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An integrated network approach to systems of innovation—the case of robotics in Japan

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Abstract

One of the paramount challenges researchers face analyzing the national system of innovation (NSI) is building effective tools to identify the strengths and weaknesses to understand the internal dynamics of the innovation system. This paper presents a systematic, comprehensive and flexible approach to analyze the innovation system in Japan in the case of robotics, one of the most successful Japanese industries. The approach formulated is based on the framework of techno-economic network (TEN), using data on patents, publications and market-related data complemented by conducting extensive interviews with key personnel in the academia, corporate and public research institutes moving from macro- towards micro-levels. Science, Technology and Market, the three major poles of an innovation system together with their linkages, mainly considered at the activity level are analyzed extensively. The findings clearly reveal the strengths of the approach in identifying the transformation of the innovation system and changing structural setups. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: National system of innovation; Techno-economic network; Robotics; Japan; Scientrometrics

1. Introduction

Concepts of innovation processes have been evolving from a combination of Schumpeter's science-push models and Schmookler's demand-pull models. Both models were generally considered as relay-type linear models, assuming only push or pull from one side which may not generally lead to successful innovations. Recently, there has been a number of evidence showing that innovation is a highly interactive complex process and fundamentally different from a linear model in terms of feedback effects and the numerous interactions between Science (research), Technology and the Market. New ideas can originate in any of the phases or interactions in the model. Another important fact this model tries to disclose is the interdependency within an innovation process. Each actor in an innovation process has its own interactive networks to acquire, use and assimilate knowledge and information.

There is no single accepted definition of a national system of innovation (NSI). Freeman (1987, 1988) defines it as a network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies. Lundvall (1988, 1992), Nelson (1993), Pa-

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tel and Pavit (1994) came up with basically similar definitions thereafter. Though there is no clear accepted definition, all broadly accept that the NSI comprises the complex interactions among various actors and institutions. The innovative performance of a country depends to a large extent on how these actors, which are primarily private enterprises, universities, public research institutes and other contributing individuals, relate to each other as elements of collective knowledge creation and use.

Having agreed that the innovation process is an integrated one and needs to be considered at the system level, the interfaces as links between various actors become equally important as the activities of each actor. Research on NSI has been active in recent years and the studies mainly involve institutional mapping and their knowledge flow networks (OECD, 1997), industrial clustering and their characteristics (Cawson, 1994; Sharp, 1994), tracking/measuring tools (Grupp et al., 1990; Archibugi and Pianta, 1996), systemic constraints and best/worst practices and policy level implications. The OECD is collecting systemic data and information on different industrial clusters across different countries with the intention of formulating internationally comparable models of NSI. The ultimate objective of the NSI studies is to develop guidelines for how innovations can be induced in different circumstances to achieve economic growth.

The concepts of NSI create a need for analysis at the system level, identifying the desired links and bottlenecks in the knowledge flows. The paramount challenge researchers face in the NSI approach is to develop effective tools to identify the strengths and weaknesses in the internal dynamics of the system. The ability of the traditional input–output approaches to measure the NSI is highly restricted and widely criticized as a mere ‘snapshot’ approach. While the concept of NSI is rich and has a strong foundation, the main problem in the concept is that it is too rich, too macro and broad—covering all aspects from institutional set up, interfirm relationships, organization of R&D, educational and training systems, natural resource endowments, financing mechanisms to even culture. Moreover, it is unable to deal with the diversity of industrial situations in one country. In other words it is difficult to analyze NSI without going through in-depth studies at the meso-level. At the micro-level, much of the work on dynamic capabilities has focused on the issue of corporate competencies (Teece and Pisano, 1994; Miyazaki, 1995; Patel and Pavit, 1997). In order to analyze dynamic capabilities at the national level, we need to accumulate studies in meso-systems, focusing on the internal dynamics of network evolution.

The framework should be comprehensive, flexible, capable of visualizing the whole picture of the dynamics of the innovation system. In search of a comprehensive model, we found the techno-economic network (TEN) model proposed by Callon and Bell (1991) provides a conceptual framework which is simple, comprehensive and flexible. The TEN framework stresses two-stage analysis, based on activity and actors, unlike most other models. In addition to its inherent features, the model proposes dimensional analysis on the final synthesis to identify the characteristics of the overall system.

In this paper we effectively utilize the TEN framework to analyze the systems of innovation in robotics in Japan. We have developed a tool for analyzing the dynamics of systems of innovation, underpinning the clear transformations of the network. The approach taken is both quantitative and qualitative. The quantitative description of the network provides a basis for qualitative analyses. The Japanese robotic innovation system has been undergoing structural changes and a new set of thinking is needed to face the emerging issues. Based on TEN, the system is analyzed in two stages of ‘activity’ and ‘actors’ analyses and is finally synthesized using integrated data sources and tools to identify its characteristic features. The integrated approach utilizing the TEN concepts proposes systematic and systemic tools to analyze the NSI at a meso-level. By introducing new tools, such as the ‘STM (Science Technology Market) profile map’, this paper examines the Japanese robotic innovation system at the activity level. The set of findings we publish on the activity level shows the fundamental changes in the traditional thinking and emphasizes new policy concerns in the NSI of Japanese robotics. The paper finally examines the capability of the integrated approach in tracking the NSI.

Section 2 discusses briefly the Japanese robotic industry. It also touches on the historical developments in robotic innovation. The main concepts and methodologies are discussed in Section 3 and we explain the data construction techniques. The empirical analysis and the results are discussed in Section 4 in detail and finally in Section 5 the findings are summarized and conclusions drawn.

2. Relevance of Japanese robotic innovation and previous studies

'Robots and robotization' have been at the threshold of very fundamental change in manufacturing systems and thus have undergone a fair amount of technological changes, especially in Japan over the years. Recently, robotic innovation has been undergoing drastic technological changes, application diversification and market challenges. It has been traditionally thought that robots are of use only for manufacturing applications. Recent technological changes taking place in this sector show that robots are no longer restricted to manufacturing. It flexes its muscles in diverse applications, such as space and underwater exploration, construction, medical, entertainment, defense and welfare. Japan, a country deserved to be called a 'robot kingdom', (Schodt, 1988) presently produces around 80% of global demand and holds around 60% of world robot stock. A forecast by MITI (the Ministry of International Trade and Industry) shows that the robotics and automation industry in Japan will grow by around 200% with a doubling of employment in the industry by year 2010. Robotics has been promoted systematically in Japan, first through the technology and market measures and then on the research front by correctly identifying its potential. It can be considered as a typical example of dynamic learning and a successful case of a system of innovation in Japan.

What is a robot? How does one define it? These are questions even scholars struggle to answer. The Czech playwright Karl Capek formulated the word 'robot' from the Czech word for forced labour. The first patent was taken by George Devol for a parts transfer machine in 1961, which was generally considered as the first programmable industrial robot. The term robot becomes more and more vague with the introduction of nonmanufacturing robots. For example, if a motor vehicle has navigation capacity, then it will become another robot. Though people seldom follow the strict criteria, ISO defines robots as: ''manipulating industrial robot—automatically controlled, re-programmable, multi-purpose manipulator programmable in three or more axes which may be either fixed in place or mobile for use in industrial automation application. Mobile robot—which carries all of the means needed for its monitoring and movement (power control and driving)''.

The first projects on mobile robots can be traced to the late 1960s when experiments began in the coupling of processors to sensors and mobile bases. Stanford Research Institute introduced the first mobile robot 'Shakey' as a part of their project, which lasted from 1966 to 1972. After a period of stagna-

Table 1
Application and technological features of industrial, mobile and micro-robots

	Industrial robots	Mobile robots	Micro-robots
Invented/ commercialized	Early 1950s (I), mid-1960s (C)	Late 1960s (I), early 1980s (C) (AGVs—automated guided vehicles)	Early 1980s (I), many prototypes developed but yet to be commercialized.
Main applications	Manufacturing—welding, assembling, painting, etc.	Nonmanufacturing and nonindustrial (personal)—inspection (pipe, wall, floor), material transport, underwater, space, etc.	Medical, micro-manufacturing, etc.
Key technologies	Mechanisms (linkage, gripper, joints etc), controls, actuator, sensors, software, intelligence, etc.	Mechanisms (locomotion, structure, joints, application specific mechanisms, etc.), controls (more complex), sensors (wide spectrum), software, intelligence, navigation, etc.	Mechanisms (locomotion, structure, etc., at micro-level), micro-actuators, micro-sensors, controls, software, intelligence, navigation, etc. Materials technology plays a key role compared to the other two.

