Summary Report on Technology Strategy for Creating a "Robot Society" in the 21st Century

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Japan Robot Assosiation

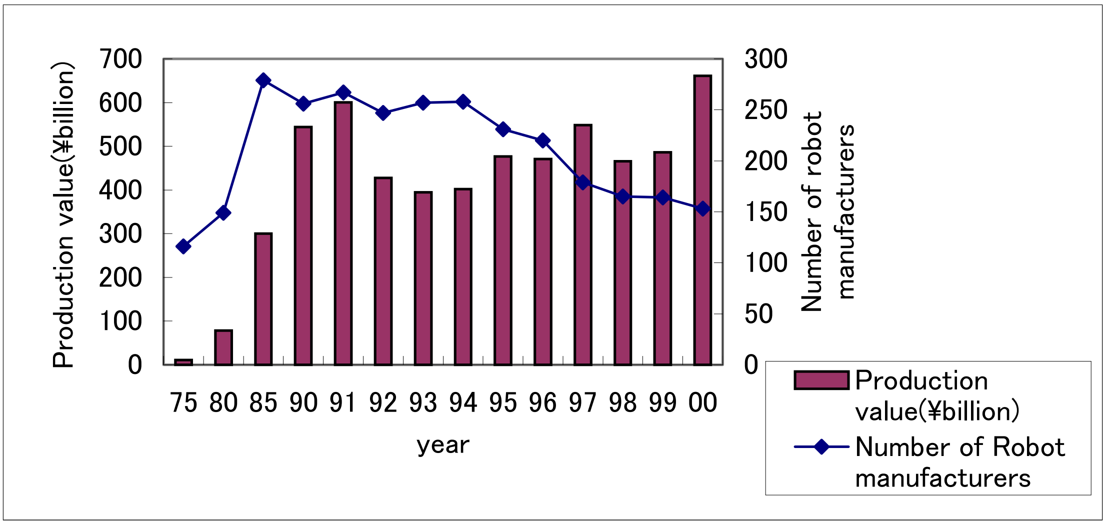
Contents

1 The Robotics Industry at Present

1.1 The current state of the industry

The Japanese robot industry has grown strongly in recent years, buoyed by heavy plant and equipment investment in the fast-growing IT industry. Production value peaked at ¥660 billion in 2000. As of 2000, robots were being produced by 153 manufacturers, although only a few were dedicated solely to robot manufacturing (see Figure 1.1.1).

Robots are used extensively in manufacturing industries such as electrical appliances and automobiles. Total added value generated by robots in the manufacturing industry overall in 1997 is estimated at ¥4.1 trillion, equivalent to 0.8% of GDP (¥500 trillion). Robots are rarely used in non-manufacturing industries (see Table 1.1.1).



Source: *Report of Survey on the Robot Industry in Japan (2001 edition),* Japan Robot Association

Figure 1.1.1 Trends in robot production and the number of robot manufacturers in Japan

Table 1.1.1 Added value generated by industrial robots in 1997 (estimates)

	Automo-biles	Electrical appliances	Other manufacturing	Total for Mfg. Ind.
A. Production (¥billion)	39,520	56,045	234,605	330,170
B. Employee compensa-tion (¥billion)	5,501	10,479	43,004	58,984
C. Added value (¥billion)	9,545	20,271	91,547	121,363
D. Added value generated by robots (¥billion)	865	1,762	1,478	4,105
E. (D／C×100)	9.1 %	8.7 %	1.6 %	3.4 %
F. % of GDP	0.17 %	0.35 %	0.28 %	0.8 %

Meanwhile, despite the longstanding enthusiasm of many companies to apply robots to new fields and applications and the general increase in public awareness of and interest in robot technology, the robotics industry itself now shows little of the initial excitement towards robot research that characterized the 70's and early 80's. Although entertainment and humanoid robots are now enjoying something of a boom among ordinary consumers, the robotics industry remains suspicious of robotics research due to the failure of the anticipated markets to emerge—for instance, teaching-playback robots did not enjoy the level of market penetration that was originally expected.

In terms of actual robot products, Japan would appear at first glance to be internationally competitive, at least with respect to the advanced robot technology employed in the manufacturing sector, one of Japan's traditional areas of strength. However, the United States and Europe boast advanced robot technology in non-manufacturing fields such as nuclear power, space, oceanic research, disaster prevention, and medical/welfare applications. Furthermore, while Japan can claim considerable expertise in basic areas such as manipulation and mobile function and lower-order controllers, the United States is clearly superior in areas such as intelligent software and media and network tools (see Table 1.1.2).

Table 1.1.2 International competitiveness in robot technology Note1)

(A) Applied technology

(○ : competitive, △ : average, × : not competitive)

Application	Japan	U.S.*	Europe**
Manufacturing (industrial robots)	○	△	△
Construction	○	×	×
Welfare applications	△	△	○
Medical applications Note2)	×	△	×
Nuclear power	△	○	○
Disaster prevention	×	△	△
Space	△	○	△
Entertainment	○	○	×
Bio-industry	×	△	△
Agriculture	△	△	○
Household	×	×	×
Service application	△	△	△
Livestock farming	△	△	○
Marine applications	△	○	○
Probes	×	○	△

Note 1) International competitiveness in applied robot technology used in the table above is based on four factors:

1. Ability to develop unique products that are subsequently copied by other nations;

2. Ability to export product;
3. Ability to have domestic market larger than other countries; and
4. Ability to create markets

Note 2) Japan has world-class technology in this area but market penetration is poor. The ranking represents an assessment of overall factors from technology research through product development.

(B) Element technology

(○ : competitive, △ : average, × : not competitive)

Type of element technology	Japan	U.S.*	Europe**
Manipulation	△	○	△
Mobile (legs)	○	○	△
Mobile (crawlers)	△	△	○
Mobile (wheels)	○	△	△
Multi-finger hands	△	○	△
Remote-controlled devices and associated controllers	△	○	○
Micro-and nano level devices	△	△	△
Simulation	△	○	○
Human interfaces	△	○	△
Intelligent control technology	△	△	△
Sensors	○	○	△
Visual recognition	○	○	△
Networking technology	△	○	△
Media technology	△	○	△
Software	△	○	○

* Includes Canada

** Limited to European countries actively involved in robotics R&D

1.2 Problems with the Japanese robotics industry

With Japanese robotics manufacturers are already moving into major markets, extensive price competition is unavoidable. Some of the other issues facing the industry are listed below.

