Strategic Vision for Smart Machining Tool and Measuring Instrument

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Establishment of the innovation driven manufacturing, which enables new value creation such as customized products and innovative products with services, is expected in the age of non-equilibrium and strategy. The holistic measurement based on integrating different measurement principles and multi-scale data fusion as well as smart in-process and on-machine measurement technologies will play an important role in the predictive control type manufacturing system. The connected smart in-process and on-machine measurement systems that give self-recognition ability to the manufacturing system is also the key technology in Industry 4.0 to establish the innovation driven manufacturing.

1. Introduction
The paradigm shift of the socio-economic structure from a "society of equilibrium" to a "society of non-equilibrium" which proliferates and penetrates on a global scale and its challenges can be interpreted as the transition from the "age of tactics" to "age of strategy" as shown in Fig. 1. With the change of the new value system and socio-economic environment, such as a sustainable society, environmental considerations, and global standards, manufacturing is also changing. Its status is termed the change from "linear society/age of railway" to "non-linear society/age of great voyage." Attention is paid to the unpredictable destination (market) and the process of getting there, rather than the foreseeable and predictable destination (product), and focus is placed on fundamental thoughts (strategy) rather than the pursuit of higher added value through improvement and enhancement (tactics). Along with these trends, the challenges that cannot be solved by extending the conventional approaches are increasing. The pace of holistic transformation in many fields from science to society and economy is steady and fast, even more accelerated in recent years. This paper will identify the potential power of strategic measurement as one of the above trends which drives the manufacturing transformation, namely, the 4th Industrial Revolution, and explore the future development of the predictive production system and smart machining/measurement.

2. Innovation driven manufacturing
In the efficiency driven manufacturing of the "equilibrium/age of strategy," focus was given to the strategy to achieve addition of higher product value through high precision and efficient production systems and the tactics to realize it. The tactics were to rapidly promote a highly developed production system. Therefore, efforts were made to breakdown the manufacturing technology into elemental technology (production tools) such as machining technology, measurement technology, and production technology (CAD/CAE/CAM/CAT) that compose of production systems and solve challenges of each element. That resulted in a significant outcome. As such, the role of measurement technology was weighed heavily as one of the production tools (measurement=testing) in Fig. 2 and used as a tactic for achieving the objectives given to the "thing" (product) such as high quality, low cost, and short delivery time. When the manufacturing process was in the "equilibrium state" for a prolonged time, "measurement in manufacturing" as a production tool played a satisfactory role.

Alternatively, in the innovation driven manufacturing of "non-equilibrium/age of strategy," strategy is weighed more heavily than tactics. Strategy in this case is new value creation, such as customized manufacturing, creation of innovative products, and the associated services in addition to the new approach of high value addition. As the tactics to respond to the strategy change over time, achieving predictive
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20th century
Equilibrium society
[Age of tactics]

21st century
Non-equilibrium society
[Age of strategy]

[Change of structure and challenges]

Fig. 1 Railway era to the age of discovery

<table>
<thead>
<tr>
<th>Society</th>
<th>Economy</th>
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<tr>
<td>Business</td>
<td>Production (Manufacturing)</td>
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<td>Business</td>
<td>Engineering</td>
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<tr>
<td>Business</td>
<td>Measurement</td>
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Production tool: measurement = inspection

Efficiency driven manufacturing

Fig. 2 Equilibrium era: Measurement technology as production tools

Strategic tool: measurement

Fig. 3 The age of non-equilibrium: Measurement technology as strategic tools

production systems is necessary. Therefore, the role of the measurement technology is significantly different from the past, in addition to applying a predictive production system, as shown in Fig. 3. The measurement technology will be required to assume the strategy itself for achieving the diversified objectives that are heavily engaged with the entire "event" processing, such as market, product, and process throughout the "things" (product), and their life cycle, tightly connected to information. Today, when the manufacturing process is transitioned to a "non-equilibrium state," the measurement, which is the source of information (resource), is required to make innovative progress as a strategic tool for "measurement for 'event' creation."
3. Concept of new production quality

