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Collaborative R&D in the robot technology in Japan: an inquiry based on patent data analysis (1991-2004)

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Summary: The growing trend of collaborative R&D has been well documented recently, both at a global level and through national and industry case studies. However, there is no general agreement on its causes as well as on the motives of the firms collaborating in R&D with other players. The Japanese innovation system (JIS) is no exception. Furthermore, in this case, it is particularly important, because the JIS has been described since the 1970s as dominated by "in-house" R&D by large firms and this feature has been considered as one reason of the limits that the JIS reached at the end of the 1980s.

By contrast to the existing literature on collaborative R&D in Japan, this paper focus on the case of the robot technology (RT), by using patent data applied in Japan between 1991 and 2004. The questions we address in this paper are as follows: Did the R&D collaboration in RT increase since the beginning of the 1990s? Did the R&D collaborations lead to higher quality of the outcomes? Is it possible to categorize different forms of collaborations and different types of players (depending on their degree of collaboration)? How to explain the evolution of R&D collaboration, if any?

Our results are as follows. First, the level of R&D collaboration in the RT in Japan is overall low and dominated by inter-firm collaborations; but it has increased between 1991 and 2004, especially in the case of collaboration between firms and universities. Second, R&D collaboration has apparently a positive impact on the quality of the patents, but should be more carefully investigated. Third, we find a significant heterogeneity across firms in the practices of collaborations (number of collaborations, choice of partners and "fidelity" with the partners). Fourth, these patterns are tentatively explained by the structural characteristics of the RT (by reference to a transaction cost argument and to the role of science-based technologies) and by firms' capabilities hypothesis; however, it is not possible to clearly identify if one theoretical hypothesis is better supported by the facts.

Key words: collaborative R&D, robot technology, Japanese innovation system.

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Introduction

The topic of collaborative R&D is the object of an increasing number of economic studies. One reason comes from the fact that collaborative R&D is one of the least expected activities that companies would be willing to share with others, as it involves the core of their strategy. Another reason is that the cases of joint R&D have been increasing dramatically (Hagedoorn, 2002)[2]. At a very general level of understanding, this increasing trend of collaborative R&D is generally thought to be related to important industrial and technological changes in the 1980s and the 1990s that have led to more complex scientific and technological development, more uncertainty, higher costs of R&D projects, and shortened innovation cycles. In addressing this question more specifically, it is important to consider the motives of the firms in joining such collaborative arrangement. Among the theories aiming at explaining the existence of collaborative R&D, one usually distinguishes among three strands: transaction cost, strategic management and industrial organization theory. However, the empirical literature did not yet lead to stable results. To put it briefly, a lot has to be done to investigate the question of research partnership (Hagedoorn et alii, 2000). Better theories are required to explain the stylized facts; more empirical research has to be done, based on more accurate data than the surveys actually used.

Japan also experienced an increasing trend of joint R&D. This fact has been analyzed in many recent papers (Odagiri, 2003; Nakamura & Odagiri, 2004; Motohashi, 2005a & b; Nakamura & Ueda, 2006, among others). The main reason is that the Japanese innovation system has experienced drastic changes since the beginning of the 1990s. These changes have to be understood as the reaction by both private institutions and the government to their perception on the limitation of the former innovation system, which could be the main reason for the slowdown of productivity growth during the so-called Lost Decade (1992-2005). The former Japanese innovation system has been characterized by the predominance of "in-house" research conducted by very large companies (Odagiri, 2004; Motohashi, 2005a). However, it appeared to be increasingly difficult for Japanese companies to maintain their competitiveness by relying solely on "in-house" R&D activities. That is why, as many suggest, firms have been increasingly trying to seek a broad range of R&D collaborations with external organizations. The institutions that face this challenge also includes universities, which had not been active until recently, partly because the large companies which have their own research capabilities have spearheaded R&D efforts in a sort of "do-it-yourself" attitude (Motohashi, 2005a). This evolution has been analyzed by many studies, being large surveys (Motohashi, 2005b) or case-studies (Motohashi, 2005a; Odagiri, 2003; Nakamura & Odagiri, 2004). However, the case-studies almost exclusively focus on biotechnologies and pharmaceutical industry; moreover, the surveys are characterized by

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[2] Our definition of collaborative R&D refers to the one by the second European community innovation survey (CIS-2), "innovation cooperation means active participation in joint R&D and other technological innovation projects with other organizations. It does not necessarily imply that both partners derive immediate commercial benefits from the venture. Pure contracting out work, where there is no active participation is not regarded as cooperation".

both a very low ratio of answers (less than 10%) and a perspective which does not take into account the outcomes of the research alliances. That is why there is room for further investigation of this topic.

In this paper, we investigate this question through the case-study of the R&D activities in the case of the robot technology, based on a quantitative analysis of patent data, complemented by into-depth interviews. Robot technology indeed presents many interesting characteristics to analyze the evolution of collaborative R&D in Japan. First, this is a typical assembling industry, in which Japan has a leading position to this point to deserve the title of "robot kingdom" (Schodt, 1988). Second, the robot industry as a whole has been stagnated from the 1990s, while the robot technology has been experiencing major changes. These changes can be characterized by the development of next generation robots, which may operate outside the plant, in a random environment and in interaction with human. This new technology - which may lead in turn to the birth of a new type of industrial robot – is obviously more science-based. It is important to note that the object of our case study is not the robot industry as a whole but this new robot technology (RT), which did not yet lead to the production of successful products in the market and is only at a R&D stage. The R&D activities on service robot have so far failed to meet a latent demand and to create a new industry. Third, according to various reports (JARA, 2001 for example), the main impediment to the development of this industry is the lack of coordination among the players and the solution would be an increasing collaboration between the players. Fourth, the RT has been selected in the 2nd Basic Plan on Science and Technology (2001-2005) enacted by the CSTP (Council for Science and Technology Policy as one (among eight) of the top priorities of the new innovation policy. Fifth, the RT involves the main players of the Japanese innovation system (JIS): firms – including leading companies of the electrical machinery sector and the car industry like Toyota, Honda, Hitachi, Canon and Matsushita but also start-ups – universities and (local and central) government. Its evolution may be therefore representative of the current changes of the JIS. Last but not least, the RT in Japan has been the object of very few case-studies in Japan (the exception being Kumaresan & Miyazaki, 1999) since the seminal studies by Kondo (1986, 1990).