1) Lack of entrepreneurial spirit

As mentioned in the introduction to this report, the domestic robotics industry has tended to concentrate on large, low-risk markets such as automobile and electrical appliance manufacturing. There has been little attempt to take venture-style risks as in Europe and the United States. This structural bias towards large manufacturing industries has restricted opportunities for the development and marketing of innovative technology ideas generated by universities and government research bodies, preventing many of the fruits of research from ever reaching industry. It also tends to restrict the boundaries of competition to the process of simply refining and improving a limited range of existing technology, which blocks funds for basic research and reduces the incentive to tackle smaller markets where the risks are higher, such as medical applications and nuclear power (see Figure 1.2.1).

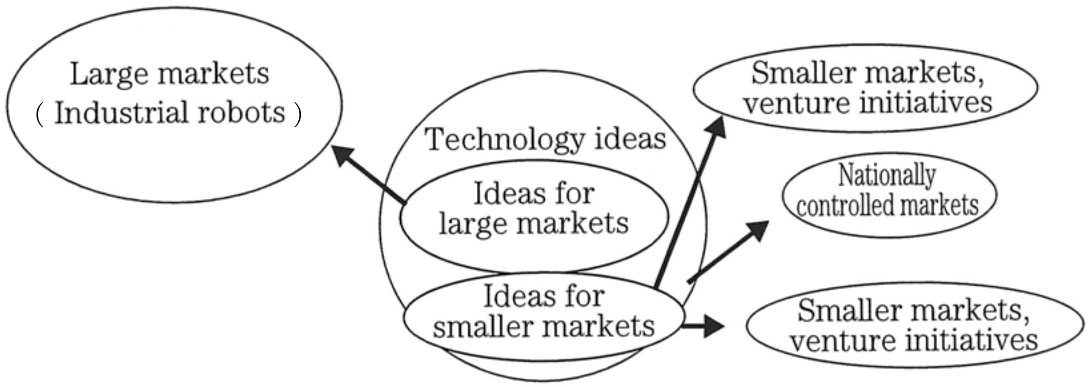


Figure 1.2.1 How robot technology research outcomes are disseminated into industrial markets in Europe and the United States

2) Absence of national technology policy and marketing schemes

In Japan, nuclear robots have not emerged as a viable industry, and robot development in fields such as space and disaster prevention is still very much at the research stage. This situation can be attributed to the absence of national policy of developing markets for military and space technology, such as exists in Europe and the United States. Thus, Japan's lack of international competitiveness in these "extreme" fields is essentially due to the fact that market principles do not apply because Japan does not enjoy the benefits of an ideal military market, which might otherwise stimulate competition and create an environment in which market principles could operate properly.

In Europe and the United States, research into extreme robot applications is undertaken as part of integrated, long-term national programs encompassing basic research through to product development. In contrast, Japanese research is primarily geared towards generating innovative technology ideas and hence is not linked to actual needs that exist in society. Furthermore, even the best research outcomes get buried unless they can be taken up by industry and translated into genuine commercial propositions.

3) Lack of incentives to develop a technology around robot applications under extreme environmental conditions

In order to develop a technology of robot used under extreme environmental conditions, not only the robot technology but also the technology to deal with extreme environmental conditions such as radiation, pressure, and vacuums need to be developed. In Europe and the United States, technical standards for military and space hardware provide manufacturers with more stringent development targets with respect to reliability and operating conditions than in Japan, where robot development is geared primarily towards consumer applications. Thus, robots in Japan is not equipped to provide a rapid response to situations such as the recent criticality incident at Tokaimura.

In light of the dangers involved, the government should take a leading role in systematically promoting the development of technology of robot used under extreme environmental conditions together with technical standards in this area.

4) Declining education level in engineering fields

Educational level in technical and engineering fields, the foundations of the manufacturing sector in Japan, has dropped alarmingly in recent years. This is starkly illustrated by the competitiveness ranking of leading nations put out by IMD (the International Management Development Institute business school, based in Lausanne, Switzerland). In 1992, Japan was ranked fourth in terms of the "contribution of the education system to competitiveness," but by the year 2000 it had slipped to 39th place.

Arresting this decline in educational standards is of critical importance to the future development of robotics engineers.

2 Robotics research and education

2.1 The current state of robotics research

While robots are proving very popular with the general public, industry seems to have lost the early enthusiasm of the 70's and 80's. One reason for this is said to be the way in which robotics research is isolated from industry. Few mechanisms exist for refining and developing research outcomes to the practical stage; as a result, successful industrial developments are relatively rare.

Meanwhile, although industry is actively engaged in robot development, the new robots produced by industry have little to do with the research performed in the academic sector. Much of the practical robot technology is confined to "classical" areas such as positioning, teaching-playback, and two-dimensional vision. Vast resources are being poured into technology research, yet the fruits of this research rarely make it to the practical stage (see Table 2.1.1).

Table 2.1.1 Practical robot applications versus technology that has not been developed past the research stage — some examples

Practical robot applications	Non-developed research
· Fast, accurate positioning servos · Teaching-playback control systems · Off-line teaching systems · Map reference mobile robot navigation systems · 2-D vision technology · Unilateral remote control systems etc.	· Force control technology · Compliance control technology · Distribution tactile sensors · Test environment awareness technology based on 3-D vision · Multi-fingered hand · Obstacle avoidance technology · Off-line task planning · Model-based intelligence technology · Walking robots (with legs) · Learning control systems etc.

The perception of robotics research as being of little practical relevance means that industry is now less likely to see robot technology as the key to future growth. Industry investment in robotics research was further discouraged by the difficult economic climate of the 1990's, resulting in a largely unreceptive attitude towards robot technology.

2.2 The current state of robotics education

Robotics research in the academic sector is flourishing, as evidenced by the steadily increasing number of research papers and reports. Research is encouraged by a succession of robot contests. Furthermore, robots are popular among students and have proven educational benefits, such as helping to arrest the trend away from science subjects.

In the education system itself, some attempt has been made to set up robotics as a genuine discipline: for instance, modifications to curricula and the introduction of robotics science subjects. In spite of these changes, practical robotics science — the conglomeration of several "pure" fields in a single, broad-based discipline —lacks substance. Furthermore, the lack of willingness to develop robotics engineering means that we are still very much confined to robotics science.

3 From robots to RT － the technology strategy

3.1 Basic principles of the technology strategy

As we saw in Chapter 1, robots generate added value. Robot technology, like information technology (IT), represents a fundamentally important form of strategic technology in terms of its potential for boosting industrial competitiveness. Thus, initiatives to nurture the robotics industry should be seen as an important aspect of industrial policy for making Japanese industry more competitive in the 21st century.