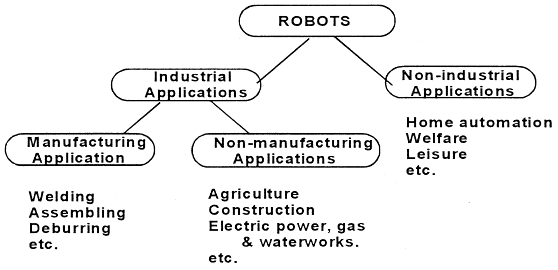


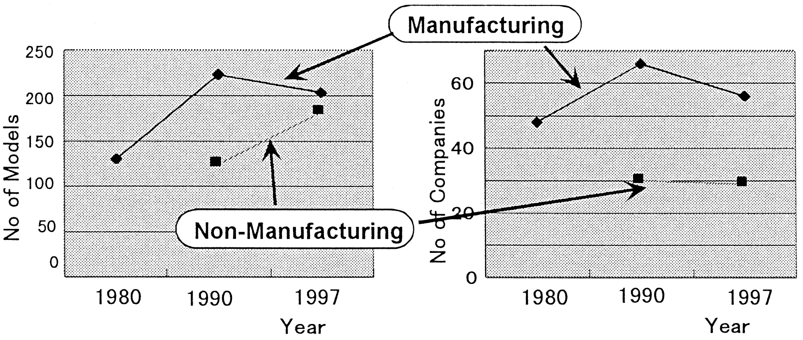
Fig. 1. Robot categories based on applications (JARA's groupings).

tion, advances in processing power and sensor systems, a strong resurgence of interest in research into mobile robots was observed in the mid-1980s. Very recently, the concept of micro-robots was introduced by MIT, with their work on microstructures. Micro-robots, unlike industrial and mobile robots, need fundamentally different capabilities to manipulate things at micro-levels. From both technological and application point of view, the three kinds of robots show highly distinctive features, though the fundamental set of technologies needed in broad terms may be the same (Table 1).

Robots can also be classified based on several factors, for example, application (welding robot, construction robot, welfare robot, etc.), structure (serial robot, parallel robot, humanoid robot, etc.), control technology and intelligence (sequence controlled robot, numerical controlled robots, adaptive controlled robot, etc.). Japan Robotic Association (JARA), which removed the word 'industrial' from its previous name, Japan Industrial Robot Association, categorizes robots into three broad groups based on application spectrum (Fig. 1). In our analysis, we use the classification of industrial, mobile and micro-robots and their key component technologies in their broader definitions. This classification helps to interpret the dynamics of the robotic innovation system and in our data collection.

Innovations in robotic technology have been incremental rather than radical, other than the invention of industrial, mobile and micro-robots. Industrial robots, from their commercialization evolved through incremental innovations. Electric actuators replaced hydraulic and pneumatic actuators initially used. Electric drives also evolved through incremental innovations to direct electric drives by replacing the complex mechanical couplings. Developments in computer hardware and software diffused rapidly into robotic systems, enabling use of complex control algorithms to manipulate with better speed, accuracy and repeatability. Sensor technology, on the other hand, developed from simple tactile to highly accurate vision sensors, which substantially improved the performance and application spectrum. Recently, the emphasis has shifted to intelligence to improve functionality.

Fig. 2 shows the changing pattern of the number of commercially available models, manufactured by the regular members of JARA, which include approximately 20–30% of all robot makers. Most of the top group of makers are regular members of JARA. A comparison of manufacturing models with nonmanufacturing models shows clearly the changing trend in the Japanese robotic industry. Nonmanu-



Note:
1. Data taken from the JARA's regular members
2. Source: Japan Robot Association (JARA)

Fig. 2. Trends in number of models and companies.

facturing applications include construction, electricity, gas and other services using robots of fixed and mobile types. Robot makers for manufacturing applications show a trend towards saturation.

The percentage change in the number of robots in each industry in Table 2 shows that there is a general increase in robots in most of the industries during this 8-year period. The industries marked bold are the industries in which the increase in levels of use is above average. Instruments and basic metals are the only sectors where there is a drop in the number of robots. The increase has been below the average level for motor vehicles, chemicals, petroleum and plastics industries. The percentage increase in industries which play a minor role in the total robot structure, are much higher than the average level of increase. Industries, such as paper, printing and publishing, nonmetal products, transport equipment (excluding motor vehicles) and other manufacturing, have a higher level of increase much more than three times in the 8-year period. This indicates that robots are diffusing faster into industries in which less automation took place before the late 1980s.

Table 2
Changing industrial robot user industries especially in manufacturing from 1988 to 1995 (% in ratios)

Branch	Japan	Germany	Sweden	UK
Agriculture	**New**			**New**
Nonmetallic mineral products	**3.54**	**2.15**	**New**	**New**
Other manufacturing	**3.53**	1.96	**New**	−0.01
Transport equipment	**3.47**	**2.07**	**New**	0.39
Paper, printing, publishing	**3.36**	1.50	**New**	
Fabricated metal products	**2.14**	1.80	**0.60**	0.25
Food, beverages and tobacco	**2.13**	**2.06**	**New**	**1.80**
Textiles and leather	**2.11**	1.48	**New**	
Wood and wood products	**1.71**	1.56	**New**	**0.88**
Electrical machinery	**1.39**	1.87	−0.06	−0.07
Motor vehicles	1.10		**1.07**	**1.45**
Other branches	0.93	1.88	0.08	**3.49**
Chemicals, petroleum, plastics	0.86	1.61	**New**	0.54
Machinery except electrical	0.78	**1.94**	−0.23	0.13
Instruments	−0.14	1.61	**New**	
Basic metals	−0.34	1.61	**New**	**New**
Total	1.20	1.90	0.47	0.72

Bold figures are the industries in which robot usage has increased more than their country average.

'New' means that the industry was not existed in 1988 and emerged in 1995.

Germany—motor vehicle is included in transport equipment but excluded in others.

Source: International Federation of Robotics.

Manufacturing applications, such as welding, painting, assembling, machining, etc., have been the major application areas for fixed industrial robots. Recently, industrial robots are being used in construction and other industries for similar applications. Mobile robot application ranges from land, sea to space. One widely used mobile robot in industrial environment is the auto-guided vehicle (AGV) and recently with the introduction of NASA's mars pathfinder, it has become well known. Applications are targeted from manufacturing (such as AGV, etc.), nonmanufacturing (such as pipe inspection, wall inspection and painting, cleaning, moving, etc.) to nonindustrial (such as welfare, entertainment, education, defense, etc.). Micro-robot applications, on the other hand, are in the development stage and a commercial model has yet to be fully developed. It is expected that micro-robot technology will have high potential in next generation manufacturing, where atomic level manipulations will be a necessity. With the convergence of biotechnology, nanotechnology and micro-robot technology, one can expect new innovations in medical applications.

Other than technologies, the common factors governing these robots in Japan are:

- Term 'robot'—widely-used not only for academic and industrial purposes but also in the media, entertainment sectors, etc.
- Promoting institutions—JARA, RSJ (Robotic Society of Japan), JSME (Japan Society of Mechanical Engineers), etc.
- Promoting national laboratories—MEL (Mechanical Engineering Lab), ETL (Electro Technical Lab), IROFA (International Robotic and Factory Automation center).
- Publication journals.
- Patenting class [USPTO office (901), Japan Patent Office (361)].

Technological and other common factors integrate the Japanese robotic innovation system within a single umbrella and justifies an integrated analysis.

Many researchers and people from business circles have carried out studies in the area of robotic innovation and basically these studies can be grouped into three categories: robotic diffusion; robotic systems and innovation models; and R&D and technology developments. The higher diffusion rate of industrial robots in Japan has been particularly extensively studied. Stronger demand-pull strategies together with the supply-push strategies of Japanese firms and the government led to an increase in demand and improved the technological capabilities. The general economic conditions prevailing in the early 1980s, lifetime employment structure, passive shareholders, long-term planning and experienced engineering managers in Japanese companies increased robot diffusion in Japan (Barronson, 1983). The superior Japanese approach of lowering barriers for the use of robots by vast majority of industry rather than just encouraging leading edge adoption as in the UK, or massively supporting high technology research and development as in the US, increased the diffusion rate in Japan (Fleck, 1987). A higher rate of imitation (i.e., higher profitability to users, low minimum rate of investment), taking advantage as a late comer to the industry and a higher intra-firm diffusion rate led to higher robot diffusion in Japan than in the US (Mansfield, 1989). James Fleck came up with an innovation model called the 'innofusion model', in which he argued, a configurational technology like robotics, 'learning by doing' or 'learning by struggling' in the implementation process has been one of the main sources of innovation (Fleck, 1994).

Extensive work has been done by Kondo (1986) on Japanese R&D in robotics. He analyzed, at the macro-level, Japan's robotic R&D system using a bibliometric approach. He grouped robots into two categories using two simple keywords of 'robot*' and 'industrial robot*' in the title of the searches in bibliometric databases. This research found some insights into robotics R&D at that time. He used macro-level input/output approaches, which can interpret little of the innovation system. Similarly, the work of Grupp et al. (Grupp et al., 1990) also considered industrial robots.

The key deficiencies found in these approaches highlight the need for a comprehensive system level integrated approach to see a broader picture not only of industrial robots. There are no recent studies on the fast-changing technological field, which can have substantial impact on other technologies and even on society as a whole. In Japan, unlike other countries, the robotics networks spans wider sectors in Science, Technology and Market and the impact spectrum of technological changes is relatively wider. Our studies have come up with concrete evidence of recent changes in the Science, Technology and Market poles in the robotic innovation system and we may alert policy makers to prepare for the change in the existing paradigm.

