domain. Furthermore, neural networks provided with a learning effect like the human cranial nerves are put to practical use. This change from the control by mathematical equations alone to heuristic control is one of the recent features.

Mill drive motors are undergoing a sea change as an electric energy application field. Power energy forms like ions and lasers are being commercially utilized.

Advances in system technology, which is common to the above three categories of technology, allow each of the ironmaking and steelmaking facilities to be operated by a single operator as much as possible while improving productivity and serviceability to operators . Formerly, electrical equipment (E), instrumentation (I), and process computer (C) were operated independently of each other. These three groups of supervisory and operational devices are now operated together in an integrated manner. This EIC integration has changed from a single-vendor environment to a multi-vendor environment. Now that high-performance computers are readily available at home, personal computers that are at least an order of magnitude cheaper than conventional process computers are employed on the industrial field. A typical example is the application of Windows NT to a steelmaking process[1].

As far as computer system technology is concerned, hardware is rapidly falling in price per unit storage capacity and unit computing speed, whereas software is rapidly rising in price per unit storage capacity and unit computing speed. Nippon Steel is implementing measures to lower the cost of software production. The company standardized its computer software production process in about 1980 and developed a support tool, designated NS-CASE (Nippon Steel-Computer Aided Software Engineering tool), in 1984[2]. The programming languages were expanded from FORTRAN to the C language, and distributed NS-CASE was developed as a downsizing version of NS-CASE. The software production cost has been sharply reduced by these measures.

The progress of a few representative technologies and their application to the ironmaking and steelmaking processes are described below.

3. Present Status and Future Outlook of Measurement Technology

Internal quality detectors for steel products, represented by the plastic strain ratio ($\bar{r}$ value) meter, and surface defect detectors that have undergone a sea change as a result of the progress of computer technology and optoelectronic technology deserve special mention as recent events in the measurement technology area. Since the $\bar{r}$ value meter is reported in another article in this issue[3], the technical changes in surface defect detectors is introduced here.

One surface defect detector shines a laser beam on the surface of steel strip and locates defects according to the change in the intensity of reflected light. Another surface defect detector pinpoints defects according to the leakage flux formed on the surface of the strip placed in a magnetic field. Here, we introduce optical defect detection, which is frequently used for inspecting strip for surface defects.

The outline of a conventional optical defect detector is shown in **Fig. 3**[4]. The surface of strip running at a speed of a few hundred meters per minute is scanned in the width direction at a high speed with a He-Ne laser beam by a rotating mirror or other mechanical device. The reflected light is focused by a converging lens into a photomultiplier tube. The collected light is amplified further and differentiated to distinguish it from image in the surrounding area. The result is quantized into four to six levels and map (area) processed to extract features. The type and grade of each defect are then judged by linear separation (such as tree branch logic).

Since map processing could not calculate defects individually, it was difficult to distinguish defects from defect-like features present in the same area. The progress of computer technology has led to the appearance of application-specific integrated circuits (AISCs) capable of superfast computation in limited applications. Object processing was performed based on the geometrical features, brightness features and moment (direction and center of gravity) features of defects. Computation was conducted on defects on a one-to-one basis, and defects were detected with high accuracy. The positions of defects could be shown in real time on the CRT monitor screen for easy observation by the operator.

In place of the laser beam system, a charge-coupled device (CCD) camera system recently appeared that electrically scans at high speed the reflected light of a halogen light source. This development eliminated the limitation of mechanical scanning and avoided increasing the apparatus size. Conventional defect detection systems consisted of complicated devices and were very expensive. Now that CCD cameras, ASIC devices, and personal computers and engineering workstations for display purposes are available at relatively low prices, today's defect detection systems are more affordable to install. The application of a neural network for judging the types and grades of defects with higher speed and reliability is also reported[5].

We are making efforts to minimize the occurrence of surface and internal defects in the ironmaking and steelmaking processes to supply our customers with the most perfect products possible. This type of technology will advance toward the detection of still finer defects.