In the future, the robotics market will extend beyond the manufacturing sector to include bio industries, public services, medical and welfare applications, and consumer applications. Whereas most manufacturing applications involve repetition of set tasks, future public-sector, medical, and consumer applications will involve non-regular tasks requiring more advanced functionality. Safety is also an issue, given that robots will be working directly alongside humans. Furthermore, the popularity of industrial robots in the manufacturing sector can be attributed partly to the fact that robots are operated by skilled technicians who can deal directly with manufacturers to ensure that the robots are designed in accordance with their needs. By way of contrast, the robots of the future will often be used and operated by ordinary consumers with no specialist knowledge. This creates an entirely different set of precedents, which may in fact hinder the development, and market penetration of robots.

If robots are to play an important role in future society, then it is most important that we take steps to nurture the robotics industry by providing the appropriate infrastructure, industry framework, and "technology environment" to enable non-specialized engineers and technicians in the field to consult directly with end users and develop products that meet their needs.

The technology strategy espoused here includes greater openness as a key concept for encouraging the emergence of markets of all sizes. Greater openness requires a joint approach involving the government, private, and academic sectors. The basic ideas underlying the strategy are explained below.

1) From robots to RT

Thus far, we have been considering robots in the narrow definition. RT, or robot technology, refers to a much wider concept of robots as intelligent systems utilizing robot technology to provide useful functions in real-world situations. RT and industrial strategy should be predicated on this wider definition.

2) From industrial robots to RT as a "business solutions" industry

In order to tailor RT to future needs, it is important to create an environment conducive to the growth and development of "business solution" providers whose job is to analyze client issues and combine various forms of existing technology to create systems that address client issues. It is also important to provide an environment conducive to the creation of new industries that can steadily grow into larger markets. Ordinary engineers and technicians rather than researchers should drive growth. To this end, we need to set up completely open structures for providing RT component devices. Together with the development of RT devices in module form, this represents a key concept in the future of the robotics industry.

3) Market structure of the future RT industry

The RT market of the future is expected to consist of many smaller markets together with a number of large markets in certain specific products. Growth in RT will be dependent on the relevant market structures and social systems being able to support a range of businesses of varying sizes. The strategy is formulated from this perspective.

4) Developing smaller markets

Smaller industry markets will emerge to serve the many groups of business solution firms using new technology. While these markets are still small at the moment, they are nevertheless important to major corporations in the sense that they have the potential to develop into larger markets in the future. Smaller markets must be supported because they provide an important avenue for venture initiatives to supply RT products for specialized forms of consumer demand that are not covered by mass-produced lines (see Figure 3.1.2).

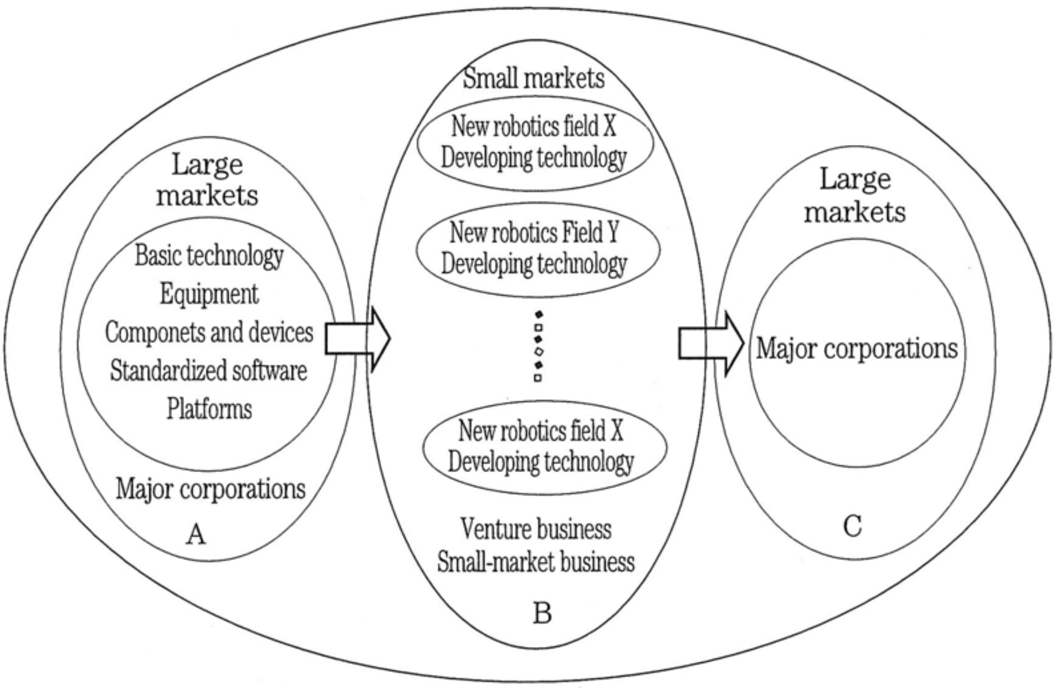


Figure 3.1.2 Small markets in the context of overall market growth

5) Promoting greater openness as a means of transforming the industrial structure

Under the strategy, the robotics industry of the future would essentially consist of three types of companies: large corporations supplying products to mass markets; system integrators, smaller venture companies designing and developing tailored systems for clients from various different forms of component RT technology; and smaller companies supplying limited markets with RT products utilizing the latest high-tech systems required in wider society. The strategy also calls for the development by 2025 of an industrial structure in conjunction with the academic sector to encourage the fruits of research to be converted into practical solutions.

To this end, the overall strategy should be predicated on greater openness of product manufacturing and technology ideas, which in essence means providing RT components (hardware and software components of RT systems and technology ideas of all types, including robotics theory) that can be readily used by ordinary engineers and technicians with suitable training (see Figure 3.1.3).