3.1 Evaluation of machining accuracy and process capacity

Taniguchi predicted that the machining limit of precision machining technology would reach 0.1 \( \mu \) m in 2000, in his 1983 paper. The progress of mechanical machining technology has been significant and it is now reaching the area of general machining limits. The machining process is a general technology involving many elements, such as machine tools, workpieces, working conditions, working environment, and products. The machining error is caused by the influence of various factors, such as positioning accuracy and thermal displacement of machine tools, geometric accuracy and wear property of tools, material and hardness of workpieces, machining conditions, such as dry machining and processing skill set, working environment, such as temperature and vibration, and high precision and complexity of products. Based on the law of error propagation, accuracy of the entire machining process cannot be improved by compensating unstable factors by stable factors. That is, if there is even one unstable factor in the machining process, the overall accuracy is decreased, as it is determined by that factor.

Machining accuracy can be tackled separately between precision and accuracy. In addition, machining requires capability to satisfy the standard size and allowance. Fig. 4 shows how to evaluate the machining accuracy and process capacity. If the upper and lower limits of the machining specification are \( LSL \) and \( USL \), respectively, and the allowance is \( T \), then when the average machining value (machining size, etc.) is the midpoint value of \( T \) and the standard deviation is \( \sigma \), the limit machining accuracy \( p \) and machining capability index \( C_{pk} \) or \( C_p \) are calculated by the evaluation equation indicated in Fig. 4, respectively. For example, when \( C_p \geq 1.33 \), 99.1% of workpieces fall within the allowance of 1/1.33=0.75.

Machining accuracy (error) cannot be directly "observed." Therefore, it is necessary to understand how to "visualize" it through the "window of measurement." Fig. 5 shows how the machining capability index is evaluated depending on the magnitude of "uncertainty" of measurement. When the allowance is \( T \), \( LSL \) and \( USL \) shows the lower and upper limits of the machining specification, respectively. For simplicity, assume the average machining value (e.g., machining size) to be the center value of \( T \) and the standard deviation that shows the machining variance to be \( \sigma \). For example, if the true machining capability index \( C_{pk} \) or \( C_p \) is observed through the "uncertain window of measurement", and when the machining capability is evaluated with the uncertainty \( U = 0.1 \) \( T \) (Fig. 5(a)), then \( C_p \) (or \( C_{pk} \)) is evaluated as 1.24. Alternatively, when the uncertainty \( U = 0.27 \) (Fig. 5(b)), \( C_p \) (or \( C_{pk} \)) is 1.04 and it is evaluated as the lower machining capability. It also reveals that the entire uncertainty \( U \), which includes the uncertainty of measurement, is larger than \( \sigma \). Therefore, the magnitude of uncertainty as the index to show that the reliability of measurement determines the reliability against assurance of machining accuracy. The uncertainty of measurement is an important index for highly efficient machining processes based on the evaluation of machining capability. In order to assure high precision/high accuracy machining by the strategic measurement "to create value," it is necessary to use measurements with higher reliability (lower uncertainty). As seen above, improvement of process capability is required by reducing machining errors from the machining process, that is, bias errors and variation errors from the absolute values, for improving the machining accuracy. To do so, it is most effective to examine all

![Fig. 4 Process capability index \( (C_{pk}, C_p) \) for evaluating the machining accuracy](image-url)
the elements of the entire machining process considering all the factors in the machining process as subject to measurement and apply improvement to the most unstable factor.

3.2 From product (quality) to production quality

Machining accuracy is determined by the complex superposition of machining errors that vary with various unpredictable factors, such as the properties of the machine tools and workpieces, machining environment, and machining procedures. The accidental errors included in the machining errors cannot be corrected, as their cause cannot be determined. However, they can be estimated with repetitive measurements and, therefore, it is effective in mass production, where the same machining is repeated for the same components (many probabilistic trials). Machining accuracy can be considered as the statistically fluctuated quantity, that is, probabilistically variable quantity. Therefore, the conventional quality control approach used in mass production of the efficiency-driven manufacturing is based on the machining accuracy evaluation of the statistical model.

On the other hand, together with the increase of demand of energy related facilities such as power generation turbines and customized products, the demand for aircraft parts is increasing globally, in recent years as shown in Fig. 6. Domestic production of large precision parts which require rigorous quality control is also increasing. For small-lot or one-unit production or customized production where new quality control concepts and strategic machining measurements as the base for production system are required, not only products but the process will also drastically change, along with the aging process of individual products in their life cycle and change of strategy. In these cases, careful consideration is required for applying quality control based on the conventional statistical concept as the systematic error in machining errors change in the environment where variation of temperature and aging of machines cause change in accuracy. In addition, when the number of units for machining is very small and the process tends to change, verification of appropriateness of the statistical assumptions shown in Fig. 4 will be difficult.