4. Dramatic Improvement in Gauge Accuracy with Environmentally-Friendly AC Mill Motors

Ironmaking and steelmaking facilities at a typical steelworks consume about 500 kW of electricity per ton of steel produced. The total installed capacity amounts to an extremely large 1,000 MW. The hot strip mill consists of four roughing stands and seven finishing stands. Each stand is driven by two very large 12,000-kW motors under an overload of about 225%. The hot strip mill is the largest electric power consumer at the steelworks. DC motors with

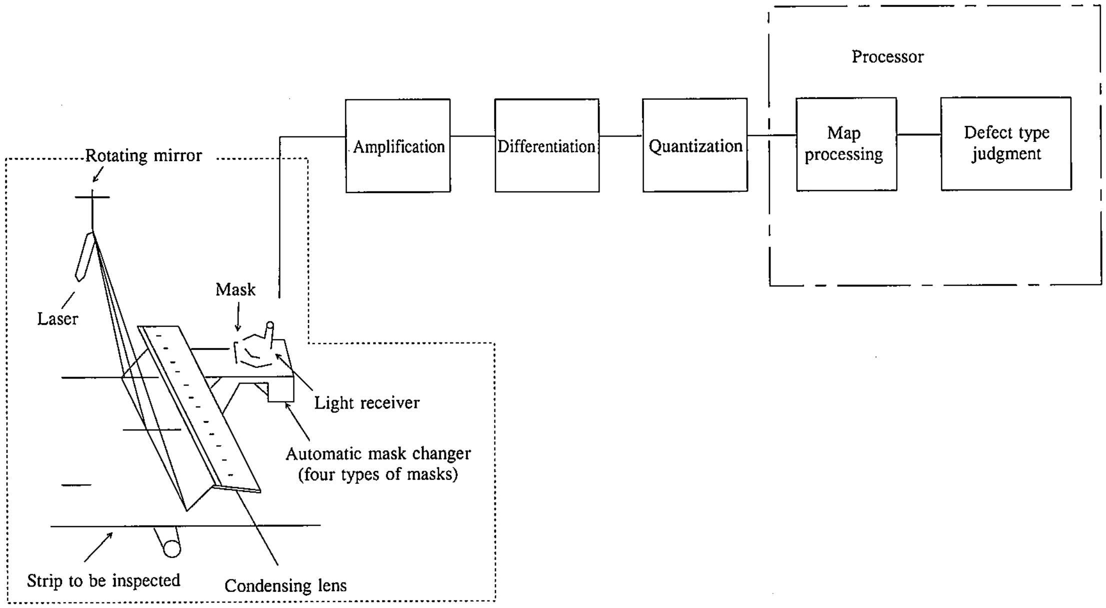


Fig. 3 Approximate construction of optical defect detection system

excellent speed adjusting performance were traditionally used on the roughing stands for reversible operation and on the finishing stands for speed zooming during rolling.

DC motors could independently adjust the armature supply voltage and field flux and were easy to operate by considering the speed (revolutions per minute) and drive force (torque). AC motors made it difficult to independently set the supply frequency and voltage and were not used in adjustable-speed applications. About 1970, Siemens AG of Germany developed the vector control method that allows control of AC motors like that of DC motors. Since analog logic alone was available then, however, vector computation errors were so large that AC motors were inferior to DC motor drive systems in terms of current control response, for example, and were not installed for large power applications. The remarkable development of computer technology in the 1980s allowed vector computation to be performed with higher speed and accuracy and helped AC drive systems to outperform DC drive systems. Since then, AC drive systems have been installed in new equipment and as substitutes for DC motors from the 1950s when they were replaced due to their obsolescence.