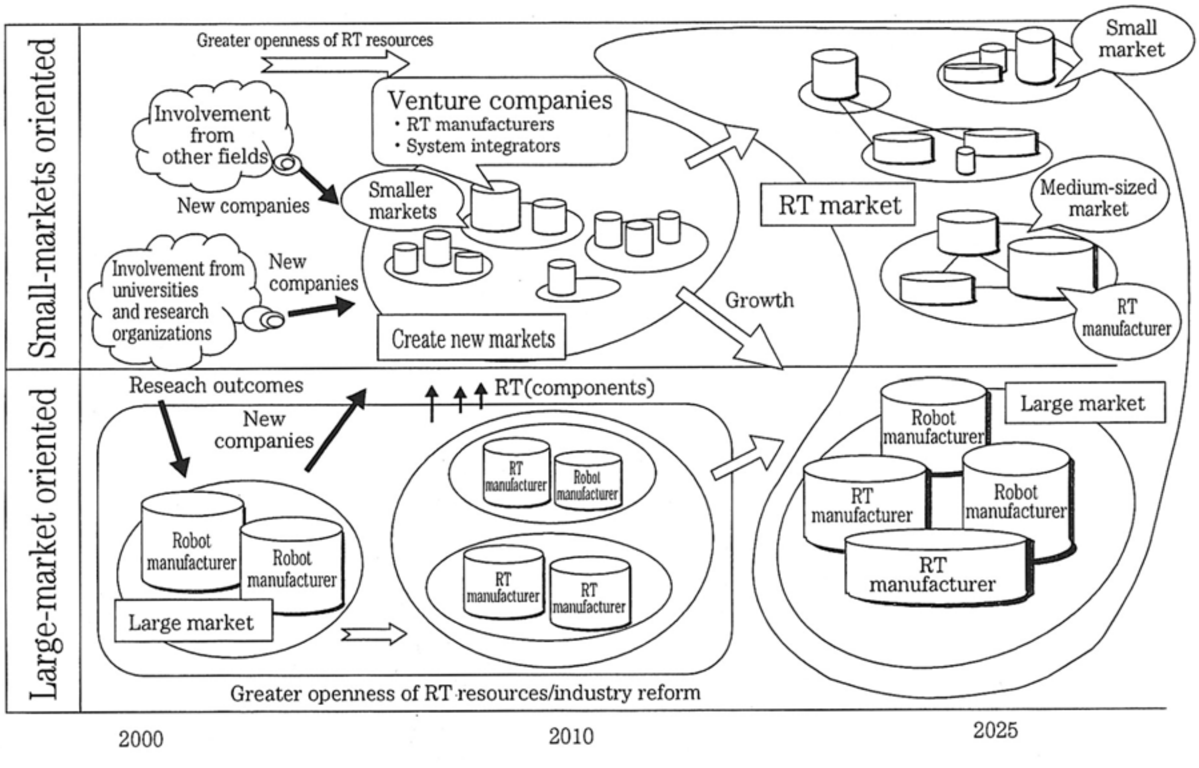


Figure 3.1.3 Transforming the industrial structure through greater openness

6) Developing robot technology in less competitive public-sector fields

Industrial strategy should also consider demand in public-sector fields such as disaster prevention systems. To this end, we should aim to develop small-scale yet competitive markets in made-to-order robot products — in other words, markets for public-sector robot products that help to make society more dependable by guaranteeing public safety.

7) Developing education and training system

We need to establish a manpower development system to educate and train RT engineers to serve the robotics markets of the future. To this end, robotics engineering should be established as an academic discipline in its own right, and the education system should be expanded to provide training for engineers engaged in the solution-provider aspect of RT. The latter would involve the development of comprehensive curriculum structures and teaching materials in the area of robotics engineering, together with the establishment of an examination system providing objective assessments of knowledge.

8) Speeding up the process of technical transfer

It currently takes ten years or more for research outcomes generated in the academic sector to percolate through to industry. In order to promote rapid growth in the RT industry, we need to speed up the transfer process. The government, private, and academic sectors must join forces in developing the technology strategy to this end (see Figure 3.1.4).

Decade	Industry	National projects	University /AIST※	Related technology
1970's	First robot boom ・Spot welding robots on vehicle production lines ・100 firms become involved in robots		Infancy of robotics ・Biped walking ・Manipulation ・Teaching-playback positioners ・2-D visual sensors, tactile sensors, force sensors ・SCARA robots	First 16-bit microprocessors
1980's	Proliferation of industrial robots; robots become entrenched in industry ・Are welding robots on vehicle production lines ・Another 100 firms become involved in robots ・Robots controlled by visual sensors (wire bonding)	1982-1989(8years) Robots for extreme applications (¥18 billion)	Advanced Robots Humanoid designs ・Multiped walking ・Intelligent remote control systems ・Highly realistic remote control ("tele-existence")systems ・Model-based intelligence ・Biped walking ・Multi-jointed manipulators ・Kansei robots	・More advanced microcomputers ・First semiconductor sensors (such as CCDs) ・Strong artificial intelligence research
1990's	Proliferation of industrial robots (80,000 produced in 1991) ・Maturity reached in automobile and appliance manufacturing ・Many firms abandon robots ・Honda releases P2 ・Pet robots, hot-line robots Market matures (60,000 produced, well over ¥100 billion)	1991-2000(10years) Micromachines (¥25 billion) 1998-2002(5years) Human-robot integration systems (¥5 billion)	Intelligent humanoid systems, micro-robots ・VR-based remote control ・Miniature on-board computers ・Kansei robots ・Multi-robots ・Micro robots ・Behavioral intelligence	・Falling computer prices ・Micromachine technology ・VR technology ・Massive growth in Internet
2000's	Second robot boom ・Application of robot technology to new fields ・Integration of RT with IT and NT ・Humanoid platforms ・Intelligent entertainment		First stage of R&D into the robots of the future Apportionment of roles between government, private, and academic sectors (synergy effect) Element technology for future robots (research ideas, performance)	・Further expansion of Internet
2010's	Proliferation of future robots (over 100,000 produced) Future concept of robots (visual image of robots, market forecasts)		Second stage of research into the robots of the future	
2020's	Robots reach maturity (over one million produced)			

※National Institute of Advanced Industrial Science and Technology

Figure 3.1.4 Changes in robotics technology

We have identified five attractive and promising fields considered deserving of priority attention (see below). These fields are considered to represent important sources of demand, taking into account changes in socio-economic conditions and international competitiveness of the domestic robotics industry in each market. The five markets are summarized below, together with estimated size.