Therefore, the concept of production quality is being proposed, as a new production control and quality control approach, as shown in Fig. 7, which can be applied to small-lot or one-unit production, or customized production solving the challenges of the conventional statistical process control approach. This approach emphasizes quality/function assurance focused on the process as the basic concept by "informatizing every process of manufacturing", not only geometric quantity of workpieces as the index to measure the quality. It establishes production quality control by defining innovative and integrated production quality that uses enormous amount of data (industrial big data), designing an entire product life cycle from production logistics to maintenance based on such definition, introducing new management / control methods for big data with advanced technology to achieve them. The technological innovation required for that includes product testing technology, machining monitoring technology, and
multi-sensor data integration technology, as shown in Fig. 7 (a) to (h). This technology, in other words, implies that the in-process/on-machine measurement technology encompassing a broad range of elements that directly determine machining accuracy, such as tools, machine tools, machining environment, and machining/measurement operation, is critical. In addition, it is expected that small-lot production and customized production or one-unit production will increase in the "non-equilibrium/age of strategy," where the adopted strategy is to generate new value by creating innovative products. Therefore, production quality control based on in-process/on-machine measurement is indispensable, which is also the key technology for achieving predictive production system.

Fig. 7 Fundamental scheme of production quality control and the required innovative technologies to establish it
4. Production quality control by holistic measurement

4.1 Current status of in-process/on-machine measurement

The role of the machining measurement for production control is "informatization" of manufacturing. In the advanced production system using diversified and vast production information, machining measurement plays an important role as the key information source on the products and machining states. The most essential purpose of machining measurement is production control, production automation, and test automation. In-process/on-machine measurement is the most efficient and effective machining measurement technology engaged directly in monitoring and controlling of machining. With the machine tools with reproducibility, the machining errors that vary over time during machining operation due to factors such as deformation and displacement of machine due to change in temperature, thermal expansion and deflection of tools, and wear may be evaluated and corrected by re-machining.

Recently, machine tools with in-process/on-machine measurement capability are being commercialized and the importance of their role is increasing. These trends are driven by diversified purposes of the measurement. In-process/on-machine measurement plays a central role for production/quality control as well. Fig. 8 shows the fundamental measurement properties required in in-process/on-machine measurement technology and the unique properties and relationship between machining factors across machine tools, workpieces, and machining environment and in-process/on-machine measurement. Of particular importance as a fundamental measurement property is accuracy and precision. For example, consideration for questions such as if accuracy and precision for evaluating tolerance range as the base for process capability are satisfactory and if absolute measurement is required due to machining bias errors is critical. In addition, the in-process measurement evaluation is affected by dynamic characteristics such as transient response and frequency response. Furthermore, properties specific to in-process/on-machine measurement are also required. These include environment factors required for installing measurement devices to machine tools and hardware/software factors. For example, in the case of on-machine 3D profile measurement using an optical comparator, vibration property, compactness, and switching process are required. The advantage of in-process/on-machine measurement is not limited to improvement and stabilization of machining accuracy but extended to higher efficiency of machining/measurement setup. As such, the scope of measurement extends from workpieces to machining state in space and time domain realizing "visualization of machining process" by quantifying machining factors.