The vector control system of an AC motor is shown in **Fig. 4**[6]. In the speed control section, the speed controller acts to eliminate the deviation between the set point speed ω_r^* and the detected speed ω_r and outputs the set point secondary current I_2^*. The vector control section generates the reference primary current I_1^* and the frequency and phase of the motor from the specified secondary current I_2^*, reference magnetizing current I_m^* and detected speed ω_r. The current control section controls the current controller so that the current flows as indicated by the specified primary current I_1^* and that the desired torque is obtained. Since the vector and current control sections acquired high-speed processing capabilities with high-speed computers, AC drive systems were practically applied to the industrial field.

Power conversion devices have brought new developments with the progress of microfabrication technology for LSIs and the like, which in turn has been the basis for the progress of computer technology. Initially, only one thyristor device was fabricated on a 4-inch silicon wafer. The progress of microfabrication technology helped to print a few thousand thyristors on a single wafer and to manufacture large-capacity gate turn-off (GTO) thyristors that can turn off conducting devices unlike conventional thyristors.

Fig. 5 shows the power quality and response of various motor drive power supplies and the rolling-direction gauge accuracy of rolling mills. With motor-generator (M-G) sets popular until the

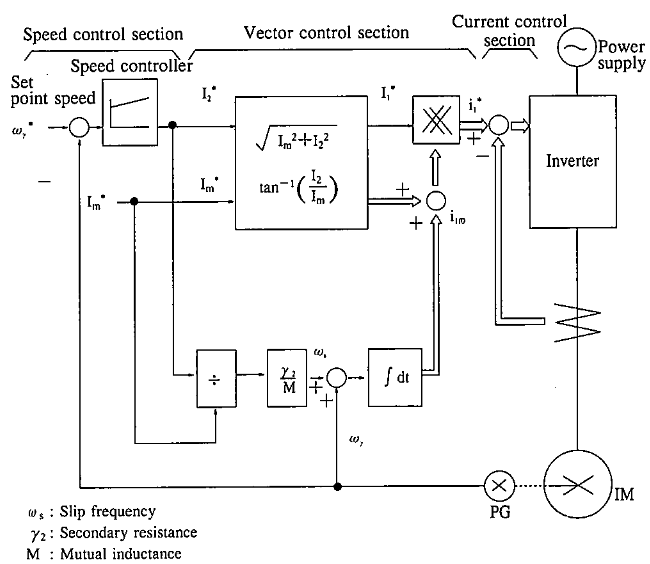


Fig. 4 Vector control diagram of AC motor

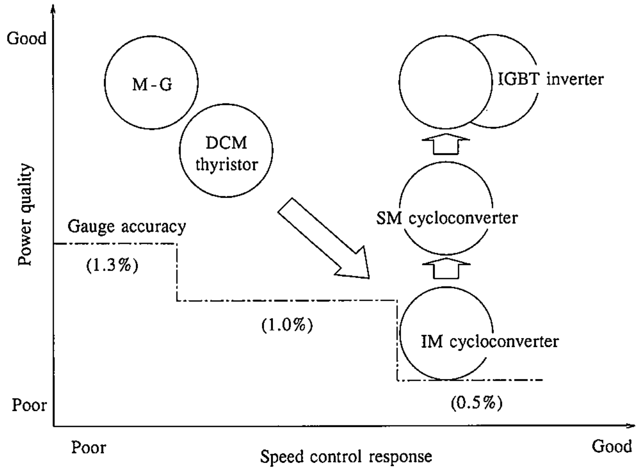


Fig. 5 Positions of drive systems

1950s, the response was about 5 rad/s, the power factor was 1.0 or on the lead side because the motor was of the synchronous type, and the power quality was extremely good with no harmonics produced in the power supply. The thyristor-Leonard system that appeared in the 1960s featured a rapid response of 20 rad/s, but the power factor was 0.7 (lag). Firing in the middle of sine-wave voltage for the purpose of power control produced harmonics, or the power quality was poor.