A. Manufacturing ･････････¥850 billion by 2010, ¥1.4 trillion by 2025
Human-machine interfaced production systems, eco-factories, networked factories

B. Bio-industries･･････････¥90 billion by 2010, ¥360 billion by 2025
Automated analysis equipment, automated synthesis equipment, bio-factories

C. Public sector ･･････････¥290 billion by 2010, ¥990 billion by 2025
Disaster prediction and monitoring, disaster prevention, emergency response procedures

D. Medical and welfare ････¥260 billion by 2010, ¥1.1 trillion by 2025
Prevention of disease, diagnosis, treatment, rehabilitation, automated and/or intelligent systems at medical facilities, medical training

E. Home ･････････････････¥1.5 trillion by 2010, ¥4.1 trillion by 2025
Education, home-based virtual training, entertainment-oriented rehabilitation systems, communication tools, household equipment

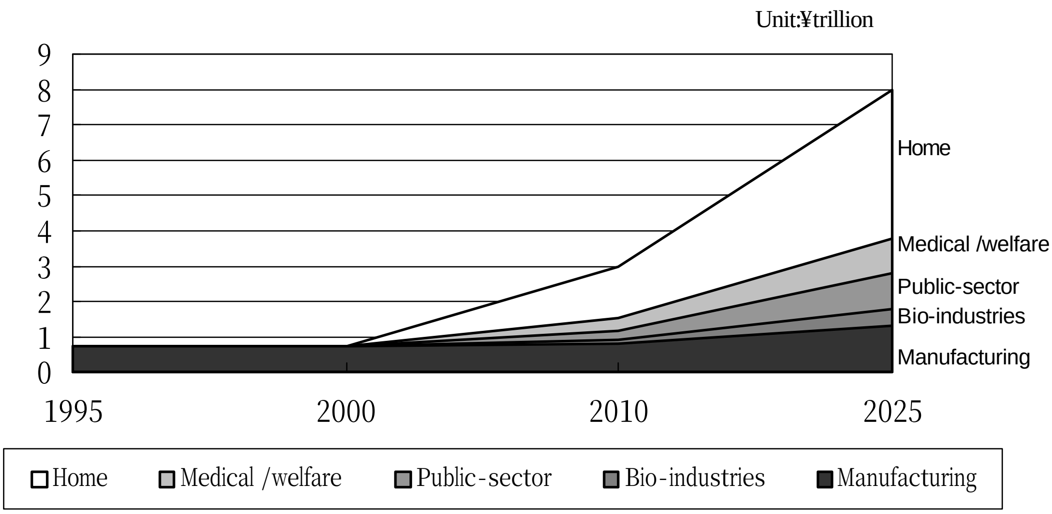


Figure 3.1.5 Predicted growth in robotics markets

3.2 The technology strategy of RT

As stated earlier, we need to move to an industrial structure that replaces the traditional emphasis on major markets with a framework that enables dynamic participation by companies of all sizes in the processes of developing and producing products for a range of different markets, irrespective of market size and product type

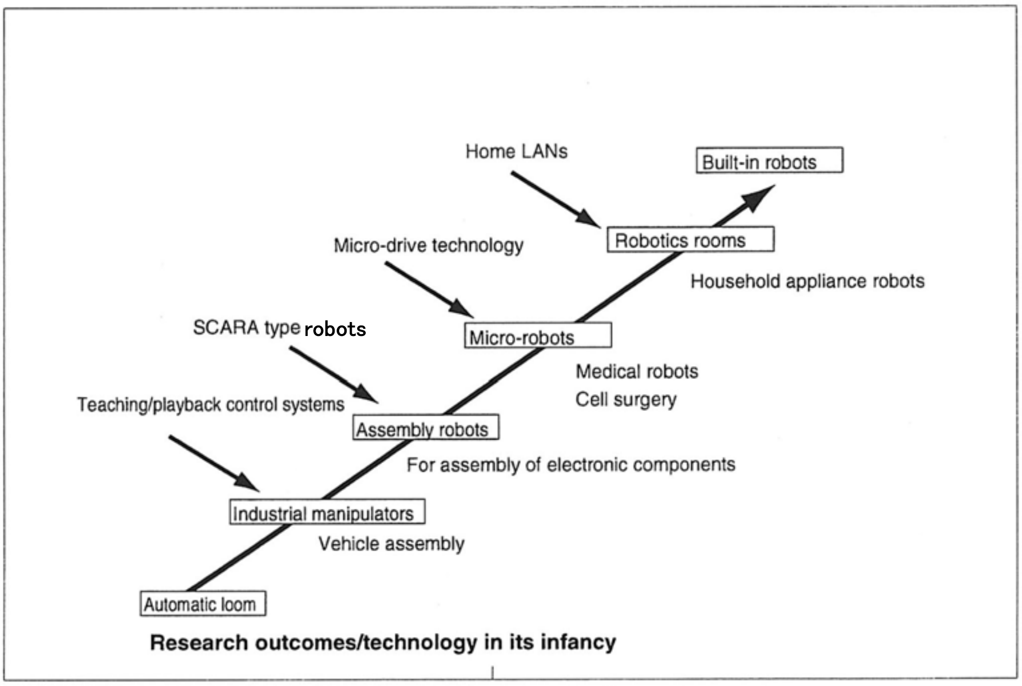


Figure 3.2.1 From robots to RT

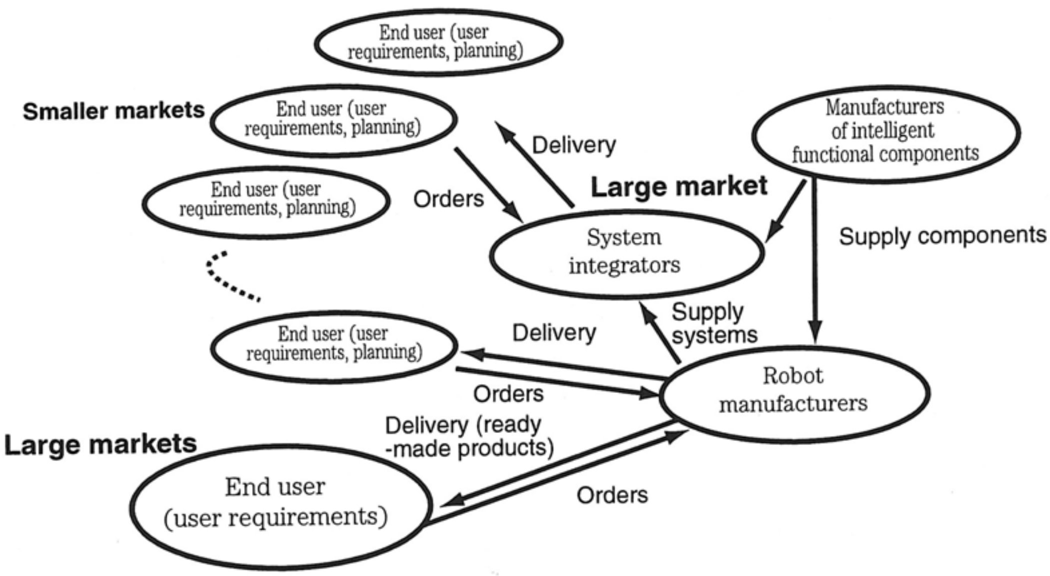


Figure 3.2.2 Apportionment of roles within industry

(i.e., ready-made lines versus made-to-order lines and products for public industries such as space and disaster prevention). In order to ensure growth in the RT industry, it is particularly important to provide an industrial environment which enables product development to marry research endeavors to the demands of the market, one in which producers can be profitable in markets of all sizes.