The questions we address in this paper are as follows:

- Did the R&D collaboration in RT increase from the 1990s?
- Do the R&D collaborations lead to a higher quality of the outcome?
- Is it possible to distinguish between different forms of collaborations and types of players (depending on their degree of collaboration)?
- How to explain the evolution of R&D collaboration, if any?

To answer to these questions, we principally adopt a quantitative perspective by analyzing RT related patent data from 1991 to 2004. Doing so, we focus on the outcome of the R&D rather than on the process itself, following a method increasingly used (Hagedoorn et alii, 2003; Giuri & Mariani, 2005). It gives us the opportunity to propose an evaluation of the quality of the outcome. This quantitative perspective is completed by a more qualitative approach, based on interviews (see the list of interviewees in annex 2), giving us the opportunity to interpret into more details our results.

This paper is organized as follows. In a first part, we present the an overview of the robot technology and industry. In a second part, we introduce our methodology and our database. In a third part, we show basic facts and results on the evolution of collaboration. In a fourth part, we assess the quality of collaborative and non collaborative patents. In a fifth part, we identity the different types of collaboration and of players from the point of view of collaboration. Finally, in a sixth part, we try to explain the patterns of R&D collaboration in the RT and the differences across firms.

1. The interest of the new robot technology (RT) as a case study

1.1. Defining robot and introducing the recent changes in the robot technology

It is important to first set a definition of some of the terms classifications related to robots used in this paper. It is difficult to have a satisfying definition of robots. We refer here to the one by METI (2005b): "robots are the machines that have a manipulation function or movement function by automatic control, and carry out various works by a program or operation".

Robots are usually classified into "industrial robots" and "personal robots". The characteristics of the two types of robots are as follows. Industrial Robots are normally fixed on a floor, surrounded by fences for security, are isolated from people, and do repetitive works. Personal robots have superior mobile functions to industrial robots, and work closely with people, and do not always do repetitive work. One way to categorize robots is to classify them by their uses. This type of classification can be seen in Figure 1.

Nowadays, Japan deserves to be called as the "robot kingdom" as it produces 80% of the total demand and holds around 60% of world robot stock (Schodt, 1988). However, the US and Europe boast advanced robot technology in non-manufacturing fields such as nuclear power, space, oceanic research, disaster prevention and medical/welfare application (JARA, 2001).

Recently, the Japanese robotic innovation system has been undergoing structural changes, which can be summarized as follows: drastic technological changes (development of next generation robots), diversification of the potential applications, and entry of new players. In particular, the recent technological changes make it possible to spread the uses of robots into non-manufacturing uses. It is possible to give some examples of newly invented robots in some fields of the sector: "Robots for families", robots helping for housework by independence movement and bidirectional communication (e.g. "PaPeRo" by NEC); "Medical care / care / welfare robots" (e.g. "My spoon" by SECOM); "Entertainment robots" (e.g. "AIBO" by Sony); "Service representation robot" (e.g. "Guard robot" by ALSOK).

Therefore, it is all the more interesting to analyze this change from an economic point of view that there are very few recent studies on this field (an exception being Kumaresan & Miyazaki, 1999)[3].

1.2 Players

A tentative and restrictive list of the major players in this field is given in the annex 1, based on METI (2005a). The three categories are private companies, universities, and government.

Private companies. As the definition of the new robot technology is itself a problem, it is not easy to classify the firms involved. Moreover, as the RT is a technology of integration, it is important to take into account not only the robots as finished products but also the components. Based on the annex 1, one can make the following comments. First, there are very firms specialized in robots (exception being Fanuc or Yaskawa). Most of the firms involved in the sector are large companies of the electrical machinery (Sony, Fujitsu, NEC, Matsushita, Hitachi, Omron), general machinery (Fuji Heavy Industries, Mitsubishi Heavy Industries), and transport equipment sectors (Toyota, Honda). For these firms, non-industrial robots are a potential for diversification. However, this first impression should be corrected by two other elements: there are some security service companies (Secom, Sougo Security Service) and the list does not include telecommunication companies like NTT and KDDI, yet involved in the personal robot sector[4]. Second, one should also underline the existence of small startups like Tmsuk or ZMP. According to evaluations by METI, the SMEs represent the half of the component makers. Nevertheless, if one looks at the finished products, result of the integration of various technologies, the market is over-dominated by very large manufacturing firms. Although there is no official information on personal robot business in private firms, it is possible to establish a ranking based on interviews and our own estimation. The personal robot business was dominated until the beginning of 2006 by a group of 3 main players, including Honda, Toyota, and Sony (which recently left the sector). A second group includes major players in the industrial robot sector like Fanuc, Kawasaki Heavy industries and Yasukawa. A third group is composed by very large companies of the electrical machinery sector like Fujitsu, NEC, Hitachi, and Toshiba. To summarize, among private firms operating in the personal robot industry, it is important to distinguish between at least 3 categories: large manufacturing companies (typically Toyota) venture business companies (typically ZMP) and service providers (typically SECOM). Finally, a last characteristic is that very few companies are selling their products; most of the companies are only at the R&D stage.

Universities. The number of universities and of research centers involved in the research on robots in Japan is impressive, as it appears in the annex 1. Not less than 44 institutions are directly involved in this research. It means that all the leading research institutions in Japan have at least a laboratory

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[3] For accurate data on recent evolution of the market and the technology, the JARA website (http://www.jara.jp/index.html) is particularly useful. They have not been reproduced here by lack of space.

[4] The main reason of their absence in this list is that, from the point of view of the robot industry, they are outside the scope of the classification by METI, as they depend on the MPHPT (Ministry of Public Management, Home Affairs, Posts and Telecommunication).

specialized in a field related to robots. Moreover, some institutions have many laboratories in robotics. For example, at Tokyo University, there are about 14 laboratories specialized in robotics. As the size and the specialization are very diverse, it is very difficult to establish a ranking. However, it is possible to distinguish some institutions: among the leading institutions, one can quote Tokyo University, Waseda University, Kyushu University, Ritsumeikan or Osaka University.