The cycloconverter, an AC drive system industrialized thanks to the above-mentioned progress of computer technology, also uses thyristors as power conversion devices. The cycloconverter performs AC-AC conversion and produces harmonics that vary with the operating frequency. Since the thyristors were utilized at a low rate, the response was markedly improved by switching to the AC, but the power quality became poorer than that of a comparable DC drive system. The subsequent change from an induction motor to a synchronous motor improved the power factor to a level equivalent to that of a corresponding DC drive system.

The large motor capacity as noted above made improving the power quality an urgent problem. The combination of a GTO inverter with a GTO converter to solve this problem provided a high-response drive system with a power factor of 1.0 and with practically no harmonics. GTO inverter/converter combinations still lack the capacity for use at hot strip mills. GTO inverters and IGBT (insulated-gate bipolar transistor) inverters using IGBTs as power conversion devices in place of GTO thyristors are increasing in capacity. GTO inverters[7] are used at 5,700-kW cold strip mills, and IGBT inverters[8] are used at 2,000-kW shape mills. The relationship between cold strip mill gauge accuracy and response is shown in **Fig. 5**. It can be seen that the gauge accuracy of cold strip mills has been markedly improved by the adoption of AC drives with excellent power quality (and environmental friendliness).

There are expectations in this field for the expansion of application scope of IGBT inverters with increased capacity and the industrialization of drive units with power conversion circuits offering excellent cost performance. Since these AC drive units have complex control circuits, easier-to-use AC drive systems with improved commissioning, maintenance, and other auxiliary functions (like auto tuning) are expected to appear.

5. Control Technology Approaching Human Thinking

Ironmaking and steelmaking processes are complex systems that must be controlled at high speed. Various new control laws have been applied with good results. New control schemes are constantly required to meet the requirements for product quality improvement and the appearance of new production processes. Recently, various improvements and developments have been made by incorporating new control laws, including $H\infty$ theory applied to mill motor shaft torsional vibration suppression[9] and genetic algorithm (GA) applied to hot strip mill process logistics scheduling[10]. Here, we give an overview of fuzzy logic applied to a continuous galvanizing line (CGL)[11].

In the CGL, strip of about 1.0-mm thickness is run at a speed of about 150 m/min, heated to about 450°C in a furnace, dipped in a zinc pot, coated with zinc, and sprayed with high-pressure nitrogen gas to control the zinc coating weight. Thermal diffusion by rapid heating alloys the zinc with the iron of the strip to increase the adherence of the zinc coating to the steel base. A galvanized coating is schematically illustrated in **Fig. 6**. The addition of heat diffuses iron ions from the steel base and gradually grows the alloy from pure zinc to the ζ layer to the δ_1 layer to the Γ layer. Since the ζ and Γ layers have an adverse effect on the peeling of the alloy, it is necessary to preferentially grow the δ_1 layer. These alloying reactions are diffusion reactions. The relationship between the temperature and the amount of diffusion is generally known to be represented mathematically as shown below and is considered to be capable of being regulated according to control theory.

The amount of diffusion, A, is given by

$$A = \sqrt{D \cdot T} \qquad \cdots\cdots(1)$$

where the diffusion coefficient, D, is

$$D = \sqrt{D_0 \cdot \exp(-Q/(R \cdot T))} \qquad \cdots\cdots(2)$$

$$C_W \cdot C = \int_{t=0}^{t=t_0} \sqrt{D_0 \cdot \exp(-Q/(R \cdot T))}\, dt \qquad \cdots\cdots(3)$$

where t = time; D_0 = frequency factor; R = gas constant; Q = activation energy; T = strip temperature; C_w = coating weight; C