In the computer and IT industries, for instance, a number of businesses provide "made-to-order" solution services involving the design and selection of hardware and software components tailored to client specifications. Such services are predicated on steady supplies of both hardware (components and units) and software in a competitive environment. Greater openness in this way is one of the strengths of the IT industry.

The transformation of the RT industry structure to promote specialization predicated on greater openness is very important for the future of the industry. Specialization will encourage the emergence of a range of solution providers, in turn strengthening the industry and promoting further growth.

Greater openness as an element of the RT strategy is designed to promote the practice of combining different functional elements. To this extent, it is a means of encouraging standardization of interfaces between the many different robot components (RC) used in robot systems. Greater openness does not represent a goal in itself.

Greater openness enables the use of common infrastructure, thereby reducing costs, encouraging joint initiatives between industry and academic sectors, and promoting specialization (since application systems developers do not have to worry about infrastructure and the level playing field promotes healthy competition). A level playing field also encourages the uptake of research outcomes by industry and speeds up the transfer process.

Greater openness in RT would be required in three main areas:

・ Hardware (including actuators, sensor units, control systems, and intelligent information processing systems)

- Speed up and simplify the hardware product development process

・ Software

- Industry growth divided between the software and hardware industries

・ Networking

- RT integrated with IT technology

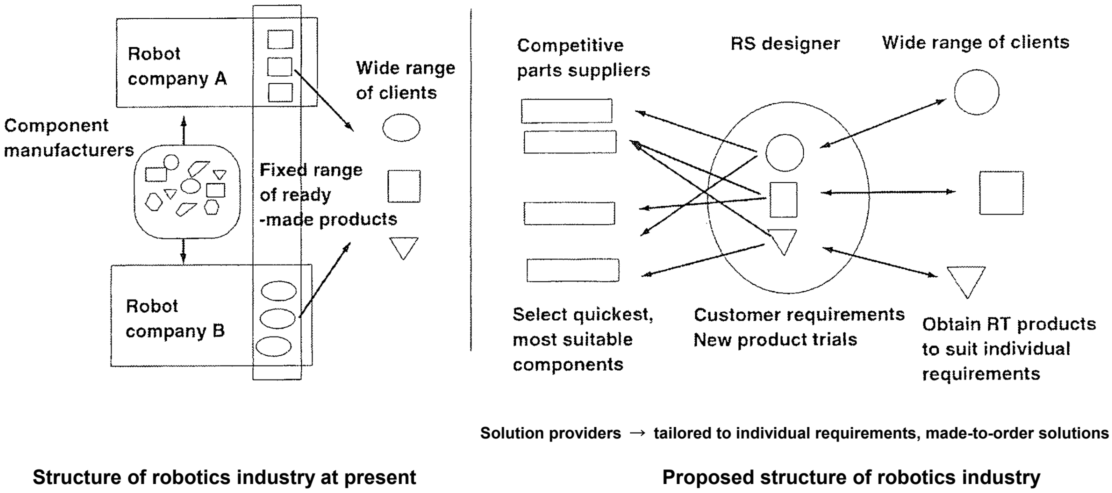


Figure 3.2.3. Proposed new structure of robotics industry based on concentration of production of RC components

Given that RT is expected to become increasingly integral to everyday life, the "dependability" of RT products — i.e., product safety and reliability — is an important consideration. We must set out dependability standards to ensure dependable RT systems, as well as drawing up standards in individual application fields.

Due to the absence of technical standards in fields such as military and space hardware, Japan lags behind Europe and the United States in the area of reliability and environmental robustness in extreme applications. We need to draw up a classification system for extreme environments encountered in disaster prevention and emergency response applications, together with associated specifications and testing standards for RT devices.

3.3 Priority research areas

The priority research areas listed below were selected on the basis of several considerations, namely: relevance to real-world requirements; links to industrial infrastructure; ability to predict future trends; potential for generating new industries; and suitability for venture-style initiatives.

1) Design and operation of remote/dispersed network systems

- Examples include remote maintenance, remote medical services, rescue services, landmine removal programs, and "remote brain" factories

2) Nano-handling technology

- Automated/bulk processing of cell manipulation, micro-medical tools, micro-electronic circuit assembly

3) Kansei interfaces, technology for interpreting human behavior, simulation systems, virtual reality (VR)

- Intelligent rooms, intelligent social space systems, physical agents with remote control capabilities

4) Robot vision

- Register-less supermarkets, post-disaster restoration systems

5) Mobile technology

- Biped walking, flying technology, etc.

6) Advanced manipulation

- Handling flexible objects, skilled manipulation, ultra-fast manipulation, precision manipulation

4 Proposals for reform in the government, private, and academic sectors

4.1 Changing perceptions in the government, private, and academic sectors

To promote the technology strategy for RT, we must first work to change perceptions in the government, private, and academic sectors. Specific changes required in each sector are listed below.

1) Industry

・*More effort to open up new application fields in line with changes in the industrial structure*

Robotics technology must work harder to develop closer links with IT and create a range of new functions for human operators with direct relevance to product development, bearing in mind the changes taking place in the industrial structure, particularly in areas such as intelligent home appliances, robotics rooms, and smart rooms. This will largely depend on the efforts of those firms who are looking to take robotics technology to the next level, beyond the traditional manufacturing applications.

・*Moving away from mass production and high-volume, low-margin sales approaches*

Japanese managers tend to avoid taking risks or embracing new product ideas; they are more comfortable to generate revenue through mass production of product ideas developed overseas.

An enterprise is an operation that develops and pursues its own plans. The traditional entrepreneurial spirit is lacking in today's industry. We need a general business climate that encourages companies to be more innovative and pursue their own strategies instead of producing products similar to those of other companies, while at the same time working to develop new markets.