The machining error, which value is constantly maintained during the repetitive machining operation, provides the same effect not influencing the accidental error. Therefore, it provides a constant bias to the
machining accuracy. In general, evaluation of systematic error which cannot be found in these repetitive measurements is difficult and often its existence cannot be detected. However, if the factor for systematic error is predetermined and its magnitude is known, it can be eliminated with correction. Therefore, a smart machine tool which can determine the factors of machining errors in real time with multiple in-process/on-machine measurements is an important concept as an elemental technology of the production system in conventional efficiency driven manufacturing. The basic concept of the smart machine tool that holistically provides machining process monitoring, recognition, and prediction using multiple sensors was presented around 1993 by Moriwaki. Since then, active research and development has been conducted on in-process/on-machine measurement and machining control aimed at application to practical systems, resulting in increased development in application fields such as advanced sensors for tool condition monitoring (TCM), signal processing methods, decision making strategy, etc. These trends of research activities on the challenges of in-process/on-machine measurement indicate that attention is paid to the solution of individual challenges for each element of tools/workpieces/machine tools which are the main elements of the machining process, and the challenges in the boundary area from interaction of these elements. In other words, adaptation to advanced and complex requirements of high-speed, multi-functional, and intelligence is sought after in addition to higher accuracy of machining processes, from the viewpoint of practical application of in-process/on-machine measurement to the real system. As the complexity of machining process increases, interaction of tools, workpieces, and machine tools has become more complex and the challenges of in-process/on-machine measurement in the boundary area have also become multifaceted and advanced.

Areas subject to in-process/on-machine measurement are expanding from geometric quantity to state quantity and the challenges are not only multifaceted, but expanding with advanced multi-axis/multi-tasking machine tools and intelligent machining process. In addition, the requirement of further improvement of accuracy for ultra-precision machining is expanding into new dimensions, such as 3D free curve profile, micro complex profile, and nano-surface pattern, which are required for commercialization of advanced functional parts. Fig. 9 summarizes positioning and scope of in-process/on-machine measurement technology in the on-machine system with tools, workpieces, and machine tools as its key elements. It indicates the boundary areas of each element and relation among measurement technology and breaks down the time-variant phenomena into short, medium, and long period and marks their
positioning in the respective time scale. The relation of in-process/on-machine measurements is indicated by ring bands connecting two elements and a ring band circling three elements. The former indicates interaction of the elements, and the latter indicates a complex interaction area where three elements are involved. In addition, the outer ring band that encloses the entire diagram indicates machining atmosphere and manual operation. The purpose of measurement is classified into evaluation of machining dynamic characteristics, machining state monitoring, and measurement of geometric quantity, such as size, shape, and displacement, with R&D examples shown chronologically from \([a]\) to \([p]\). For example, in the case of \([a]\), on-machine measurement of tool wear (1976) is positioned as the on-machine measurement technology with the purpose of monitoring machining state that changes over time in the boundary area between tools and machine tools. Also, the in-process/on-machine measurement technology that corresponds to the solution to challenges other than the interaction between elements are only indicated with factors as the challenges to be solved in the future.

4.2 New in-process/on-machine measurement strategy

As the basic concept of new in-process/on-machine measurement by multiple sensors, an example of high functional measurement information is shown in Fig. 10

\[\text{Multi-sensor fusion: improved detection capability by using characteristics of different physical quantities}\]

\[\text{Multi-sensor cooperation: optimized configuration of components which measure the same geometric quantities}\]

Therefore, a machining monitoring system \((8)\) \((9)\) and on-machine dimensional measurement systems are built and installed on the machine tools based on the concept of “multi-sensor fusion” and “multi-sensor cooperation,” respectively.

Fig. 10 (a) shows the concept of multi-sensor fusion on-machine measurement for machining state monitoring. By conducting state estimations combining feature amounts from multiple sensors, characteristics of different physical amounts can be used to improve the detecting capability of machining monitoring. In the machining process that requires long time, measurement information (physical amount varied over time) obtained from the respective sensors is integrated in real time. Use of advanced signal processing to detect feature amounts that correlate with abnormality based on the time-frequency analysis provides adaptive threshold management in machining monitoring. Its high adaptability to environment and abnormality symptom detection capability reduces the risks related to production quality, such as chattering and tool failure, which is the most important measurement strategy for achieving a zero-defect process. In addition, in the future it is expected to both maintain production quality and improve process capability by integrating estimation methods and machining monitoring information considering multiple analysis technologies and uncertainty, such as cutting phenomenon, cutter path, tool/workpiece shapes, and by optimizing machining conditions based on the process model.

Fig. 10 (b) shows the concept of multi-sensor cooperation on-machine measurement for high precision measurement of geometric quantity. Higher accuracy of measurement is pursued by optimizing...
and allocating respective roles for multiple components with the purpose of measuring the same geometric quantity (e.g., size, shape, attitude, and position) based on their measurement elements. The example of on-machine dimensional measurement systems integrated with the large CNC lathe for machining large precision parts consists of laser interferometer, laser tracker, tough trigger probe, and block gauge to realize high precision, multi-sensor cooperation for on-machine measurement providing absolute length calibration.