Government. We classify the major public institutions into central government, related agencies, and local government. The main government player in the sector at the central level is METI. It is possible to classify its contribution in two categories, the publication of reports (or "visions") on one side, the setting up and the funding of programs on the other side (especially through its agency for R&D funding, NEDO). They constitute the core of the public policy to promote the collaborative R&D in the sector. MEXT plays relatively less important role. This is because the current RT technology has passed the basic R&D phase and now entered the applied R&D phase. However, MEXT supports two specific types of technologies, the brain type computers and the rescue robots. As for the Ministry of Public Management, Home Affairs, Posts and Telecommunication (MPHPT), he plays an important role in the case of network robots. A coordination role within the robot industry is also plaid by local governments (especially by the Industry Promotion Division of the prefecture). In 2003, the robot special ward was set up in Fukuoka prefecture (Fukuoka-shi and Kitakyushu-shi). Similar projects were conducted in Osaka (robot city), Tochigi (robot valley), Kanagawa, Kobe, Gifu, Niigata and Nagoya. There, the role of local governments is important to support the constitution of clusters. The most developed and promising locations are certainly Fukuoka and Osaka.

1.3 The lack of cooperative R&D has been recognized as one of the most important issues that the players in RT are facing

Innovations in robotic technology have been incremental rather than radical, other than the invention of industrial, mobile and micro robots. Robotics generally is thought of having less science linkage compared to medical-related fields and other more science based fields. However, as revealed by the increasing trend of the paper to patent ratio, the linkage between science and technology in robotics has been growing. Increasing complexities in robotics technologies and higher level of technology convergence bring about the close integration of science and technologies (Kumaresan & Miyazaki, 1999).

The lack of cooperation at the R&D level is clearly not the only problem to transform the new robot technology into a new industry. Other problems are localized on demand and technological sides. However, this lack of collaborative R&D has been recognized as one of the most important impediments to the birth of this new industry. For example, according to JARA (2001), "Robots are systems, and as such contain many different forms of highly specialized technology. No one company can possibly handle all aspects of robots systems. A faster and more efficient way to develop robots products is for several companies to work together and pool their resources". From the characterization of the RT (see § 1.1), it appears indeed that no one company can deal with all highly specialized technologies of RT. This characteristic means that firms have to be more or less dependent on outside resources to develop a finished product. That is why R&D cooperation is a helpful method to develop RT. However, the conventional wisdom was until recently that this cooperation among firms has been relatively limited at least until 2001. That is why one of the main goals of the technology policy in the sector has been to promote this cooperation.

Our purpose is therefore to investigate this question of collaborative R&D from a quantitative point of view, based on patent data. To our limited knowledge, this study is the first one using this methodology in the case of RT in Japan.

2. Methodology and database

2.1 Use and abuse of patents

2.1.1 Merits -Why do we use joint applied patent data as a proxy for R&D collaboration?

As noted in the preceding part, it is very hard – if not impossible - to find direct data on R&D cooperation among firms, except through questionnaire surveys. Generally speaking, firms are very reluctant to disclose the relevant information on their cooperation with other institutions as it involves their core strategies. On the contrary, firms are keen to apply for patents quickly to get a right of invention (“first to file rule”). With this publicly available dataset of patents, one can identify the partners of R&D activity of firms which brought about patent application. Moreover, the information they contained is particularly valuable: they include, among others, the information on applicants, inventors, their addresses, citations, claims, and technological fields[5].

One important merit of the use of patents data has to be emphasized. According to Hagedoorn & alii (2000), the literature on this topic did not yet produce satisfying answers to the question of the benefits from participation in research partnerships. Besides case studies (generally showing very positive effects but submitted to problem of selection bias), the empirical evidence on this point is limited. One reason is that the methodology generally lies on questionnaire surveys with little information on the output of the collaboration. That is why the focus on patents (which is one output of R&D, among others) can be very beneficial. This is all the more the case since our database contains information relative to the quality of the patents (through information on claims, citations, inventors and technological fields).

In the economics of innovation literature, one observes a recent rise of interest in the use of patent information to quantify the R&D collaboration. For example, Hagedoorn - who contributed so

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[5] However, it is important to note that our database does not contain any information on firms’ characteristics.

much to the literature on research alliances based on surveys (see Hagedoorn & Van Kranenburg, 2003; Hagedoorn, 2002; Hagedoorn et alii, 2000) - recently investigated research collaboration based on patent data (Hagedoorn, 2003; Hagedoorn et alii, 2003). Basically, the starting point is to quantify the increase of joint patenting amongst companies (in the case of US companies between 1989 and 1998) and to investigate the reasons for this increase, which is rather paradoxical, as companies have a clear incentive to monopolize the property rights (Hagedoorn, 2003). Another example is the work by Giuri and Mariani (2005). They sent questionnaires to inventors in the European countries and constructed a database of patent inventors including 9,017 European patents (PatVal-EU). Then, they found that the percentage of co-applied patents is only 6.1% of the total number of the patents, but the percentage of patents developed in collaboration with other partners (from the point of view of the information on inventors) is 20.5%. This implies that the information on inventors is more relevant than the information on applicants, when one analyzes R&D collaboration. However, in spite of the usefulness of the information of inventors in the patent data, there are only few studies which examine inventors in Japan probably due to the heavy work required for its examination, as mentioned by Odagiri (2003): “More importantly, the collaborating researchers may opt not to appear as joint applicants. Particularly in universities, professors are often said to relegate patent rights to companies in return for research grants from them. In view of this fact, it is desirable to inquire into the names of joint inventors than joint applicants. Unfortunately, however, the affiliation of inventors is not given in patent documents and, hence, it is extremely difficult to investigate the extent of joint invention”. For example, Okada et alii (2006) conducts a detailed research on patents in Japan in the case of biotech patents and partly investigate the question of R&D collaboration. However, their focus is the assignees of biotechnology-related patents, not inventors, which is a limitation of their study from the point of view of the analysis of collaboration. To our limited knowledge, our paper is the first one in Japan to investigate systematically the R&D collaboration based on patent data analysis, focusing on inventors.