3. Concepts and methodologies

3.1. NSI and TEN

The concept of TEN put forward by Callon and Bell (1991) provides a basic analytical framework to analyze the systems of innovation in a comprehensive manner. A TEN can be defined as a coordinated set of disparate actors, such as government laboratories, technical research centers, firms, financial organizations, users and public authorities, which participate collectively in the design, development, production and diffusion, some of which may give rise to commercial transactions (Callon and Bell, 1991; Callon, 1995). The model rejects the traditional concepts of taking the firm, research center or the consumer as the unit of reference, but considers the system of coordinated links that exists between different actors. One of the prime advantages of the TEN model is that the concepts of innovation system can be analyzed within this framework in a flexible and dynamic way without losing the ideology. The NSI is a very broad network that can be grouped into different subnetworks based on technologies, sectors, products or programs. The system of innovation in robotics can be considered as a subsystem of the NSI in Japan. The relationship between NSI and TEN is shown in Fig. 3.

The ideology of TEN is set up around three major poles called Science—mainly the activities for producing certified knowledge, Technology—mainly characterized by the conception and development of material products that are coherent (durable and reliable) and capable of rendering services, and market

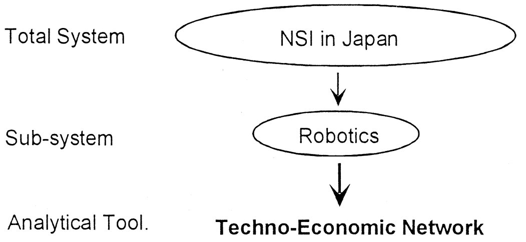


Fig. 3. The relationship between NSI and TEN.

—mainly referring to the users (state of demand). Each pole is defined by the type of products or intermediaries circulated by the members of the network (Callon and Bell, 1991). The intermediaries, which include codified knowledge (publications, patents, reports, etc.), embodied knowledge (mobility of researchers and engineers, technical objects, etc.), tacit knowledge (informal contacts, mobility of experienced personnel, etc.), money, etc., link the actors and activities internally and externally and play an important role in strengthening or weakening the network.

There is no static concept in network analysis and the links continuously change, forming new ones and destroying old ones. Links can strengthen or weaken depending on the exogenous factors of the system and links can even become critical depending on changes in the environment. A combination of databases and analytical tools depending on their availability and suitability for particular poles or links, were chosen. Another aspect of its flexibility is that the number of poles may be increased depending on the system under consideration. Although the financial and regulatory poles play a considerable supportive role, our main concerns in this paper are the three major poles: Science (S), Technology (T) and Market (M) which play a major role in the innovation process.

3.2. Data sources

The data sources have been selected specifically and generally to analyze the different poles and the linkages in the TEN. The specific sources are (a) Science pole: in our model, publication activity is considered specifically as one of the main activities to represent the Science pole for the analytical purpose. Compendex Engineering database, a specialized engineering and technology database developed by an American company called Engineering Information is widely used to analyze the Science pole. It covers mainly the journal and conference publications in science and engineering all over the world. Robotics is a multidisciplinary field and a large amount of research activities is still applied in nature. The application spectrum of robots is spreading in almost every industry especially in Japan. Therefore, an engineering database compendex covering multidisciplinary engineering fields in robotics was chosen.

(b) Technology pole: patenting is considered as a representative activity for the empirical analysis in the Technology pole. Though patents do not cover the entire domain of technological inventions and all patents do not lead to innovation, it has some strength to be used as a representative tool (Grupp et al., 1990; Miyazaki, 1995; Pavit, 1985, 1988). Patents are the direct outcome of the inventive process and because of the cost and time involved in patenting, a commercial benefit can be expected and thus lead to innovation (Archibugi and Pianta, 1996). Furthermore, they are publicly available and not covered by confidential clauses and time series data can be obtained.

In our analysis, the US patent database is used through accessing the official homepage of the US Patent Office through Internet browsers. It is a dynamic database and the changes are updated on a regular basis. The following reasons led us to select the US patent database for the analysis.

–The US is the number one importer of Japanese robots over the years, so the US is considered to be the largest market for Japan. Therefore, one can expect that Japanese companies apply for US patents for most of their potentially valuable inventions.

–Advantage of third country patenting where the volume of national patenting in large third countries is a good proxy measure for the volume of national innovative activities (Pavit, 1985).

–Japan maintains a considerable share in US patents but, on the other hand, the share of US and European patents in Japan is considerably less. Therefore, a valid comparison is possible through US patents.

–US database is well established and easily accessible.

(c) Market pole: international trade data taking into account the national difference compiled by International Federation of Robots (IFR), a body comprising most of the robot-producing countries and annual data of JARA (JARA) are used specifically to analyze the Market pole.

In addition to specific data sources, the OECD database, specialized journals in robotics and related articles are used for general sources for overall analysis. Empirical analysis was followed by extensive interviews with the representatives in companies, universities and public research institutes.

3.3. Methodologies

Under the framework of TEN, the system is analyzed at two levels: (1) activity level—the main activities in the innovation system and their linkage networks are analyzed in the Science, Technology and Market poles; (2) actor level—the major actors contributing directly to the innovation system and their linkages are analyzed at the actor level. The analytical results obtained through the activity level are related to the actor level to obtain a better picture.

The two-level analytical approach is carried out moving from macro- towards micro-level (meso-level) in order to understand the internal structure and changes in the innovation system. Macro- together with meso/micro-level approaches helps to complement one another and thus creates more meaning in the interpretation of the results. A combination of scientrometric tools followed by extensive interviews is used in an integrated way to analyze the NSI in robotics. Co-classification and co-word techniques are the main scientrometric tools used to analyze the Science and Technology poles, from macro- towards micro-level. The integrated network at the activity level is the main focus of discussion in this paper.

3.3.1. Co-classification analysis

The Compendex database in the Science pole is analyzed using the 'cal' classification code. The classification analysis considers the entire spectrum of the publications in the database and analysis can be applied in a consistent way. It is also easy to analyze without any information loss. The main criticism of this approach is its fixed classification system without considering the dynamic nature of the evolving fields. Furthermore, the motive for the classification codes is just to retrieve the information and thus does not reflect intellectual concepts (Engleman and van Raan, 1991). To capitalize on the merits of the classification technique while reducing the above limitation, we combine it with the co-word technique, which is explained below. Robot-related publications are first extracted using a broader definition of robots using the keyword 'robot*' in the title, abstract and descriptor fields of the database. We call this the main cluster. The uniqueness of the terms 'robot' and 'robotics' helps to increase accuracy when extracting the related data from the database. The robotic research activities are categorized into five broader groups as core, complementary/peripheral, application, emerging and general technologies based on their contribution to robotic research (Table 3). Publications have been grouped by identifying the group within the main cluster using the classification codes shown in Table 3.

Co-classification mapping technique uses co-occurrences of classification codes in a set of publications and maps the network of relationships between the classified fields. As shown in Fig. 4, co-classification matrix formulated based on the co-occurrences is analyzed using multi-Dimensional scaling (MDS) and cluster analysis. By combining MDS and clustering techniques of multivariate analysis (Kruskal, 1977; Spasser, 1997), the changing relationships between different fields are analyzed in the Science pole.

3.3.2. Co-word analysis

A combination of carefully selected keywords is being used to extract the required information from the database in the Science and Technology poles. Words are the foremost carrier of scientific and technological concepts, their use is unavoidable and they cover an unlimited intellectual domain (Engleman and van Raan, 1991). The main concern here is that of the descriptive meanings of words, which may have different meanings depending on the situation and style of writing.

Robotics is further classified into three main kinds of robots in a broad sense and key component technologies. The selection of the kind of robots and

Table 3
Co-classification grouping

Category of fields	Class codes	Major groupings	Remarks
Control engineering	ccl-73*	Core technology	Key engineering fields contribute to robotic research fundamentally
Computer software	ccl-723*		
Mechanical engineering	ccl-6*		
Engineering mathematics	ccl-92*		
Engineering physics	ccl-93*		
Computer hardware	ccl-722*	Complementary / peripheral technology	Supportive fields
Optical technology	ccl-74*		
Electronics and communication	ccl-71*		
Electrical engineering power	ccl-70*		
Computer logic and circuits	ccl-721*		
Acoustic technology	ccl-75*		
Instruments and measurements	ccl-94*	Application technology	Representative fields used in applications
Civil engineering	ccl-4*		
Mining engineering	ccl-5*		
Chemical engineering and agriculture	ccl-8*		
Bio-engineering	ccl-46*	Emerging technology	Representative fields of emerging nature
Aerospace engineering	ccl-65*		
Underwater engineering	ccl-47*		
Engineering management	ccl-91*	General	General fields
General engineering	ccl-90*		

component technologies is made considering the fact that they can interpret the internal dynamics of the innovation system more clearly covering factors, such as technology life cycle, nature of the kind of robot or technology, ability to interpret the changing dynamics and the coverage. The keyword ‘robot*’ in the title and the abstract and the robot classification code ‘ccl-901’ according to US patent classification system are used together. Tables 4 and 5 show the co-word groupings used to identify the kind of robots and the key component technologies in the Science and Technology poles.