In the case of the machining process of steam turbine rotors, the operation of moving the work from machine tools to the measurement system was difficult and on-machine measurement was manually conducted using large micrometers, etc. Therefore, the problem was that it involved many measurement processes, resulting in increased uncertainty. To solve this problem and achieve efficiency of the manufacturing process and machining quality assurance, a high precision on-machine measurement system was developed. **Fig. 11** shows an example of on-machine measurement system for large structural parts by “multi-sensor cooperation” targeting steam turbine rotors (max. length of 10m or more, diameter of 1m or more, and dimensional tolerance of 0.1mm or less) of large CNC lathes. It shows configuration of the system which conducts absolute measurement of wheel position and axis diameter of the steam turbine rotor of the large CNC lathe by probing measurement method 10). An inline length measuring system using laser tracker is introduced as the external coordinate system and a wireless touch trigger probe is implemented on the tool carriage. In addition, as the parts and machine elements are both affected by shrinkage and expansion (about 0.1mm of impact per 1m if the rotor temperature changes from 20°C to 100°C), a calibration method of absolute length is implemented using a block gauge to correct bias errors.

**4.3 Concept of holistic measurement**

For the predictive production system, which is the foundation for innovation driven manufacturing, development of smart in-process/on-machine measurement as the strategic tool for machining measurement technology innovation is required to realize production quality control. As its foundation, the measurement strategy is to realize "informatization of every process related to manufacturing" by developing high degree of "multi-sensor fusion" and "multi-sensor cooperation," and with holistic measurement 11) based on integration of different measurement principles and multi-scale data fusion. For realizing holistic measurement, new theory for evaluating uncertainty, new comprehensive measurement principle to encompass the calibration technology, and conventional measurement principle and broader research regarding the compatibility among them are required.

As a specific example, a basic concept of intelligent multi-sensor coordinate measuring machine (CMM) is presented 12). The holistic measurement uses new measurement technology, such as multi-sensor CMM with metrology X-ray CT (volumetric measurement). With the advancement of measured data fusion technology by integrating CAD/CAE/CAM/CAT data, this builds the foundation for advanced production quality control while different measurement systems become connected with each other through the Internet. The new strategic machining measurement which extends the concept of this measurement fusion technology to in-process/on-machine measurement is the smart in-process/on-machine measurement that realizes environment adaptive measurement with such properties as real-time, wide range, and multi-point simultaneity. As shown in **Fig. 12**, the optical non-contact measurement technology in a broad sense, including X-ray, is making rapid progress and technology that can measure surface micro-profile, 3D profile, and 3D internal structure has already been developed. Metrology X-ray CT technology in particular is making significant progress and its incorporation into inline processes and applications for assembly process inspection are being proposed 13). When building multi-sensor CMM using these measurement technologies, 3D measurement data fusion technology is required for measurement integration of micro-profiles to complex large 3D profiles and volumetric measurement data. Efforts for developing measurement fusion technology 14) is already in progress. However, some technical challenges still remain, specifically related to multi-scale data fusion, such as measurement data quality including uncertainty, standard and calibration.
methods, the basic quantity of measurement such as one-dimensional length and displacement, and two-dimensional surface micro profile with different angles and scale.