2.1.2 General problems associated to the use of patents data

Patents data are often used for the empirical studies on innovations as proxy for innovative activities. However it should be noted that there are a couple of limitations in using them. Jaffe and Trajtenberg (2002) point out two kinds of problems. First, the range of patentable innovations constitutes just a sub-set of all research outcomes: for a patent to be registered, it is indeed required to be “novel”, “non-trivial” and with potential “commercial application”. Second, firms may deliberately choose not to apply for patent but to keep it secret. Hence, not all patentable innovations are actually patented, because of this trade-off between patenting and secrecy.

Moreover, patenting is principally the activity by firms, and does not include those of universities and public research institutes. If the number of patent application by universities and public research institutes has recently increased in Japan following a change in the legal environment (e.g. “TLO Act” in 1998 and “Japanese Bayh-Dole Act” in 1999), patenting is however still a small part of the whole research activity conducted by universities, by comparison to publication of articles for example.

Furthermore, what one can observe by looking at the "inventors" of patent is "collaborative invention." An invention is defined as "collective invention" if more than one inventors who belong to different organizations are mentioned in the bibliography of the patent. It includes contract research, research grant, technology consulting, training, technology transfer, R&D service (e.g. testing), and use of patent (Motohashi, 2005b). On the other hand, "collaborative R&D" is defined as a research, for which at least two researchers - who belong to different institutions - work together on a common issue as equal partners, and is a more restrictive concept than that of "collaborative invention". The gap between these two notions is summarized in the figure 2.

Finally, we asked to our interviewees if the use of patent data in the case of RT is appropriate to quantify the collaborative R&D. They generally agreed with this idea. Yet some of them answered that patent data is insufficient to recognize the complete trend of R&D collaboration because of the following reasons: 1) the collaboration supported by government leads to biased results, because government urges the participating firms to obtain patents, as it the way to evaluate the outcome of the project; 2) professors of universities (especially public ones) would like to write a paper before firms apply for patents; thus, there is a possibly that the collaboration with national universities are underestimated; 3) patents are basically outputs by firms because of the necessity of commercial application. For this reason, some interviewees from the academic sector advised us to use the data related to the number of articles published in the RT field. We do not follow this road as our focus is on the firms' research activities, eventually in collaboration with universities.

2.2 Methodology - How do we classify patents through the information on inventors?

As already noted, we utilize the information on applicants, inventors and their addresses to identify R&D collaboration. Through checking these pieces of information, we can classify the types of collaboration into different categories, mainly firm only, firm & firm, firm & university. In this section, we explain the methodology and give some examples.

2.2.1 General principles

The items that we use to classify the type of R&D collaboration are as follows: applicants, inventors, and their addresses. One problem of using the inventors' information is that the names the institutions to which the inventors belong are often not specified. Thus it is often hard to identify the institutions. In this case, we try to identify the inventors through various search engines (including ReaD, the search engine by Japan Science and Technology Agency, JST). Through this classification, we can recognize the trend of R&D collaboration.

We categorized players into three categories: firms, universities and public research institutions (mainly AIST, Riken and JST). Then, we classify the patents by type of collaboration from the inventors' point of view. We have 10 possible cases (figure 3). Three cases are non collaborative inventions: one firm only, one university only, one public research institutions only. Three other cases are collaborations with partners of the same nature: collaboration between firms, collaboration between universities, and collaboration between public research institutions. Finally, we have four cases of collaborations with partners of different nature: firm(s) and university(ies), firm(s) and public research institution(s), university(ies) and public research institution(s), firm(s), public research institution(s) and university(ies). In doing so, we put in the same category the cases with two players and more than two players: for example, at the final stage, we do not distinguish collaboration between four firms and one university on one hand and collaboration between one firm and two universities.

2.2.2 An Example

The followings are some examples of identification of the type of R&D collaborations by using the patent data. We take Tmsuk as a reference. Tmsuk is a venture firm based in Kyushu which typically collaborates with various firms in order to supplement its R&D capability[6]:

Case1 - Firm ONLY- (*apn=2004348050, name of invention: A robot system with two arms*): We find the records of the names of five inventors in the patent. Their addresses are written and the institution to which they belong is directly observable. We easily found that the inventors are researchers from Tmsuk.

Case2 - Firm & Firm- (*apn=2001144494, name of invention: A monitor robot system*): This patent includes two inventors; we identified that one of them as a researcher from Yokogawa Electric Co. and the other one as a researcher from Tmsuk, in looking at applicants and their addresses.

Case3 - Firm & University- (*apn=2003400775, name of invention: A walk robot with four pairs*): This patent includes four inventors. Three of them can be identified easily as researchers of Tmsuk by their addresses. Yet the last one cannot be identified with this information. Finally, by using search engines, we found that he is a professor of Waseda University, Prof. Takanishi.

2.3 The dataset

2.3.1 Data sources

We use two complementary data sources: Industrial Property Digital Library or IPDL ("koho text kensaku") and Standardized Data ("seirihyojyunka data"). The data of IPDL enable us to clearly classify 4 macro and 26 micro technological fields of RT (figure 4). However, for some reasons[7], JPO does not give information on 6 categories ("other robot", "modular structure", "attachment", "control unit to operate with a foot", "virtual reality", "and networking technology"). So we limit the analysis to 20 technological fields.

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[6] In what follows "apn" means application number.

[7] We could not receive any satisfying answer from JPO about this selection. This is certainly due to identification problems for the 6 concerned technologies.

Moreover, IPDL only covers the patents from around 1991 and does not contain the information on citation. Contrary to this, Standardized Data include the information on citations. Yet we cannot clearly identify the RT related patents, and it covers patents until around 2001. Therefore we merger these two data sources to get a more complete dataset.

2.3.2 Contents of data

We collected 16,767 patent numbers through IPDL (12,863 patents of the total are matched with Standardized Data). The data include patents from 1989 to 2004. Yet, only a part of the patents of 1989 and 1990 are included. Thus, we excluded the data for the years 1989 and 1990 and ended up with 16,736 patents data.