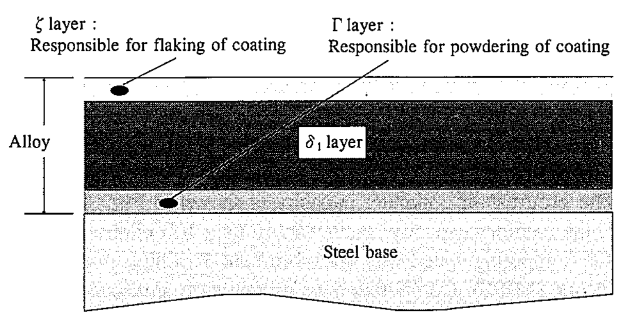


Fig. 6 Composition of surface layer of galvanized steel

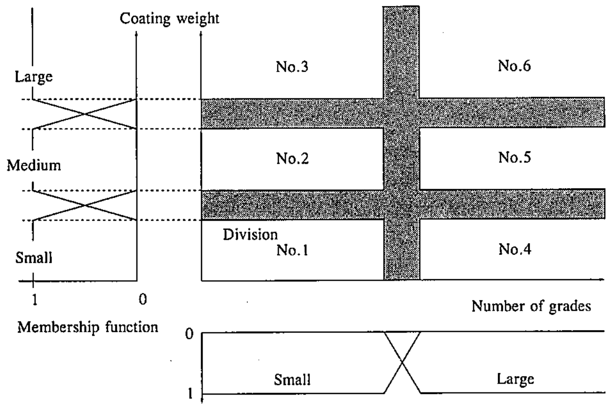


Fig. 7 Fuzzy division and membership function

$=$ iron content of the coating; $A = C_w \cdot C$, t_a = alloying time $= \ell / L_s$; ℓ = alloying furnace length; and L_s = line speed.

Actually, measuring the strip temperature in the alloying furnace was made difficult by the heat radiation from the furnace, no methods were available for measuring the alloy condition, and the line was operated by operators while using their sensory organs. Thereupon, fuzzy theory was applied. Fuzzy theory can incorporate the know-how of the operator as rules into a control system and can linearly represent the conclusion part in an easy-to-identify manner. The premise was divided into three parts by the coating weight and into two by the number of grade, which is a function of the steel grade, and the heat input model space was divided into six parts as shown in **Fig. 7**. The conclusion has linear equations built by the alloying count, heating furnace temperature, and zinc input. This fuzzy control improved the yield by 1%.

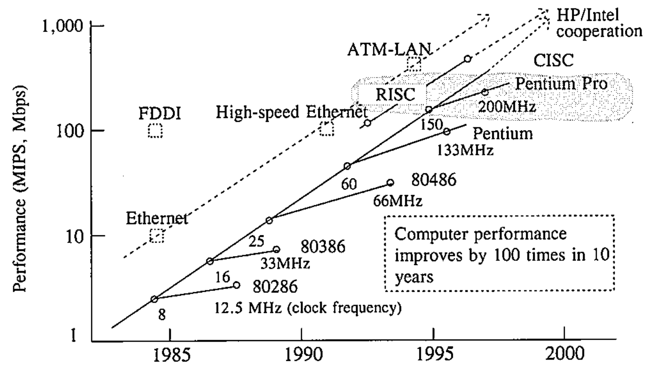
In this way, control is expanding its domain close to that of human thinking. Recently, there have been moves to fuse neuro-fuzzy (combination of fuzzy logic and neural networks), neural networks, genetic algorithm, and chaos theory by making the most of their individual characterisics[12]. $H\infty$ and μ-synthesis theory will be used in applications where the models to be studied can be accurately represented by mathematical equations and events can be measured. Fuzzy, neuro-fuzzy, genetic algorithm, and artificial intelligence will be employed in applications where the phenomena to be studied are difficult to model and depend on human senses and where the constitutive equations are large in scale, complex and difficult to solve, as represented by the process of transporting products.

Needs will not be exhausted but will ever expand in the control technology field. In this sense, control technology constitutes an area worthwhile for us to actively engage in.

6. Control Computer Systems with Increasing Distribution

The progress of computer capacity is shown in **Fig. 8**. About 1975, the memory capacity was not more than 100 kilobytes (KB), and the computing speed was not more than 1 million instructions per second (MIPS). Computers have dramatically improved in performance since then, with the internal memory capacity and the computing speed exceeding 64 megabytes (MB) and 100 MIPS, respectively. These advances of computers are effecting immense changes in information and control systems in the steel industry.