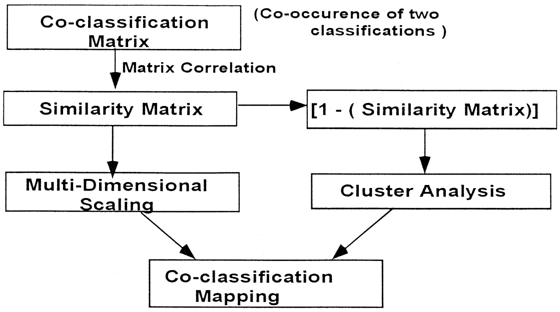


Fig. 4. Flowchart of co-classification mapping.

3.4. Limitations and some remedies

Innovation is a multidisciplinary concept involving heterogeneous entities and processes ranging from

Table 4
Co-word grouping for robot kinds

Categories	Co-word combinations (within the robot main cluster)	Remarks
Industrial robot	Industrial robot	Complemented using ‘OR’
	Manipulator	
	Arm	
	End effector	
	Wrist/gripper	
Mobile robot	Mobile	Complemented using ‘OR’
	Leg*	
	Navigation	
	Obstacle avoidance	
	Biped	
	Quadruped	
Micro-robot	Micro*	Individually checked

Fields searched: title and descriptors.

Table 5
Co-word groupings for key component technologies

Categories	Combination of keywords (within the robot main cluster)	Remarks
Kinematics and dynamics	Kinematic	Complemented using ‘OR’
	Dynamic	
Sensors	Sensor	
Controls	Controls	
Actuator	Actuator	Complemented using ‘OR’
	Motor	
	Drive	
	Hydraulic/pneumatic	
AI	Neural	Complemented using ‘OR’
	Fuzzy	
	Intelligence*	
	Learning	
	Expert	
Software	Program	Complemented using ‘OR’
	Simulation	
	Language	

Fields searched: title and descriptors.

basic research to marketing. Grouping the processes around three main poles of Science, Technology and the Market is based on the intermediaries flowing in and out from these poles, is the first assumption here. The contribution of science and technology to innovation contains considerable intangible components, which are not quantifiable. The database coverage, home country advantage and English bias are some other general limitations. Several studies in recent years identified the strong and weak points of the bibliometric techniques. Nevertheless, it is generally accepted that if properly used and interpreted, bibliometric analysis can be a useful indicator of the dynamics of the technology system (Miyazaki, 1995). With the available data sources, we found those selected ones were a more practical choice with greater justification for quantitative analysis. The results are verified through the survey carried out (JARA data) and our interview data. The interviews with university, public institutions and the company researchers, partly based on the findings in the scientrometric analysis, helped to reduce any misinterpretation.

4. Network analysis

The innovation system is examined under the TEN framework, using empirical and other analyses in two stages: activity and actors. Each stage is analyzed moving from macro- towards micro-levels in order to pinpoint the insights and the linkages among them in the innovation system. The empirical results related to the activity analysis are mainly discussed in this paper. The findings of the empirical analysis assisted the formulation of interviews with the main actor groups and to cross-evaluate them.

4.1. STM profile—macro-level analysis

The dynamic changes in the robotic innovation system at the macro-level are identified in a comparative way by formulating an integrated profile called an STM profile (Fig. 5). In the Science and Technology poles, a tool introduced by Patel and Pavit (1997) for categorizing the technological competencies of firms was used in our analysis and the profile in the Market pole was formulated consistent with other poles. The X axis in the Science and Technology poles represents the share of activities and Y axis indicates the revealed technology advantage (RTA) of the countries. RTA is calculated by dividing the country’s share in a specific field by its national average to measure the comparative advantage of the technological strength. A value above 1 indicates relative strength and a value less than 1 relative weakness. The regions of high share and high RTA can be interpreted as countries having relatively more share in the Science pole (i.e., relative importance to competencies in robotics) and having distinctive advantage nationally in robotics, compared to other fields. Similarly, the region of low share and low RTA reveals countries allocating relatively less resources to robotics and having less distinctive advantage nationally. In the Market pole, the X axis represents the market share and the Y axis indicates an index called the EIC index which is net exports as a percentage of the national consumption, formulated in order to be consistent with the Science and Technology poles profile. For example, an EIC value of 0.5 (positive) indicates that the country is a

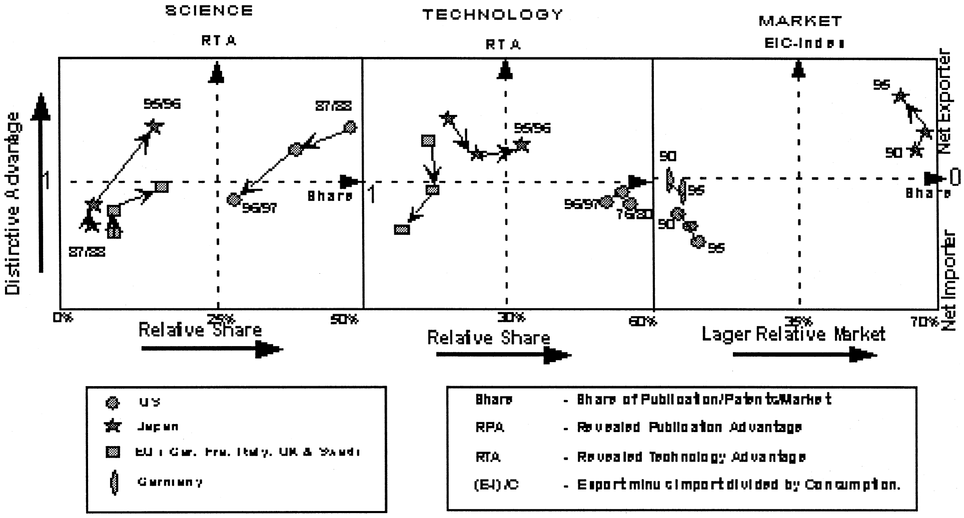


Fig. 5. STM profile map of different countries in the robotics.

net exporter and exports minus imports are 50% of the national consumption. A value around zero can be interpreted in two ways. One interpretation is that the country does not import or export much and the other may be that the country imports and exports equally. It is to be noted that the value of benchmark share in the X axis is difficult to identify and varies depending on various reasons, such as the countries considered, innovation process analyzed, national requirements, etc. In this case the break-even share is chosen in order to accommodate all countries in such a way that a proper comparison of their innovation system can be made. Therefore, in this analysis, what matters is the direction of movement and comparative positions rather than absolute positions.

Based on the above explanations, the Japanese position in the Science pole moved from a low share and low RTA zone towards a high share and high RTA zone. The Japanese contribution in robotics research was less in the early 1980s and then it slowly picked up to around 11% in 1993/1994 and 15% in 1995/1996. The RTA was less than 1 in the early 1980s and then it rose to 1.18 in 1993/1994 and to 1.56 in 1995/1996. This indicates that relative to other domains, the research system has been gaining strength in recent years in Japan.

On the other hand, the US trajectory is moving in the opposite direction to Japan. It has been losing both its relatively higher share in robotics research and the national importance in robotics research. The decline in the percentage of share in robotic publications may be because of the entry of many other countries into robot research activities. While the EU contributes relatively little higher percentage than Japan in the Science pole, its distinctive advantage in robotics is still low (RTA is less than 1). The direction of Japan and EU are approximately the same in the Science pole but the direction of the US is opposite to that of Japan.

From Table 6, it can be seen that the ratio of publications by the US and Japan was 7:1 in the 1980s but became 2:1 in the 1990s. Another interesting observation in this pole is that around 72% of the activities were by done by the G-7 countries in the 1980s and this percentage has been steadily declining, their contribution amounting to 65% in the 1990s. Of these G-7 countries, Japan is the only country which has doubled its effort in robotic scientific research.

In the Technology pole, the trend has been analyzed for more than 20 years from 1976 to 1997. Japan's position in the Technology pole is moving from the low share and high RTA zone to the high share and high RTA zone. The RTA has been more than 1 throughout the analytical period while gaining strength. Though there was a slight dip in the RTA

Table 6
Share of robotic-related publications

	1987–1988	1991–1992	1995–1996
Germany	0.04	0.03	0.04
France	0.03	0.03	0.04
Italy	0.01	0.02	0.03
England	0.03	0.03	0.05
EU	0.11	0.11	0.16
Canada	0.04	0.05	0.06
USA	0.50	0.38	0.28
Japan	0.07	0.07	0.15
All-7	0.72	0.61	0.65

EU includes Germany, France, Italy and UK.
All-7 includes EU plus Japan, Canada and US.
Source: Compendex data base.