Each one of patent data includes the following pieces of information:

- patent numbers (application, registration),
- dates (application, priority),
- applicants and their addresses,
- inventors and their addresses,
- backward and forward citations (the number of patents which inventors cited to develop the invention and the number that a patent is cited by other patents in the future),
- claims (which includes description sentences that specifies the range of invention for which applicants demand protection by a patent),
- the number of inventors (the total number of inventors in patents),
- the technological classifications (4 macro and 20 micro classification, from the International Patent Classification) and the technological scope (total number of technological fields - 20 micro classifications - of a patent).

Citations are usually used as a proxy for the quality of patents, but there is a truncation problem (time lags for citation). Thus, we supplement them with other data, claims, the number of inventors, and the number of technological scopes.

3. Basic Facts and evolution of the collaboration

3.1 Basic facts

Among the 16736 RT related patents that have been applied in Japan between 1991 and 2004, 279 cases have been excluded, as we could not identify the inventors. Moreover, 1000 of them have been applied by non Japanese institutions and are not considered in our analysis, as we are focusing on the behavior of Japanese players. The number of patents we are analyzing is therefore 15457 (eventually 16457, when one considers also patents applied by non Japanese institutions).

We first present some basic results about the evolution of RT related patents. According to figure 5, the total number of RT related applied patents decline between 1994 and 1999 and between 2001 and 2004. The decrease between 2001 and 2004 can be explained by the lag of application and should be therefore related to technical reasons rather than to a technological trend. However, claims, the number of inventors, the number of technological scopes do not decrease as much as the total number of patents. As a result, these variables analyzed by patent are at least stable (inventors and technology field) or increasing (number of claims) over time. As it can be seen below (§ 4), these variables are proxies for the quality of patents. However, in the case of two other proxies for the quality of patents, the forward and backward citations, these numbers are declining dramatically, which indicates a classical truncation problem (Jaffe & Trajtenberg, 2002).

If we look at the macro classification level (figures 6-9), we can see that the patents of "partial structure technology" suddenly decrease after 1994. One observes a similar evolution for the control technology patents, but less dramatic. Thus, the decreasing trend of the total number of patents can be explained by the decline of these two types of technology. On the contrary, total structure technology and outside environment technology related patents relatively increased[8].

If one decomposes the 4 macro classifications into 20 micro classifications, it is possible to analyze the evolution in detail (figures 6-9). In most of the cases, the number of patents is stable or declining over time. There are, however, three clear cases of drastic increase: "mobile robots", "sound recognition" and "image processing" related patents (after 1999 in this last case). It is important to note that these three technologies are those of the five "science based" technologies which are classified by JPO (2006) and are closely related to the development of next-generation robots[9].

Therefore, an important question is to check if the decrease of partial technologies related patents and the increase of next-generation robots patents are going hands to hands with a relative increase of R&D collaboration (§ 3.2). Moreover, it is possible to check more carefully, if the quality of patents related to collaborative R&D is higher than the cases without collaboration (§ 4). By exploring these two questions, it will be possible to interpret the mechanisms at the origin of the observed evolutions.

3.2 Evolution of the collaboration

Among these 15457 RT-related patents, which have been applied in Japan between 1991 and 2004, 13702 (89%) have been applied by only one company. Therefore, the number of collaborations is strictly limited. However, if we look at the evolution between 1991 and 2004, we clearly see a

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[8] Once again, one generally observes a decreasing trend after 2002, due to missing data because of time lag in the application process.

[9] The classification by JPO (2006) is very exploratory and unsystematic. Contrary to classical studies in this field (e.g. Gemba et alii, 2005), it does not lie on the construction of a science linkage index. This is based on interviews of experts of the field and on the recognition that the published academic articles in these fields have increased drastically recently. One should not forget this important limitation, while interpreting the results on increasing collaboration and determinants of the increase (§ 6).

decreasing trend of the “F” type patents - from 91.5% in 1991 to 85% in 2004 - and an increase of collaboration cases - from 7.4% in 1991 to 9.9% in 2004, or on average, 8.4% between 1991 and 1999, against 9.9% between 2000 and 2004 (table 1).

If we now focus on the 1391 cases of collaborations between 1991 and 2004, we find that the large majority of collaborations are between 2 or more firms (69%)[10]. As for the other cases of collaboration, 18% are between firm(s) and university(ies), 8% between firms and public research institution(s) and 3% between university(ies) and public research institution(s), the other cases being negligible (table 2).

Whatever the type of collaboration one considers, the majority is between two partners only: 93% in the case of FF, 87% in the case of FU and 86% in the case of FP. Regarding the difficulty of collaboration and of sharing the property rights between many partners, this result is not surprising and confirms the one by Goto (1997).

If one now looks at the evolution by types, one observes the collaborations between firms are relatively declining, as well as the collaborations between firms and public research institution(s). On the contrary, the cases of collaborations between firm(s) and university(ies) are increasing, especially from 1997 (from 14% on average between 1991 and 1996 to 22% on average between 1997 and 2004). This impressive trend should be however carefully analyzed as this result depends heavily on the figure in 2003 (44%), which is potentially an outlier (figure 10).

4. Assessing the quality of patents

As indicated in the last part, there are at least four indicators of the quality of patents: number of claims, the number of (backward and forward) citations, the number of inventors and the number of technological fields. Here we proceed in three steps, considering first separately these indicators, constructing then a composite index based on these indicators (following Lanjouw & Schankerman, 2004) and finally proposing an econometric estimation allowing us to control the differences in propensities by players.