・*More effort to provide products for smaller markets*

With respect to the development of technology ideas, cutting-edge technology ideas tend to require more time and effort to reach the mass-market stage. The idea is to begin as a venture-based enterprise geared towards small markets, then steadily grow the markets, in much the same way as with biotechnology. However, the robotics industry has not made enough effort to develop markets and technology. Efforts to develop technology and markets need to be built into corporate activity, for instance through company subdivision and venture initiatives with universities.

・*Greater use of outsourcing*

Robots are systems, and as such contain many different forms of highly specialized technology. No one company can possibly handle all aspects of robotics systems. A faster and more efficient way to develop robotics products is for several companies to work together and pool their resources. The industry must be prepared to embrace the venture approach if we are to compete with the pace of technological progress in the United States.

・*Closer links with the academic sector and greater utilization of research outcomes*

To enable the robotics industry to develop basic technology ideas into totally new fields of industry, it is not enough just to develop the most promising ideas as proprietary technology; rather, industry must be prepared to actively search for new ideas and set up business plans that involve the academic and government sectors (the sources of ideas). It is particularly important for industry to move on from the model of simply improving and refining technology originally developed by others, by casting its attention further afield in the search for the potential technology of the future. The robotics industry must be prepared to commit resources and training to this end.

・*Support for labor mobilization*

The "10,000 Postdoctoral Fellows" program has seen a gradual shift towards a system of fixed-term research appointments in public universities and research institutes. But mobility of labor will still be restricted for as long as private industry perseveres with practices such as hiring new staff only on 1 April each year and placing undue emphasis on the academic background of applicants. Industry should be prepared to hire staff throughout the year, and to do so on the basis of the skills and capabilities of applicants rather than their age, university pedigree, and academic qualifications. This is particularly true in Japan, where industry has a responsibility to take a leading and guiding role with respect to universities.

・*Active involvement in the work of academic groups*

Generally speaking, private industry is primarily interested in the immediate future. For this reason, industry pays little attention to work going on in the academic sector. The lack of proper survey and research work in industry hinders the development of sound research strategies designed to generate new technology, and this in turn is causing a steady decline in technology standards. Industry needs to be more actively involved in the work of academic groups by actively sourcing information on new technical developments.

2) Universities

・New educational targets and objectives

The expansion of robotics technology will require a great many innovative researchers with the willingness to experiment with system integration on the basis of extensive knowledge and experience in the field. To this end, the education system, in addition to furnishing students with knowledge and providing hands-on experience in the area of system integration, must make more effort to explore teaching techniques and approaches designed to instill enthusiasm and motivation, so that students finishing their doctoral courses are inspired to use their skills to start up venture-type businesses.

・More awareness of the importance of robotics research

Because research from a scientific perspective is seen as engineering research and is judged according to the same criteria, robotics research is widely considered by industry to be of little use. This perception has created a significant misunderstanding between industry and the academic sector.

We need to reconsider the special nature of robotics research, including its role and significance and the criteria by which it is evaluated, based on a proper understanding of the differences between research intended to contribute to science in general and research intended to serve industry.

・Reappraisal of performance evaluation techniques in research

While purely scientific robotics research can readily be assessed in terms of the number of papers published, robotics research geared towards industry does not lend itself to academic papers and therefore cannot be properly assessed in this manner. Given that under the present system industry-oriented research tends to be seen by academic researchers as a less "genuine" form of research, we need to set up evaluation criteria other than the number of academic papers published and look at other ways to assess the performance and achievements of researchers in this field. This will in turn create stronger bonds between the academic and private-industry sectors.

・New research structures predicated on links with industry

In order to ensure that research is relevant and useful to industry, researchers themselves need to identify the needs of industry and liaise with industry on research and development projects. Given that the research prowess of universities is largely dependent on the skills of post-graduate students, we need to set up structures that give graduate school students the freedom to shuttle back and forth between industry and school while pursuing their research. To this end, graduate schools should establish solid links with private industry and take a more flexible approach to joint research initiatives and academic qualification procedures.

・*Researchers permitted to act as industry consultants; use of sabbatical schemes*

For the academic sector to create stronger links with industry, it needs to allow university personnel to act as consultants to industry. For instance, academic structures should be relaxed to enable researchers to take their own technology ideas to industry and work alongside company employees on developing the technology to product level. Similarly, the sabbatical system, under which researchers are granted leave to go outside the public system for a specified period of time, could be used to create new links with industry.

・*Introduction of contracts for research on consignment*

Due to difficulties obtaining guarantees of outcomes and schedules, Japanese industry tends to avoid outsourcing research to local universities, instead relying on American universities for its outsourcing needs. Japanese universities could help to redress this situation (and create stronger bonds with industry) by embracing business principles and setting up outsourcing systems based on the principle of strict adherence to schedules and outcomes.

・*Embrace the principles of competition; speed up the process of change*

While the government and private sectors clearly recognize the need for reform, the academic sector has been slower to embrace change. The principles of competition should be instilled in the academic sector by introducing new performance evaluation techniques in research (see above). Thus, factors other than the number of papers published should be considered: for instance, the number of times a researcher has been quoted, the number of patents obtained, and the extent to which the fruits of his or her work have been taken up by industry. In addition, research in general should be more productive.

3) Government research organizations

・*More joint research initiatives with industry*

It is important to ensure that the work of government research organizations is consistent with the actual needs of industry and society. Research topics should be selected on the basis of surveys of industrial technology and general social trends in order to ensure that the research generates genuinely useful technology. To this end, government research organizations should engage in regular information exchange, for instance through academic societies and committees, as well as training sessions involving industry representatives.

Once a topic has been selected, it is important to set up clearly defined targets and timetables for the research project. Research outcomes should be evaluated on the basis of the usefulness of the technology (irrespective of whether or not the technology is subsequently transformed into actual products), rather than on theses and technical papers.

・*More research into basic (pure) technology and areas considered to harbor future potential*

The role of government research institutes should be to make predictions about future trends in industrial technology and pursue research in areas designed to address potential future problems. Instead of choosing research topics on a whim, or for reasons of personal interest, or in response to trends or fads in the academic sector, we need to refine our basic technology and create systematic structures that will stand us in good stead in future times. Industry will not be interested in working with universities unless they exhibit a flair for original technology ideas and demonstrate depth of talent.

・*More encouragement for tackling combined research themes*

Robotics (or "robot engineering") is essentially a myriad combination of many different forms of technology, a marriage of machinery and physical mechanisms with fields such as information processing and ergonomics. The ultimate aim should be to create new technology from this fusion of different fields. It is important to be imbued with a sense of curiosity and a willingness to take on new challenges. Researchers in managerial or supervisory roles should be willing to take the initiative in pursuing research that brings together so many different fields.