Table 7
Share of robotic-related patents (inventors basis)

	1976–1980	1981–1985	1986–1990	1991–1995	1996–1997
Germany	0.03	0.05	0.08	0.05	0.06
France	0.07	0.05	0.04	0.03	0.01
Italy	0.02	0.03	0.02	0.03	0.01
UK	0.02	0.03	0.03	0.01	0.02
EU	0.17	0.18	0.18	0.14	0.12
Canada	0.01	0.02	0.02	0.02	0.05
USA	0.52	0.51	0.49	0.47	0.47
Japan	0.20	0.26	0.28	0.33	0.32
All-7	0.90	0.97	0.97	0.96	0.96

EU includes only Germany, France, Italy and UK.
All-7 includes EU plus Canada, Japan, US.

in the late 1980s, it picked up again in the mid-1990s. This means that Japan's contribution in robotic technology development has been increasing continuously and Japan gives higher priority to robotic development. The US has been in the high share and low RTA zone throughout the period but has been moving in the direction towards the low share and low RTA zone. It indicates that although the US has been allocating relatively large resources in technology development, its relative advantage is becoming less. On the other hand, EU was in the low share and high RTA zone like Japan in the early 1980s but has been moving towards the low share and low RTA zone. EU was allocating as large an amount (17%) of resources as Japan (20%) for technology development in the 1970s and but its share has slowly been declining in the 1990s (12%). Its relative technological advantage in robotics dropped from 1.58 in the 1970s to 0.88 in the 1990s.

Table 7 indicates that the G-7 countries hold more than 95% of patents except in 1976–1980, unlike the case of publication share. Japan and the US have around 80% of patents in robotics.

The market profile for robotics indicates that Japan had been almost on the axis in between the zones of low share, low EIC and low share, high EIC in the early 1980s and quickly moved towards the high share, high EIC zone. But the US, on the other hand, has been in the high share, high EIC zone in the early 1980s and then shifted to the low share, low EIC zone. Germany is in between the low share, low EIC and low share, high EIC zones. Japan holds 60% of the world market share of industrial robots and it recently exports around 60% of local installations (Table 8). It can also be observed that while slightly losing its relative share, the EIC index increased from 0.18 in 1990 to 0.59 in 1995. This means that demand for robots has increased in many other countries and Japan is the chief supplier for that increasing demand. On the other hand, demand for robots is increasing in the US but other countries (EIC index too dropping) are fulfilling a higher percentage of this demand.

From Table 8, an increase in the stock levels can be observed in Asia and in absolute terms the stocks have increased by five times from 1990 to 1996. During that period, if we look at the absolute stock increase, it has only increased by 46% in Japan, 82% in the US and 120% in Germany. A slow down in

Table 8
Share of operational stock of industrial robots

Country	1983	1990	1996
Japan	0.44	0.60	0.59
USA	0.21	0.08	0.10
Germany	0.13	0.06	0.09
UK	0.05	0.01	0.01
Italy	0.05	0.03	0.04
France	0.04	0.02	0.02
EU-4	0.26	0.12	0.16
Asia-4	0	0.02	0.05
Total	0.91	0.80	0.86

EU-4 includes the above four European countries.
Asia-4 includes Australia, Korea, Taiwan and Singapore.
Source: Japan Robot Association and IFR.

demand was observed in Japan and a sharp increase was observed in the US and Germany.

The STM profile macro-level analysis demonstrates the overall positions of the Japanese Innovation System in a comparative way. To identify the dynamic positions internally, we complement it with a meso/micro-level structural analysis.

4.2. Structural—a meso / micro-level analysis

A macro tool, such as the STM profile, can only reveal the overall relative positions and the trend of the countries in the three poles. For policy making, the facts revealed by the macro tools will be of less use if they are not complemented with a meso- or micro-analysis. The changing internal structures, technology directions, overall strategies are some of the characteristics policy makers look for, which cannot be traced by macro tools.

4.2.1. (a) Science pole

Fig. 6 is a profile similar to the one in the STM profile discussed earlier, showing the US and Japanese contributions in different technology groupings. The five major groupings explained in Section 2 are used in this figure. The path of the different technology groupings is examined in a comparative way.

A consistent increase in relative share and RTA can be seen in core and peripheral technologies in Japan. A noticeable difference can be found in emerging technologies. Japan's contribution in these technologies at the research level was considerably low until the early 1990s and a sharp increase can be seen in the 1995/1996 period. Although the US, on the other hand, has seen an overall drop in activities, it maintains a larger share in emerging fields. Japan and the US together contribute around 45% in core and complementary technologies and around 63% in emerging technologies. But both have around 37% in application and general kind of publications. It indicates that new entrants in robotics play a lesser role in emerging technologies. The category of emerging technologies include robots for space, underwater applications and the use of bio-engineering to develop biologically stimulated robots for various applications, such as legged robots, snake robots, etc. Japan's recent interest in unmanned spacecraft, underwater explorations and other unconventional applications, such as nuclear power plant inspection, human friendly robots for welfare, entertainment, etc., reaffirms the steep increase observed in emerging technologies in the Japanese case as in Fig. 6.

The STM profile map showed the overall picture of the Science pole and the classification analysis explained the absolute strengths and weaknesses in the robotics structure in a broader way. These two analyses do not suggest anything about the relative internal structures and changes in the knowledge

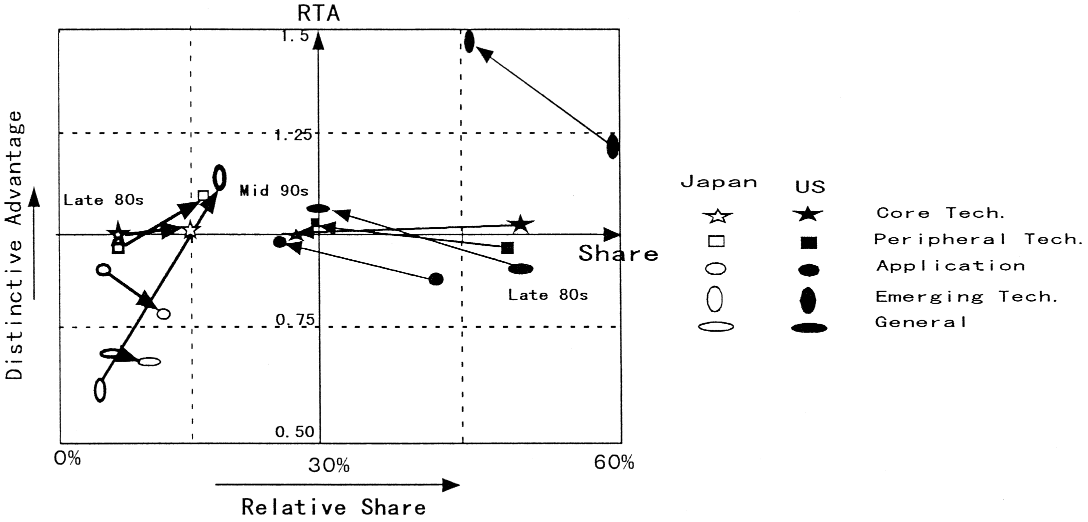


Fig. 6. Technology trajectory of the robot technology groupings.

diffusion structures. Knowledge diffusion activities are mapped using co-classification technique (explained in Section 3.3), thus, the changing pattern in robotic knowledge diffusion structure may be identified.

Fig. 7 shows the co-classification maps based on robotic related publications activities in 1988 and 1995 in Japan. In 1988, robotic activities were clustered around four major groupings namely controls, computers, electrical and mechanical related fields. Each cluster was considerably separated from one another, resulting in less knowledge diffusion between the cluster groupings. The closeness within each cluster was also notably less than in 1995. It would be an indication that the internal diffusion within each cluster was also less. There were fewer interdisciplinary departments or departments especially for robots in Japanese universities until 1988 (Kondo, 1990). Rigid divisional structures and administrative difficulties were the two main reasons usually preventing convergence and formation of interdisciplinary divisions within universities.

The map in 1995 indicates a structural change. The activities' coalescence is taking place among the three main clusters of control, computer and electrical and the activities within each cluster has become