The functional hierarchy of the steel industry's information and control computer systems is shown in **Fig. 9**. The control business computer (batch processing) as a steelworks control job support system for production planning, technology control and equipment control, among other jobs, is located at the highest level. The ironmaking and steelmaking processes are controlled by the hierarchical system composed of business computers (on-line processing), process computers, and electrical equipment and instrument controllers. The iron and steel production processes can be classified by the control speed and the number of functions as shown in **Fig. 10**. Testing equioment, water treatment equipment, and other auxiliary facilities with relatively few functions and low control speed,



ATM : Asynchronous transfer mode
HP : Hewlett-Packard

Fig. 8 Performance improvement of computer system equipment

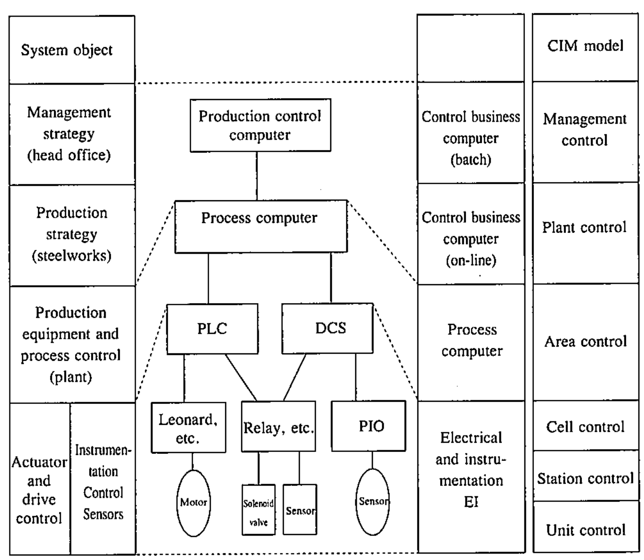


Fig. 9 Functional hierarchy of steel industry's information and control systems

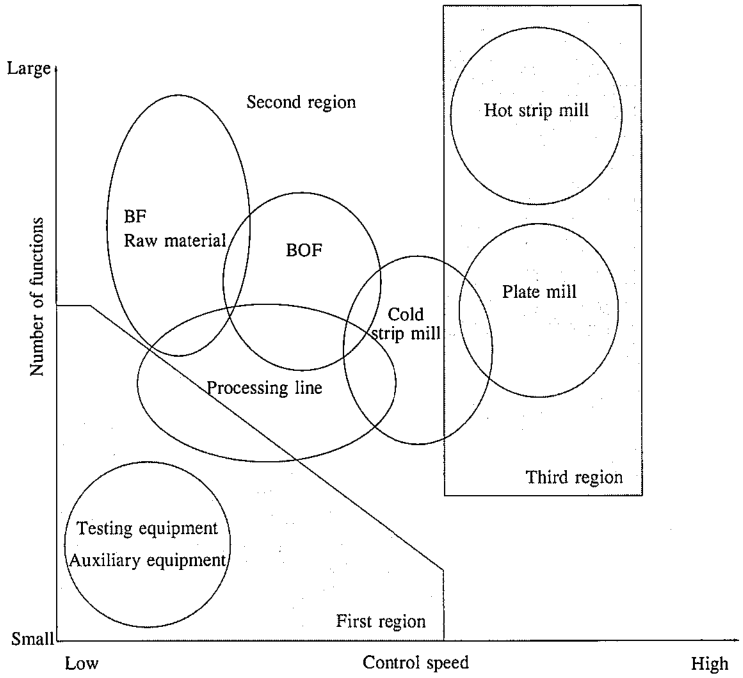


Fig. 10 Classification of processes into regions (process patterns) by control speed and number of functions

and low-speed processing lines like the electrolytic tinning line (ETL) are grouped into the first region. The third region includes processes with high control speed and many functions, such as the hot strip mill that rolls many types of products at a speed of 1,000 m/min or more and the plate mill that calls for one-by-one control of plates produced in many types and lots. All other processes fall in the second region.