・*Refinement of software and digital technology*

Japanese universities are poor at teaching software and digital technology. Japan has no proper system for training researchers in this field. Consequently, we are behind in this area. Yet these skills are absolutely vital not just for the development of robotics but also for the future creation of new IT industries. In the age of science and technology, software and digital technology provide the "powerful, necessary, and indispensable" tools that underpin the work of researchers and engineers in all fields. Japan is in a dangerous predicament, lacking the necessary expertise to make full use of these tools. Something must be done to redress the situation.

・*Flexible, mobile administration*

Research is to some extent a leap into the unknown, where things do not always proceed as planned. Yet researchers are too often bound to pre-determined schedules, and this prevents them from looking into areas of genuine importance and resolving problems for the sake of future generations. This situation should be addressed by, for instance, adopting a more flexible approach towards project implementation and ongoing changes to project details, particularly with respect to improving the mobility of labor. At the same time, we need to alleviate the influence of budgetary restraints, eliminate overly short-term management attitudes, and shorten budget implementation periods, which are sometimes ridiculously long.

・*Emphasis on tackling challenges*

Research work should not be stifled by an overbearing emphasis on outcomes from the outset. There is little point in setting out known outcomes as targets at the project planning stage. Rather, we should allocate plenty of time to the planning process and to the research stage itself. Moreover, rather than focussing to heavily on outcomes achieved during the project period, we should assess project outcomes as they eventuate, on their own merits. Similarly, penalties for research outcomes should be assessed objectively based on proper reports of research work, taking into account considerations such as how the research is conducted.

・*Acting as a bridge to the private and academic sectors*

Government research organizations should fulfil a neutral, independent role, supporting the practical development of new technology concepts identified by industry. They should utilize the knowledge of specialist groups of experienced robotics researchers to assess new technology concepts in robotics and provide consulting services to industry. In addition, they should encourage the development of skills for identifying useful technology with practical potential for industry.

4.2 The role of the government, private, and academic sectors in promoting the RT industry

The government, private, and academic sectors can each play a different role in promoting the RT industry.

1) Industry

In order to transform itself into an RT industry, the robotics industry must be prepared to identify current problems and commit to structural reform through greater openness in existing products and re-training programs geared towards the solution provider model.

To this end, the Japan Robot Association should fulfil a cross-industry role, providing wide diversity and specialization capable of responding to future needs, and act as a focal point for the government, private, and academic sectors to liaise over the future direction of the industry. The Association should also serve as a fully networked information center and in this capacity should draw up de facto standards for RT.

2) Universities

The role of universities is to: set up robotics engineering curricula and structures geared towards the establishment of open robot technology structures; provide student training and associated curricula in robotics system integration; and provide training for project coordinators responsible for linking research projects to real-world demand together with engineering courses to this end.

3) Government research organizations

The role of government research organizations is to: pursue combined research on common infrastructure as part of the RT strategy based on areas of research considered to have significant potential; provide links between different fields of research; conduct long-term surveys of technology trends; map out future paths and directions; provide the administrative expertise for building and operating a common infrastructure for applications development; training engineers and researchers with an interest in venture initiatives predicated on industrial and academic exchange schemes; generating new ideas and proposals; and promoting inter-industry links.

4) Government

In order to achieve the aims of having the government, private, and academic sectors share the RT vision outlined in this technology strategy and promoting greater openness in the RT technology structure, the government should actively promote a new approach of nurturing the RT industry with an infrastructure based on open technology foundations. Other policies that the government should pursue include: developing research programs geared towards practical outcomes; promoting joint technology development projects between the private and academic sectors; creating systems for re-training of engineers and for accreditation of qualifications; introducing tax benefits designed to encourage the use of robots; promoting deregulation and "social infrastructure" investment; promoting entrepreneurial endeavor; and encouraging public-sector research in fields such as nuclear power, space, and disaster prevention in a bid to generate new markets.

Conclusions

Liaison between the government, private, and academic sectors is crucial to the growth of the RT industry

The technology strategy espoused in this paper is predicated on the broad concept of robot technology (RT) as opposed to robot machines in the traditional sense. Robot technology represents a universal foundation of industrial technology which is highly relevant in a very wide range of fields, such as: manufacturing, the traditional domain of robots; bio-industries, considered the strategic industries of the future; public-sector fields, from disaster prevention and rescue to the preservation of vital public utilities, considered increasingly important in the 21st century, not least because of their relevance to public safety and well-being; medical and welfare applications, in the context of the aging of society and the trend towards smaller families; and finally household uses, in the same context. This paper has presented a technology strategy for the development of robot technology.

In order to create an RT industry capable of providing RT solutions tailored to diverse market demands, it is important to promote venture business schemes that capitalize on research work being performed by universities and government research organizations and also to encourage participation by other industries. We must also create a business environment that supports the establishment of even small-scale business operations. These objectives can be achieved through greater openness, as espoused in this technology strategy. Greater openness is one aspect of the overall business environment which will allow researchers and engineers in the government, private, and academic sectors to creatively and freely develop a range of different RT products with the potential to be developed into major markets, and which will accommodate even those robot businesses designed for smaller markets.

Closer cooperation between the government, private, and academic sectors, considered crucial for achieving greater openness in RT, is predicated on three key concepts.

1) Mutual support between the government, private, and academic sectors for internal reform

We must set up a support structure to encourage mutual understanding and cooperation between the government, private, and academic sectors as each strives to identify and tackle its respective problems and issues, while also working to resolve problems and issues in other sectors.

2) Good coordination between the government, private, and academic sectors in training workers for the RT industry

Universities should produce talented professionals who are creative, practical, and entrepreneurial. Industry, meanwhile, should take on university graduates and allow them to display their full potential. To this end, companies should inform universities (and perhaps some government research organizations) of the skills and abilities they require of researchers. In this way, good coordination between the government, private, and academic sectors will provide the ideal workers for the benefit of the RT industry.

3) Cooperation between the government, private, and academic sectors on international standardization and intellectual property rights strategies

International standardization and intellectual property rights strategies are of critical importance to Japan's ability to maintain its relative superiority in robotics technology and develop RT as a key strategic industry. To this end, the government, private, and academic sectors need to work together to promote RT research linked to the requirements of the real world, to develop new markets, and to attain a position as international standard.