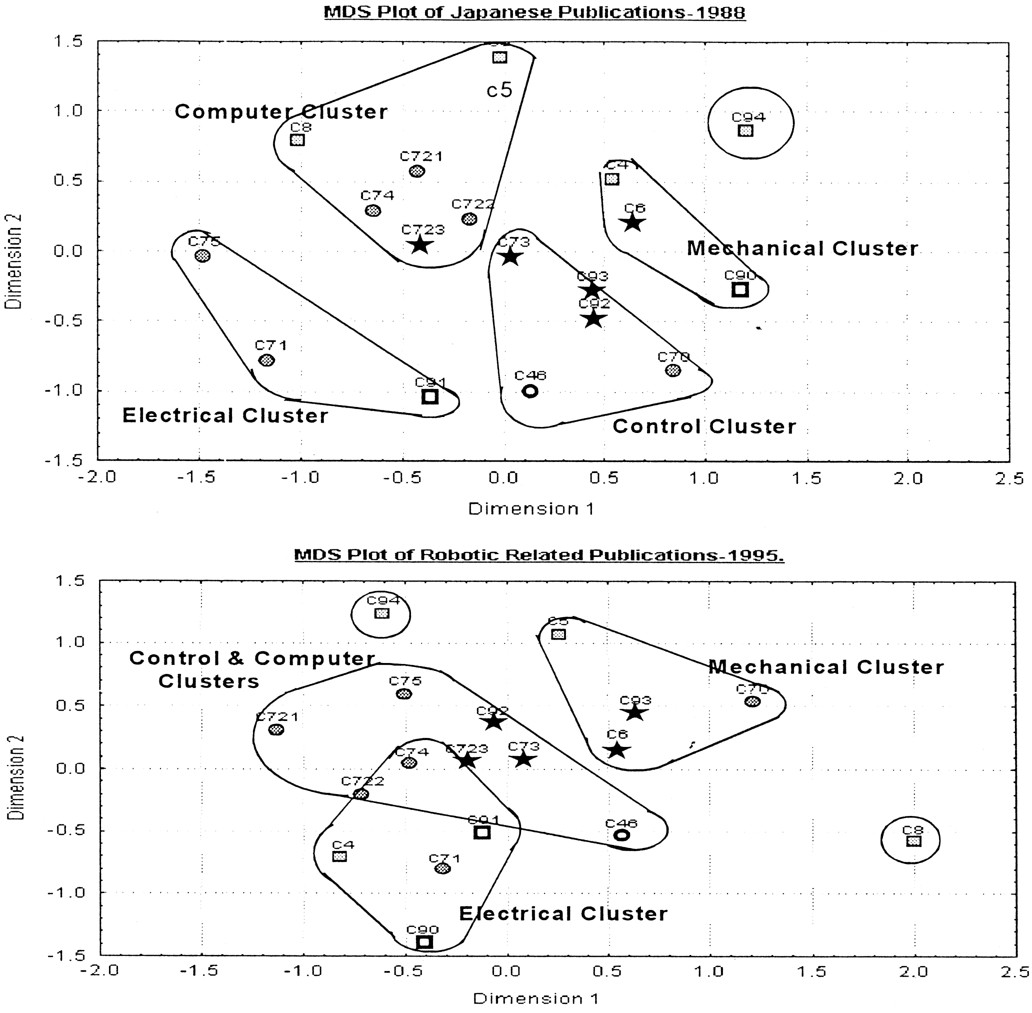


Fig. 7. Co-classification mapping of Science pole.

closer too. Universities have been forming interdisciplinary departments to face the growing technological convergence in robotics technologies. Robotic-centered knowledge generation activities are taking place in an integrated way and the diffusion link among the fields is also becoming stronger. Furthermore, the higher integration of user level application fields would lead to cross-knowledge flows of core technologies into application fields.

To summarize the co-classification mapping analysis, though it has some disadvantages in analyzing multidimensional data, it is still used by many researchers as a useful tool to trace structural changes. It highlights the internal structures and relations and explains whether the innovation system functions in a highly dispersed or integrated way. The Japanese structure shows some distinguishable differences in the correlation between different fields over the years and diffusion structure has increasingly become close. A close diffusion network would facilitate better knowledge flows among multidisciplinary fields and any development in one field has more possibility to diffuse into larger groups.

Co-word analysis helps to specifically identify activities unlike classification analysis. Here we analyze three different kinds of robots of varying technological life cycles, target markets and key component technologies. Industrial robots initially induced robotic research activities and were highly diffused in industry. Then mobile robots became the main driving force for robotic research and rarely diffused into the market. Very recently, the concept of micro-robot is becoming popular and is expected to drive the research into the next century. The key technologies include the key drivers from the traditional to intelligence fields.

Table 9 shows the publication shares during the three time periods in the three kind of robots and key component technologies. It clearly shows the way Japan has been dynamically building competencies (learning) through innovation. Classification analysis showed that Japan's share was around 7% in 1987–1988 and 15% in 1995–1996 in core and component technologies. Japan's contribution to mobile robots, micro-robots were 13%, 13% in 1987/1988 and then reached 21%, 40% in 1995/1996, quite different from the contribution in industrial robots. On the other hand, the US contributed around 60% in both mobile and micro-robots in the 1980s and equally dropped its contribution to 23% in the 1990s. Japan together with the US contributes a higher percentage on emerging robot technologies (Table 9: mobile: 76% in 1987/1988 to 44% in 1995/1996, micro-robot: 75% to 63%, respectively). This percentage is 60% to 41% for industrial robots, which is considered to be a more mature technology. The research agenda has been progressively shifting from industrial to mobile and micro-robots. Furthermore, a heavy push in micro-robot technologies can be clearly observed through this structural analysis. Control seems to the driving field in robotics research. Japan had a smaller share and spent fewer resources on

Table 9
Share of publication actitvities

	1987–1988			1991–1992			1995–1996		
	US	Japan	US + Japan	US	Japan	US + Japan	US	Japan	US + Japan
Types of robots									
Industrial robot	0.51	0.09	0.60	0.39	0.09	0.48	0.23	0.18	0.41
Mobile robot	0.63	0.13	0.76	0.38	0.10	0.48	0.23	0.21	0.44
Micro-robot	*0.63*	*0.13*	*0.75*	*0.21*	*0.50*	*0.71*	*0.23*	*0.40*	*0.63*
Key components technology									
Kinematics and dynamics	0.58	0.07	0.66	0.42	0.06	0.47	0.29	0.14	0.42
Sensor	0.52	0.09	0.61	0.43	0.10	0.52	0.29	0.17	0.46
Actuator	0.41	0.11	0.52	0.26	0.14	0.40	0.20	0.15	0.35
Control	0.51	0.09	0.60	0.37	0.08	0.44	0.27	0.15	0.42
AI	*0.62*	*0.07*	*0.68*	*0.36*	*0.07*	*0.43*	*0.27*	*0.17*	*0.44*
Software	0.53	0.07	0.60	0.40	0.07	0.46	0.26	0.17	0.43

software and intelligence related fields until the early 1990s and managed to pick up in both fields recently, which seem to be the emerging driving force in robotic technologies.

To summarize the empirical results obtained through structural analyses in the Science pole, Japan spent fewer resources in emerging fields (bioengineering, space engineering and underwater engineering) in robotic research until the early 1990s. Japanese robotic research has concentrated less on intelligence-oriented research fields. Furthermore, the Science pole was clustered into four main groups (control, communication, mechanical and computer related) and the activities have been more dispersed. But the trend is changing and the Japanese Science pole is gaining momentum by allocating more resources to emerging and intelligence oriented fields. Clusters are becoming closer facilitating a greater knowledge diffusion network. Both analyses show that the systems of innovation in Japan, though slow, managed to adjust to dynamic changes in the global environment.

4.2.2. *(b) Technology pole*

The STM profile map indicated the strength of the Japanese in the Technology pole both in share and national importance. In this section, we analyze the structural changes in the Technology pole in a comparative way. As explained before, patents are considered to be the representative data for this pole. To make the analysis more comprehensive, it is analyzed into three groupings in terms of three kinds of robots, six main component technologies and main application areas. The co-word technique is used to extract information from the database.

As shown in Fig. 8, Japan together with the US, holds a higher percentage in the three kinds of robots and key component technologies. The percentage is higher for mobile and micro types of robots. The US has been steadily losing its share in almost all robotic-related activities. Compared to its drop in the Science pole, the percentage drop in the Technology pole is less. The US still maintains its lead in software-related activities in robotics and to some extent in artificial intelligence (AI). Japan, on the

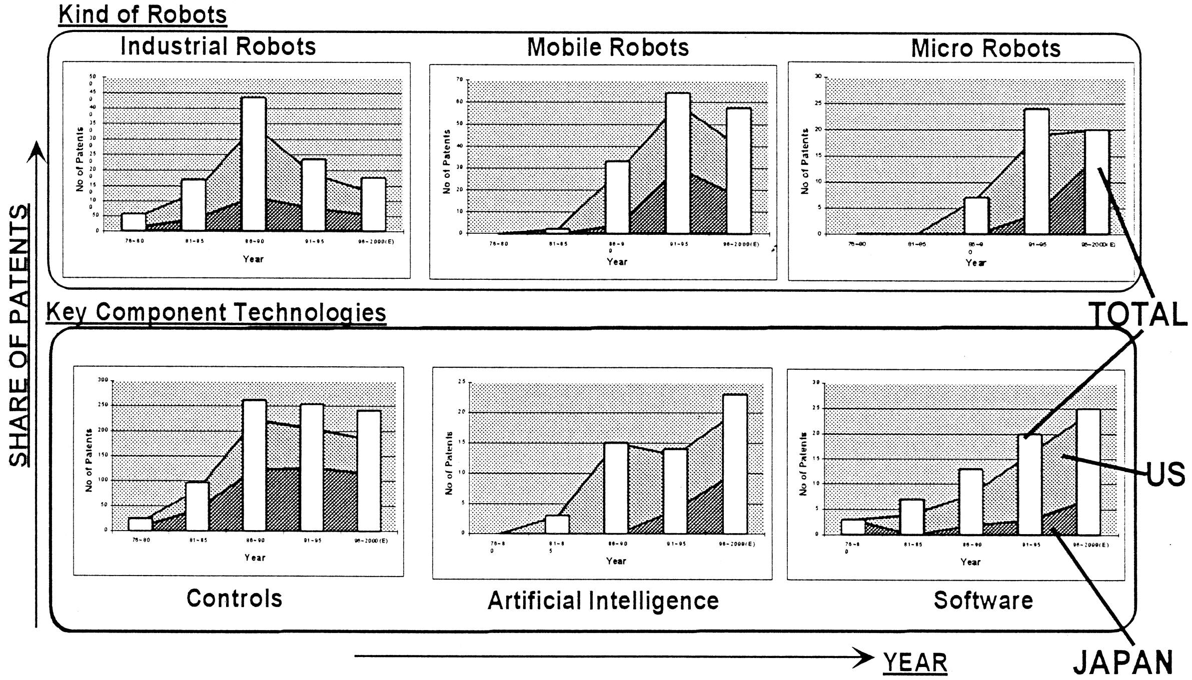


Fig. 8. Share of patents and technology life cycles.