4.1 Claims, citations, number of inventors and of technological fields

The **claims** in the patent specification delineate the property rights protected by the patent. The principal claims define the essential novel features of the invention and subordinate claims describe detailed features of the innovation. The patentee has an incentive to claim as much as possible in the application but the patent examiner may require that the claims be narrowed before granting. Most of

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[10] Moreover, for these cases, the label “external collaborations” should be carefully used as a first impression (to be confirmed by further analysis: see § 5.2) is that these collaborations are often between two companies belonging to the same group.

the recent studies consider that the most important index on patent quality is the number of claims, except for some specific industries like the drug industry (Lanjouw & Schankerman, 2004). The larger is the number of claims, the broader and the greater is the expected profitability of an innovation. What can be learned from the analysis of the number of claims per patent (table 3)? First of all, the cases "UU", "PP" and "FUP" should be excluded from the analysis, as they are characterized by many missing values (ND). As for UP cases, there are a little less missing values but the overall number of patents is quite small, so that the interpretation of the high number of claims per patent should be interpreted carefully. If one looks first at non collaborative R&D, the quality of "F" and "P" is relatively low (respectively 5.3 and 5.7 claims per patents on average), but recently the quality of "F" has gradually increased from 2.5 claims per patents to a number comprised between 7 and 8. As for the patents applied by only one university, they are simply the highest (6.9 on average) and their quality has increased (from 6.4 on average between 1991 and 1997 to 7 between 1998 and 2004). From this point of view, there is not so much difference with the cases of collaboration between university(ies) and firm(s) ("FU" type), which has on average on the period 7 claims per patents. From the point of view of the firms, the collaboration with one or more universities leads to higher quality than in the cases of collaboration with one or more firms (“FF” type: on average 5.7), with public research institute(s) (“FP” type: on average 5.1) and no collaboration (5.3). Moreover, one observes an impressive increasing trend of claims per patent in the case of FU, from 4.4 claims per patent on average between 1991 and 1999 to 10 between 2000 and 2004.

The most commonly used variable to analyze the quality of the patents is the number of **citations** (for example, see Nagaoka, 2005). An inventor must cite all related prior patents. Then, a patent examiner is responsible for insuring that all appropriate patents have been cited. Like the claims, this information identifies the rights of the patentee. For each patent (taken from IPDL and matched with Standardized Data, which contain the information on citations), we obtained the number of prior patents cited in the application (backward citation) and the same information on all subsequent patents that had cited a given patent (forward citation). In the case of citations, there is an important problem of data availability. First, only data before around 2000 are available (because only Standardized Data cover the information on citations). Second, there is a citation lag in the case of forward citation)[11]. Thus, the main result is that the quality of patents as measured by (backward and forward) citations is higher in the case of (non collaborative and collaborative with private firms) R&D done by public research institutions (tables 4 & 5). However, it is difficult to interpret this result, as the sample data are apparently small before 1999.

The next proxy for the quality of patents is the **number of inventors** per patent. More precisely, this variable is a proxy for the scale of a research project and the accumulation of human capital: the larger is the number of inventors of a patent, the bigger is the research project. If the

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[11] This is one of the reasons for which we should in fact consider very carefully the information on forward citation.

project is big, players invest much money and human capital (knowledge). According to Goto et alii (2006), this variable is directly related to the quality of patents. In this case, our results are very clear: non collaborative R&D leads to lower quality patents, whatever the player one considers, on average 2, 1.9 and 2.5 respectively for the “F”, “U” and “P” types (table 6). Again, it is impossible to analyze UP, PP, UU and FUP types, as many values are missing. Therefore, we focus on types of collaboration involving at least one firm: the numbers are respectively 3.6, 4.5 and 3.8 for the FU, FP and FF types of collaboration, that is almost double that the type with only one firm. Therefore, from this point of view, collaboration leads to higher quality patents. However, these results should be interpreted carefully, as R&D collaboration involves by definition more than one inventor… That is why we compare the collaborative cases to the non collaborative cases excluding the cases with only one inventor for “F”, “U” and “P”. The “corrected” non collaborative cases lead to higher numbers of inventors per patent than without correction (respectively 2.9, 2.8 and 3.5), but still lower than the collaborative cases, without any exception.

The fourth proxy is the **number of technological fields** per patent. If a patent covers a wide range of technological fields, it has usually many claims and will be easy to be cited by other patents in the future. Again, because of data availability, we focus on non collaborative patents and on collaborations involving at least one firm. In this case, the clearest result is that the patents applied by public research institutions on one side and by firms which collaborate with universities on the other side are of higher quality from this point of view than the other types of patents, collaborative and non collaborative ones: respectively 1.46 and 1.40 for “P” and “FU” types, against 1.32, 1.36, 1.30 and 1.29 for the “F”, “U”, “FP” and “FF” types (table 7). However, the significance of these numbers is again difficult to interpret.

4.2 Composite index

As a whole, the results above are not completely clear, as they depend on the proxy we consider. That is why, following Lanjouw and Schankerman (2004), we try to build a composite index based on these five indexes (claims, backward & forward citations, inventors, technological scope). The most crucial question is of course about the respective weights of these indexes. We calculate the weights, based on the former results: they indicate that R&D collaboration ("FU", "FP", "FF") lead to higher quality of patent than non collaboration, except in the case of "P". Considering this fact, we construct composite indexes by principal component analysis (all data are normalized considering their averages and standard deviations)[12]. More precisely, we build three composite indexes: one based on the five

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[12] In their study, Lanjouw and Schankerman (2004) find that the number of claims was the most important index of the patent quality and give it a weight of 50%. The other indexes are each given a weight between 15 and 20%. In our study, we got the following weights. In the case of the composite index1: Claims (38%), Inventors (32%), TechScope (30%); in the case of the composite index2: BackwardC (26%), ForwardC (24%), Claims (23%), inventors (21%), Techscope (6%); in the case of the composite index3: ForwardC (37%), BackwardC (36%),

indexes but for a sub-period (1991-1997) because of lack of data concerning citations; another one based on only three components (claims, number of inventors and number of technological fields) but for the whole period (1991-2004); a third one based on only three components including citations and for a sub-period[13]. Our findings are as follows (tables 8 and 9). First, as expected, R&D collaborations lead to higher quality of patents. Among these collaborations, "FP" type generates the most valuable patents. Second, apparently, "F" type generates lower quality of patents. Among non-collaboration, "P" type lead to higher quality. These results are therefore consistent with the results of the analysis of the five indexes considered separately.