As discussed above, computers have dramatically increased in speed and cost performance, so that individuals can now easily purchase personal computers with the same functions as those of conventional process computers. Instead of conventional high-performance programmable logic controllers (PLCs) and distributed control stations (DCSs), personal computer PLCs and DCSs composed of personal computers and general-purpose controllers (sequencers) with I/O functions have been practically applied as electrical equipment and instrument control systems in recent years. In the process computer area, personal computers that use Windows NT with excellent real-time characteristics as the operating system (OS) have begun to be applied on small-scale continuous annealing lines, for example, as substitutes for process computers. Given these trends, systems in the first region will be implemented as ultralow-cost systems by combining personal computers with general-purpose controllers.

Motor drive systems and field controllers (such as flow control valves) are being equipped with microcomputers and made intelligent at an increasing pace. In the control technology field, these intelligent devices will be functionally differentiated from PLCs and DCSs. Downsizing process computers operating on Windows NT will acquire sufficiently high performance to take the place of process computers for blast furnaces and cold strip mills. The information processing area in the second region will embrace downsizing process computers, and the control area will embrace EI controllers for common use of electrical equipment and instrumentation, and intelligent devices. This is because general-purpose controllers are unable to meet the speed at which drives and gas flow, for example, are controlled at high-speed processing lines, such as the cold strip mill and the continuous casting line.

The hot strip mill in the third region is a seven-stand finish rolling mill. For quality control, it is necessary to collect data at one longitudinal point of strip as the strip is rolled through the respective stands. The computer must start processing the data at stand start time intervals of 10 to 20 ms. The plate mill is a reversible rolling mill. The time during which set points for the next pass are calculated and specified after the end of the previous pass is idle time. This means that the computer must process the relevant data at an extremely high speed. Personal computers offer fast processing times, but have no mechanism to guarantee the longest time for interrupt processing. Conventional process computers are thus indispensable. Drive systems must also be controlled at high speed, of course. In the third region, conventional process computers will be used in combination with electrical and instrumental controllers.

The above system configurations will be downsized with the progress of computer technology and will be divided into three main regions according to the characteristics of specific ironmaking and steelmaking processes as shown in **Fig. 11**.