other hand, increased its share in most of the activities. In micro-robotic activity, Japan has over taken the US and now leads in this field. The total share of both the US and Japan recently dropped in industrial robotic activities indicating that many new comers are entering this field. Control technology has been the driving technology especially for Japan and it maintains a comparatively higher share throughout the period. Japan's activities in intelligence- and software-related fields has been considerably low compared to the US until the mid-1990s. The Japanese presence in these two fields can be observed in the recent results with changes in the trend.

Table 10 shows the share of resource allocation based on patents for the different kinds of robots and the key component technologies within Japan, the US and the world. It can be observed that technological activities in industrial robots are decreasing while mobile and micro-robots show an increasing trend. The total share of industrial robot-related patents dipped from 100% to 91% from 1976/1980 to 1986/1990 and further reduced to 69% in 1996/1997. Japan had a higher percentage than the total in 1986/1990 in industrial robots but its share is declining. AI- and software-related activities are getting more prominent in robotics. It confirms that in correspondence with the Science pole, robotic intelligence is more emphasized in recent years in the Technology pole.

In micro-robotic activity, Japan has overtaken the US and now leads in this field. A similar trend was observed in publication activities too, indicating the national determination to push forward in micro-robot technology. In component technologies, Japan's strength in controls and a comparatively weaker position in software can be clearly observed. The national structure of activities reinforces this fact with Japan's greater than average efforts in controls and mechanisms and less than average efforts in software and AI. But increasing efforts can be seen in AI and software recently.

4.2.3. *(c) Market pole*

The STM profile analysis shows that Japan has been maintaining a strong demand for robots since the early 1980s and has been a major exporter of robots to the world. Japan holds around 60% of the world industrial robot stock. Japan correctly identified the importance of the robotic technology in its early stage and promoted heavily through demand-pull and technology-push strategies. A mere overall analysis which is done in the STM profile analysis would not indicate anything about the internal structure of the market.

The changing internal structure of the Market pole, which is found to be the main driving force of the Japanese robotic innovation process needs to be analyzed integrally with the Science and Technology

Table 10
Structure of Japan and US in robotic-related patents

Categories	1976–1980			1986–1990			1991–1995			1996–1997		
	Japan	US	Total	Japan	US	Total	Japan	US	Total	Japan	US	Total
Kind of robots												
Industrial robots	1.00	1.00	1.00	0.97	0.88	0.91	0.69	0.72	0.73	0.63	0.72	0.69
Mobile robots	0.00	0.00	0.00	0.03	0.09	0.07	0.28	0.19	0.20	0.20	0.23	0.23
Micro-robot	*0.00*	*0.00*	*0.00*	*0.00*	*0.03*	*0.02*	*0.04*	*0.10*	*0.07*	*0.17*	*0.05*	*0.08*
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Component technology												
Mechanism	0.14	0.12	0.10	0.16	0.13	0.13	0.09	0.17	0.11	0.11	0.13	0.10
Sensors	0.00	0.24	0.10	0.04	0.29	0.19	0.07	0.17	0.12	0.15	0.09	0.17
Control	0.57	0.59	0.63	0.69	0.37	0.49	0.71	0.45	0.59	0.62	0.52	0.58
Actuator	0.07	0.06	0.10	0.10	0.13	0.13	0.09	0.09	0.09	0.03	0.06	0.03
AI	*0.00*	*0.00*	*0.00*	*0.00*	*0.06*	*0.03*	*0.02*	*0.05*	*0.03*	*0.05*	*0.08*	*0.06*
Software	0.21	0.00	0.08	0.01	0.02	0.02	0.02	0.07	0.05	0.04	0.13	0.06
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

poles, in the TEN. This helps to identify the backward effects on other poles due to changes in the Market pole.

Japan had been producing more than 85% of the world robot need as shown above during the late 1980s and the early 1990s. Very recently, the percentage has dropped to slightly more than 75% (Fig. 9). This indicates that other producers from other countries have increased their market share. Another reason may be that producers from other countries are targeting new markets. Out of Japan's total consumption, it only imports less than 1%. Fig. 10 shows the breakdown of robot production by Japanese companies. In the 1990s, out of its total production, 16% was exported, 8% was used to replace the existing stock and 77% was new stock used by companies. The trend changed radically in 1996 and out of total production, the new stock increase has only been 20% and the huge 43% were just replacement stocks. Even in absolute terms the drop is substantial.

Recently, most robots are being used to just replace the old stock and new users are on a decreasing trend. This may be due to:

- Industrial robots may have saturated in most of the matured Japanese industries and/or
- The present industrial needs may be changing and the options the robots offer may not be enough to satisfy the needs and/or
- Companies are finding some other ways to satisfy the needs, such as off-shore production or manual production.

The higher replacement rate indicates that those who introduced industrial robots find it worth or the necessity to replace their robots. In Japan, the service period generally given by companies would be around 8 to 10 years. If we see the recent trend for replacement robots, it highly correlates with robot installation 8 to 10 years earlier. Therefore, though the net stocks are decreasing, if a similar trend continues Japan's robot producers would find no difficulty in selling their products to the Japanese market.

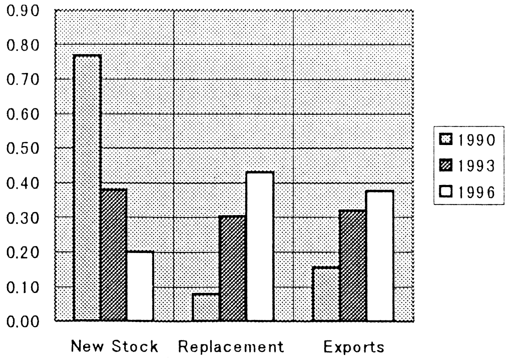


Fig. 9. Japan's robot production as a percentage of world supply.

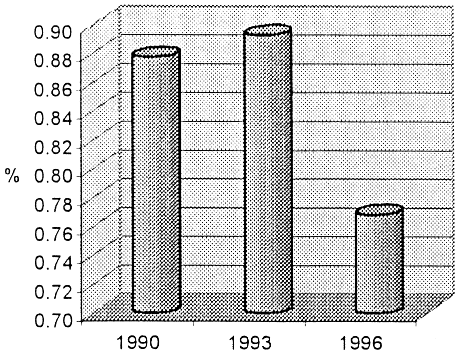


Fig. 10. Japan's robot production breakdown.

4.3. Activity linkages

Identifying the knowledge flows and Technology flows is crucial in the NSI approach. Linking the Science pole with that of technology is one important linkage to transfer knowledge. In the Japanese robotic innovation system, the Science pole is highly controlled by universities and the Technology pole by companies. An integrated network, in addition to better knowledge diffusion, reduces duplication of efforts leading to less waste and better resource allocation.

4.3.1. (a) Paper to patent ratio

Paper to patent ratio is an indicator to show the activities of the companies both in the Science and Technology poles. Table 11 shows the ratio of publication (based on Compendex) to patents (based on US patent data) of the leading robot makers, users and institutions.

Two vital points can be observed in the table: (1) The ratio is higher in robotics than the total. Companies are actively engaged in research on robotics. (2) The ratio is on increasing trend.The linkage between science and technology has been increasing. Institu-

Table 11
Paper to patent ratio in robotics and in total

	Robots			Total		
	1987–1990	1991–1994	1995–1996	1987–1990	1991–1994	1995–1996
Makers						
Fanuc	0.03	0.11	0.33	0.02	0.04	0.20
Toshiba	0.50	0.53	1.00	0.28	0.21	0.52
Yaskawa	0.36	0.47	1.00	0.63	0.49	1.25
Kawasaki HI	0.50	0.27	1.67	0.10	0.12	0.26
Users						
Toyota	0.32	0.75	4.00	0.20	0.49	0.70
Nissan	0.20	0.18	1.00	0.09	0.18	0.32
Institution						
ETL	3.80	2.67	3.80	1.30	1.55	3.31

tions have more propensities to publish than robotic companies and recently companies too started to concentrate on publications (ratio equal to or more than one). Changes in robotic developments, changes in publication policies in the companies and desire to be in the research front in order to access a widening network, are some of the reasons for this trend. User companies, on the other hand, have reduced patenting because of the maturity in industrial robot activities and this has led to the increase in the ratio in the table.