4.3 Econometric estimation

There appear to be different propensities of patent applications and claims for each player. The preceding analysis based on the average per patent is biased, if there are outliers. Yet, it is possible to remove this bias by constructing panel data as follows:

$$Quality_{ijt} = f(dummy_{ijt}, Z_{ijt})$$

where i is the patent number; j, the first applicant ID[14]; t, the year; Quality, one of the composite indexes; dummy, the type of patents (F, FF, FU, U, P, FP, FUP); Z, the other characteristics of the patents (e.g. the number of inventors, year dummies, technological scope).

Here, we present 4 estimates (table 10). In all the cases, Hausman test conducts to prefer the fixed effects model to the random effects model. Our results are as follows. If we look at the results on quality1 and quality2, collaboration (especially FU and FF) leads to higher value of patents after controlling individual fixed effects. For example, if we look at the coefficient of FU, the quality of FU patents is higher than that of F patents (about 0.615 and 0.467 respectively). However, if we consider the composite index 3 (index based on claims, backward citations and forward citations), there is no difference between collaboration and non-collaboration (no significant coefficient), without including the number of inventors. This implies that collaboration does not actually generate higher quality of patents and that the number of inventors affects the quality (consistent with Goto et alii (2006), Giuri & Mariani (2005)). Actually the coefficient of Ninventors (the number of inventors) is significant at 1% level in the equation of quality3. Collaboration usually includes many inventors, so collaboration indirectly affects the quality, not directly.

Claims (27%). From these results, we see that the information on citations is important in our database. Unfortunately, as recalled above, Standardized Data are incomplete from this point of view.

[13] The third composite index is only used in the econometric estimation.

[14] The best way to construct player ID is to focus on the “first applicant” because property rights of patents belong to applicants. However, we found that our database (especially Standardized Data) is incomplete concerning the applicants: some of them are missing or include errors. On the contrary, there are apparently few errors concerning “first inventor” ID (their belonging institutions). Moreover, the institutions that the first inventor belongs to are usually the same than the one to which the first applicants belongs to. That is why we focused on “first inventor” ID.

As a whole, our conclusion about the impact of collaboration on patent quality is essentially negative. Our results lead to a call for further research in this area. In particular, it is difficult to conclude based on patent data which are only weighted by citations on the effect of collaboration on the quality of patents, as Nakamura & Ueda (2006) do, for example, in the case of collaboration between firms and universities.

5. Identifying the different types of collaboration, the collaborative players and the non collaborative players

5.1 The most active patenting institutions

If we consider the individual players it is first possible to identify which institutions have been the most active in applying RT related (collaborative and non collaborative) patents between 1991 and 2004 (table 11). In the cases of firms, we find the following ranking: Matsushita Electric Industrial Co., Ltd (694 patents), Sony (686), Yaskawa (468), Fanuc (434), Toshiba (367), Mitsubishi Heavy Industries (335), Mitsubishi Electric (292), Honda R&D Co. (272), Hitachi (255), Fujitsu (215), Kawasaki Heavy Industries (205). These results are a little different from the hierarchy currently admitted by the main players themselves (§ 1.3): in particular, Toyota is absent from this list, and Honda is not in the top five companies; it means that the patenting cannot be by itself an absolute criterion to classify the players (especially because of the trade-off between patenting and secrecy recalled above). As for the universities, the results are as follows: Tokyo University (24), Tokyo Institute of Technology (19), Waseda University (9). Finally, in the case of public institutions, we have the following ranking: AIST (77), JST (21), Japan Atomic Energy Agency (4).

We then try to identify the most collaborative players by type of collaboration.

5.2 The FF type of R&D collaboration

In the case of the FF type (collaboration between at least two private companies), the top six collaborative companies are (table 12): Hitachi (86 cases), Toshiba (78), Toyota (78), Sony (75), Yamaguchi Robotics Research (42), Mitsubishi Electrics Co. (37). With the exception of Yamaguchi Robotics Research, whose collaborations are essentially with Sony (which is not surprising as this institution is directly related to Sony, even if external to Sony group), the most collaborative companies with other private companies are the biggest ones, from the point of view of the absolute number of collaborations. If one looks at the percentage of collaborative cases relative to all the applied patents, the picture is a little changed: Hitachi (24% of collaborative patents for a total number of 352), Toyota (28%, 277), Toshiba (16%, 470), Sony (9.8%, 769), Mitsubishi Electric Co. (11%, 334). If we create a ranking of the most collaborative private firms based on the percentage of collaborative patents (with more than 10 patents), we find the following results (table 13): Chubu Electric Power Co. (100%, the total patents are 14), East Japan Railway Company (100%, 12), The Tokyo Electric Power Co. (94%, 19), Kyushu Electric Power Co. (92%, 25), Hitachi Keiyo Engineering (91%, 34), Tokico Giken (81%, 11), Toshiba Engineering Co. (67%, 18), Yanmar Co., Ltd (60%, 15), Obayashi Co. (58%, 12), Toyota Central R&D Laboratories (58%, 48). These companies are either companies with very little capability in the RT (e.g. Chubu Electric Power, East Japan Railway Companies) or R&D companies related to a very large player (e.g. Hitachi Keiyo Engineering, Toyota Central R&D Laboratories).

At this stage we should recall that the JIS as a whole has been characterized by the fact that large share of R&D collaboration are done within the boundaries of the group, keiretsu type or others (Goto, 1997). That is why it is important to qualify the former results by evaluating the respective shares of external and internal collaborations among all the cases of collaborations between firms. This is not an easy task as it depends fundamentally on our definition of the "group". We do not refer here to the notion of *keiretsu*, which has been criticized and which experienced drastic changes during the 1990s. We define the internal collaboration as the one with the firms in their same groups and external as the one with firms that are outside of their groups. The definition of group firms varies from company to company. It usually includes subsidiary firms and affiliated companies and sometimes firms with long-term transaction and human interconnections. We used this definition as the relevant information, which is readily available at the companies' homepages; it corresponds therefore to the companies that firms subjectively recognize as closely related. For example, in the case of Toyota, we include eighteen Toyota group companies (Toyota group in the wide definition) and the members of its two supplier company association (Kyohokai and Eihokai).