5. Outlook and challenges of smart machining/measurement machines

5.1 The 4th Industrial Revolution and predictive production system

The 4th Industrial Revolution is a disruptive transformation unlike the previous industrial revolutions, as significant innovation is expected not only in the manufacturing process but also across the entire product life cycle due to the rapid technological innovation in information technology, as evidenced by the promotion of Industry 4.0 in Germany and Industrial Internet in the U.S. The ultimate objective of the 4th Industrial Revolution is achievement of a new predictive production system based on the total optimization and efficiency of the manufacturing process, development of predictive maintenance, etc. That is, creation of new value by innovative products that fill the gap of “invisible value” and shift from mass production to complete customized production (one-unit production). In the manufacturing process with completely different mechanisms from the past, production quality has better adaptability than the quality control approach used in mass production. Furthermore, the basic concept of the 4th Industrial Revolution requires intelligence with autonomy (e.g. self-recognition, self-maintenance, and self-prediction) as its core property to the members of the manufacturing system (e.g. products and individual manufacturing facilities). The key is to build predictive production systems with self-recognition capability. Internet of Things (IoT) which converts everything to data and connects them to the Internet through sensor technology, smaller and faster processors, and adoption of cloud technology, industrial big data which is collected by IoT, and cyber physical system (CPS) which use them will play the central role as the mechanism for such intelligence. In addition, the measurement technology, which plays the role of information resources, is required to undergo transformation as a strategy tool. Particularly, smart in-process/on-machine measurement technology is an important and high-quality source of production information together with controllers and network systems, and requires technology innovation as a strategy tool, such as self-recognition and self-prediction embedded in the measurement systems.

5.2 Smart in-process/on-machine measurement network

The approach of intelligent machine tools by on-machine measurement using multiple sensors is a concept for standalone machine tools. Its objective is to increase efficiency of individual machining/measurement systems with knowledge base and incorporation into the machines. Therefore, it remains in the scope of efficiency driven manufacturing. On the other hand, innovation driven manufacturing requires intelligent environment adaptive in-process/on-machine measurement, i.e. open and intelligent machine tools through integration with smart in-process/on-machine measurement. Configuration of multi-sensor fusion and multi-sensor cooperation

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![Diagram of measurement technologies](image-url)
based on holistic measurement changes in real time according to measured content (information on measurement environment, measurement condition, measured amount, subject of measurement, machining condition, required accuracy, allowance, uncertainty, etc.) to achieve advanced prediction. Its mechanism is based on the network of smart in-process/on-machine measurement connected in virtual space, as shown in Fig. 13. That is, the measurement content and measurement information are shared among intelligent machine tools connected to IoT, to drive predictive production systems which control production quality. The smart in-process/on-machine measurement is required to have the capability to sufficiently satisfy conditions of its measurement information such as amount, speed, diversification, and reliability. Capabilities such as self-recognition, self-maintenance, and self-prediction are obtained by CPS.

6. Summary

The most recent “2017 White Paper on Manufacturing Industries” reports the initiatives and measures that the manufacturing industry in Japan is taking for the 4th Industrial Revolution. The white paper mentions that the value of virtual data from activities on the Internet is predominantly dependent on the "quantity" of data which is already dominated by the U.S. IT companies. However, the value of the real data collected by sensors in real life activities, such as operational data of the factory facilities, is potentially dependent on the "quality" of data and the companies in the manufacturing industry may be able to take a leading role depending on the future course of action. In fact, the survey results regarding data collection of the production process in Fig. 14 indicates the trend that the activities of "visualizing" operational states across the machines in the individual process, production line, the entire production process, traceability management, collection of production process data from overseas factories, etc. are all increasing. Therefore, it is considered that smart in-process/on-machine measurement will be increasingly important as a high-quality information source. In addition, solutions using recent digital technology are considered to be the "engineering chain" and "supply chain" indicated in Fig. 15, which also shows the mechanism to make those chains more efficient by quickly feeding back the smart in-process/on-machine measurement data. In contrast, the requirements for smart in-process/on-machine measurement, such as improvement of reliability and quality on the measurement data, are becoming higher and higher, as the data is more integrated, complex, and significantly larger.

Fig. 16 indicates the transition of machining measurement technology up to the 4th Industrial Revolution and transformation to the strategic machining measurement, as the foundation of production quality control. Machining measurement technology has been playing a role in element technology for production systems that satisfy the requirements of automation of inspection, production control, automation of production, etc. In that process, it underwent a series of revolutionary improvements in measurement capability, such as improvements in measurement accuracy and speed, higher sophistication from one dimensional to two dimensional, etc. However, the measurement technology required for the 4th Industrial Revolution is not an extension of conventional technology, but a fundamental transformation. That is, the predictive production system that takes advantage of IoT, industrial big data, and CPS based on real time holistic measurement.
that uses intelligent in-process/on-machine measurement is considered to achieve the ultimate production quality control with self-recognition of the intelligent production elements.

**Fig. 14** Research results on data collection of production process

**Fig. 15** Effective utilization of IOT in Industry 4.0
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