4.3.2. (b) Patent citation to publication

Another scientrometric tool to identify the science–technology linkage would be publication citation in patents. A field like robotics usually has less science linkage compared to medical-related fields and more science-based fields. The above paper to patent ratio shows that those robot-related leading companies and institutions are increasing their science linkages. In addition, science linkage using patents gives another useful clue of the changing linkage dynamics. The study of percentage of Japanese papers cited by the two top makers, one top public institution and one top user firm shows the strengthening effect of the linkage (Table 12). The last column shows that the Japanese publication citation is clearly on the increasing trend though the percentage is comparatively less. These four institutions have been active in robots from the early stage and would be a representative sample. Both measures reveal the fact that science linkage to technology in the robotic innovation system is increasing. Our interview with corporate researchers, university academia and researchers of public research institutes, confirmed the trend stating that increasing complexities in robotic technologies, higher level of technology convergence and cost-cutting pressures bring about the close integration of Science and Technology poles.

Barronson (1983) pointed out that closer links between the users and makers would be one of the reasons for the success of Japan in robotics. Japanese makers have been maintaining a wider product range based on the level of applications and technologies. JARA, on the other hand, conducts regular surveys from the current and potential user groups and disseminates the information to the makers and other interested groups. Japanese robot makers introduced new models at frequent intervals for targeting specific needs of user industries. The higher diffusion

Table 12
Publication citation in patents

Year	Total patents	Total citations	Japanese citations	Japanese % of total
1976–1980	4	24	5	0.208
1981–1985	56	301	64	0.213
1986–1990	102	574	190	0.331
1991–1995	113	774	323	0.417

Two top robot makers, one top user and one top institution are considered for the analysis.

rate and higher replacement rate of customers are indicators of technology market linkages. Still there are around 200 robot makers in Japan covering a wide range of robots. Some of the makers cover only a niche market, which could even strengthen the user linkages. Strong user participation in the Science and Technology poles and the companies strength in application-oriented technologies further strengthen the linkage. The interview data showed that quite often the customers are the main source of information for innovation especially in industrial robots. Strong customer service by the Japanese firms was an important reason quoted by one US producer during the interview, for their little penetration into Japanese market.

5. Summary, policy concerns and concluding remarks

The innovative approach based on TEN to analyze the three poles of Science, Technology and Market and the linkages among them has been found to be effective in highlighting the internal dynamics and transformation, the strengths and the weaknesses of the innovation system in Japan, in robotics. Such an in-depth, meso-level study focusing on one sector has been able to highlight the structural transformations in the system of innovation and the direction of competence building at the national level. By introducing new tools in an integrated way together with extensive interview data, our empirical findings revealed the evolving trajectories in all three poles. The three stages of STM profile (macro-level), structural (meso/micro-level) and linkage analyses helped, in addition to complementing one another, find new attributes of the innovation systems and link their characteristics to visualize the network-based model in a comprehensive way. Though this paper has not covered the actor level analysis, which was also part of our research, empirical and other results quite support us in tracing the changing internal dynamics of the innovation system.

The findings show that the innovation system in Japan in robotics has been maintaining a strong position in the Technology and Market poles since the late 1970s and that recently the Science pole is also gaining strength. The STM profile analysis indicated a positive trend in Japan in robotics compared to the US and Europe in all three poles. The integrated analysis clearly elaborates the changing life cycles of the three kinds of robots, i.e., industrial, mobile and micro. It shows that industrial robots have reached the declining stage in their life cycle in the Science and Technology poles and a decreasing trend of new robots introduced in the Market pole has been observed in Japan. Mobile and micro-robots, on the other hand, show a clear positive trend in the Science and Technology poles and increasing signs of market potential. The shift is also seen in the total resource allocation for robotics in Japan through our structural analysis.

The structural analysis of our studies indicated an integration of component technologies of robotics at a rapid rate. Robotics, which has long been considered as a field of ‘technology absorber’, has been changing recently into a ‘technology absorber/supplier’. Control technology, which was one of the core technologies for modern robots, has been a field in which Japan took the lead and in which it has managed to maintain its lead. Compared to other component technologies, AI and software show clear signs of growth potential in the Science and Technology poles. The US has been maintaining a comparatively strong position in these two emerging fields. Recently, Japan’s emphasis has been shifting towards AI and software-related fields, which are considered to be the key technologies for next-generation robots. The national system has correctly identified and shaped itself with changing patterns.

The activity level linkage analyses empirically showed the improving linkages between the Science and Technology poles. Our interviews with several interest groups indicated that Japan is transforming itself from a follower to a front runner and to compete as a front runner, they stressed the need for a close linkage with the Science pole. Japan systematically built a strong infrastructure to strengthen and link all three poles.

The in-depth empirical studies together with interview data shows that the robotic network is becoming more convergent and highly connected. The crucial role of bridging institutions, especially the JARA, is found in harmonizing the activities of the Science, Technology and Market poles and maintaining a virtuous loop of innovation among them. In addition, continuously introduced national projects, conferences and seminars facilitated further the strengthening of the linkages by creating opportunities for formal and informal interactions. In addition to the infrastructures, we found in all actor groups the awareness of the need to improve links with other actors. The MITI in Japan in recent years are taking steps to encourage the linkage by relaxing some of its regulatory rules and forming liaison offices inside universities. The interviews with corporate personnel confirmed that the changing nature of the competitive environment and the continuous need for innovation forces them to be active in the Science pole, forming effective linkages with other actor groups.

Evolutionary trajectories of the innovation system demonstrated that unlike the US, Japan as a follower country, concentrated on the Market and Technology poles in the initial stage and once a virtuous cycle was established, the emphasis shifted also to the Science pole. Throughout the period for various reasons, the Japanese manufacturers and the government identified the potential of robotic technology and encouraged its use by various means and maintained a strong Market pole. Japan was able to catch up strategically in robotic technologies within a relatively short period and compete equally with other nations in the Science pole.

Structural changes taking place in all three poles were also confirmed through the interview results which emphasized that interest has been shifting mainly because of the saturating trend of industrial robot technologies and wider unresolved research and application potentials of mobile and micro kind of robots. Basically, it becomes a challenge to policy makers, to effectively manage three different kinds of network in their different stages of the life cycle. Building an effective system to transfer competencies acquired in industrial robots to other emerging networks is one of the main policy concerns needing further attention.

Unlike industrial robots which are considered as capital equipment to produce consumer goods, mobile robots used for welfare, entertainment and other service industries are targeted directly to end users as consumer durable. The traditional productivity concerns, which policy makers applied in industrial robots, may not be the right yardstick in the new environment. The trend leads to a new era in which human beings cohabit with intelligent machines. In addition to helping human beings, they may even become a potential threat. These intelligent machines can be made or copied with less cost and effort and can even be directed to potentially dangerous applications, such as suicide bombing, intelligent war, etc. The emerging environment urges policy makers to formulate new rules and regulations, firstly to ensure a smoother co-existence of intelligent machines and human beings and secondly to identify economic and other effects. The emerging trend has the potential to form a new frontier in technology and market and its economic impacts will be another issue where policy level attention is needed. Combined with mobile robots, micro-robots can accelerate the rate of technological change, which we saw with clear evidence in all three poles, which may lead to a new wave of changes in the industrial robot paradigm.

Technology integration, which we found to be taking place in the Science pole in Japan, on one hand, substantially helps knowledge cross-diffusion, considering robotics as a source of linkage. On the other hand, at the management and policy-making level, this raises the need to formulate interdisciplinary fields to face growing challenges. Many Japanese universities have already started new interdisciplinary programs to face emerging challenges, but our interview results indicated their slow response rate. The lack of administrative and supportive infrastructures, regulations and the accumulated values over the years still do not allow the system to be flexible enough to form new cross-disciplinary fields quickly enough. The reasons for the phase lag in intelligence (AI) and software fields can be to some extent traced to this slow response rate.

The above changes in the Science, Technology and Market poles indicate signs of major structural transformations in the existing paradigm of the Japanese system of innovation in robotics. Completely new manufacturers targeting nonindustrial applications, new technologies with higher level of intelligence, new applications close to end users and new thinking about robots are changing the existing paradigm in which industrial robots in manufacturing applications were the dominant design. In the emerging knowledge economy, the new robot paradigm may influence a wide variety of activities spanning from manufacturing, nonmanufacturing, education, entertainment, welfare, etc. In addition, new frontiers opening up in space and underwater explorations may accelerate the transition.

Though there are general and specific limitations in the data sources and data construction methods, we found that the integrated approach is a useful starting tool to analyze the innovation system in a country. The research also raises further questions, which need more investigation. How to effectively transfer competencies acquired through industrial robots to other emerging networks, would be an important issue to explore. How to shape the structural changes and new frontiers opening up in the Science, Technology and Market poles for better economic benefits in a competitive environment, will also be an interesting area for further study. Integrating other poles, such as the financial and regulatory, into the network and investigating the complete system of innovation may be a further step.

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