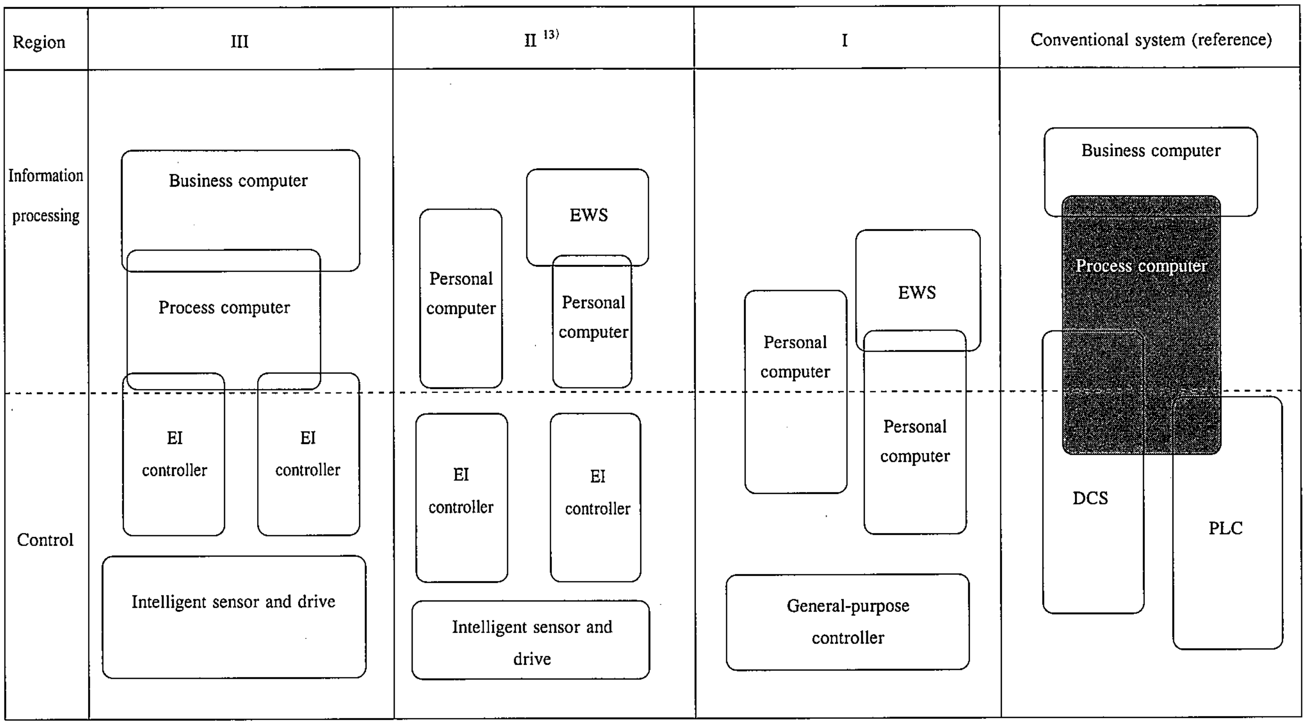


Fig. 11 Future system configurations adapted to process patterns

7. Conclusions

The present and future of system control technology and their rapid progress as supported by the remarkable advancement of computer technology have been described. As compared with the Windows 95 fever at the end of 1995, the present situation appears calm, but computers are certainly improving in execution speed, and de facto standard networks are ever increasing in speed. Multimedia is approaching such a level that it can be now applied in our plant control area.

The areas of measuring instruments, power electronics, and control technology are based on these electronic technologies. The performance of instruments, power electronic devices, and controllers will continue to advance significantly. We will apply the latest in technology to Nippon Steel's ironmaking and steelmaking facilities to supply our customers with steel products of higher quality. At the same time, we intend to furnish through Nippon Steel's divisions the technologies we have developed as users, including control middleware for Windows NT[1].

Note: Windows NT and Windows 95 are registered trademarks of Microsoft Corporation of the United States, and Pentium and Pentium Pro are registered trademarks of Intel Corporation of the United States.

References

1) Kawahara, K. et al.: Shinnittetsu Giho. (363), 37 (1977)
2) Fukuda, F.: Technical Meeting on Metal Industries Div., Tokyo, February 1996, IEEJ
3) Akagi, T.: Shinnittetsu Giho. (364), 30 (1997)
4) Naitou, S.: 105th Nishiyama Memorial Seminar, Tokyo, January, ISIJ
5) Nakano, K. et al.: Trans. IEEJ. D-111 (1), 29 (1991)
6) Masada, E. et al. (eds.): All about Power Electronics. May special issue of OHM, Ohm Co., May 1994, p. 62
7) Hoshino, T. et al.: Technical Meeting on Metal Industries Div., Tokyo, July 1995, IEEJ
8) Hattori, Y. et al.: Technical Meeting on Metal Industries Div., Tokyo, March 1997, IEEJ
9) Hoshino, T. et al.: AMC-94, Berkeley, California, 1994, AMC
10) Ogai, H. et al.: Journal of System Information Processing Society. (March 1997)
11) Masuda, M.: Private communication, Nippon Steel, May 1996
12) Tanaka, K. (ed.): Intelligent Control Systems. First Edition, Tokyo, Kyoritsu Shuppan, 1996, p. 183
13) Nakakita, T. et al.: Journal of Society of Instrument and Control Engineers, 34 (11), 843 (1995)