Another difficulty is related to our data, which do not contain any information on the relationship between the firms, except their R&D collaborations as measured through joint application for patent. That is why we limited our investigation to 8 representative firms: Hitachi, Toshiba, Toyota, Sony, Mitsubishi Heavy Industries, Mitsubishi Electric, Yasukawa and Nissan (table 15). Without surprise, the first result is that, globally, the internal form of collaboration is dominant. The second result is more striking: we found a strong heterogeneity among the cases we considered. To put it simply, we have 3 types of cases. First, Hitachi, Mitsubishi Electric and Mitsubishi Heavy Industries rely heavily on internal collaboration. Second, in the cases of Sony, Yasukawa and Nissan, the external collaboration is dominant[15]. Third, internal and external collaborations are balanced for Toyota and Toshiba. Even if, to our limited knowledge, it is not possible to relate this result to former analyses of the collaboration strategies of these firms in other field of R&D and their determinants, it seems possible to conclude to a structural heterogeneity in their collaboration strategy, at least in the

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[15] For Sony, the results should be particularly carefully interpreted as they depend on the 39 cases of collaboration with Yamaguchi research institute, an independent company headed by a former engineer of Sony, who owns Sony's patents.

case of RT. It may be related to structural differences of resources within the group across leading companies. It may also be related to differences in the motivations of the companies in being active in the RT as well as collaborating with another institution. However, due to limitation in our data and in our definition of group, these results should be interpreted carefully. Here again, there is room for further research.

Another important distinction is between horizontal (among the final product makers) and vertical collaborations (between final product maker and component makers, users). There are many cases of vertical cooperation (for example between Yaskawa and Toyota, or between Yaskawa and Kyushu Electric). However, the cases of horizontal cooperation seem to be very rare if not inexistent. In fact it was impossible to clearly distinguish them based on our database.

A related question concerns the “fidelity” of this collaboration. Do the firms more or less collaborate with the same players or do they have many partners at the same time or through the time? To our limited knowledge, very little has been done on this topic. One exception is the exploratory study by Hagedoorn et alii (2003), which is indirectly concerned with this topic. Their initial question is to know if research alliance affects the sharing of intellectual property (joint patenting). Their result is quite surprising as they show that the degree of joint patenting of companies is not directly related to their experience with formal R&D partnering, not even for a group of companies that is heavily involved in both joint patenting and formal R&D collaboration through alliances. However, they show at the same time that the history of companies in joint patenting with a variety of partners indicates that firms may strategically select the joint patenting option and that they may have mastered the necessary knowledge relevant to arrange joint patent applications. It could be potentially an explanation of the heterogeneity across firms. Back to the question of fidelity, based on a strictly limited sample of 8 companies (Hitachi, Toshiba, Toyota, Sony, Mitsubishi Heavy Industries, Mitsubishi Electric, Yasukawa and Nissan) we analyze the continuity of collaboration with various players. In the table 16, we calculated the total number of partners for our sample of firms. On average, they collaborated with more than 20 firms and applied jointly with them 2.5 patents. It means that they often collaborate only once with a given partner: on average 16, that is always more than 50% of the total number of partners. From this, we can conclude that our sample firms generally collaborate with a variety of firms, without concentrating on some particular partners. However, there appear to be some differences across firms: for example, the average number of collaborating patents by partner appears to be relatively high for Sony (3.6) and low for Mitsubishi Heavy Industries (1.8). The same can be said if we look at the number of partners collaborating only once: they represent approximately 50% for Sony and 90% for Nissan. This heterogeneity across firms is confirmed if one looks into more details (table 17). In four cases (Hitachi – Hitachi Keiyo Engineering & Systems; Toyota – Toyota Kôki; Mitsubishi Heavy Industries – Seiryo Engineering; Mitsubishi Electric – Mitsubishi Electric Mechatronics Software Corporation), we have typically a close and long term R&D collaboration. For these four cases, we have at the same time a high percentage of collaborating patents with the same partner (ranging from 1/3 to ¼) and high number of years of joint application (meaning that the intense collaboration was not concentrated on few years). These four cases can also be characterized as follows: the partners belong to the group (case of internal collaboration); they have specific capabilities that are related to the R&D in robot (such as robot technology, energy plant and machinery). The nine other cases depicted in the table 18 are also characterized by close and long-term relationships, but less than the former two cases. The partners are obviously selected for their specialties (as in the other cases). However, in another four cases involving Sony, Nissan and Yaskawa, the collaborations are external.

5.3 The FU type

With regard to the collaborations between firms and universities (FU type), the most collaborative universities are respectively (table 12): Tokyo University (33 cases), Tokyo Institute of Technology (23), Waseda University (17), Nagoya University (11). Concerning this point, it has been pointed out that the so-called “corporatization” in 2004 of national universities should facilitate the collaboration with private companies. What our results show is that, prior to this 2004 reform, national universities like Tokyo University, Nagoya University and Tokyo Institute of technology already collaborated a lot with private companies. From the point of view of firms, Toyota is the most collaborative firm with universities (10 cases). It is followed by Tmsuk, Sony, Rhythm Watch Co., Fujitsu, TechExperts Co., Iseki & Co. (manufacturer specializing in farming machinery) if one considers again the absolute numbers.

If we looks at the percentage (players with more than 10 patents), the picture is changed (table 13). As for the universities, Nihon University (75% of the 12 patents are applied in collaboration with one or more private companies), Tohoku University (67%, 15), Nagoya University (64%, 17), Waseda university (61%, 28) are the most active players. They are followed by Tokyo University (52%, 63) and Tokyo Institute of Technology (51%, 45). As for the privates companies collaborating with universities, if Toyota, Sony and Fujitsu are active from the point of view of the absolute numbers, this is less the case in term of percentages, which are respectively 4% (of a total number of 277 patents), 0.8% (769) and 2.7% (226). From this point of view, the small companies are more active: this is the case for Tmsuk (41%, 17) or Rhythm Watch Co. (70%, 10). This is also the case of specialized companies, which obviously need some capabilities, which may be found in the universities: THK Co (38%, 13), Iseki & Co. (23%, 26), Ube Industries (20%, 15), Tokai Rika Co. (21%, 14), Kajima corporation (15%, 20), Nitta Corporation (12%, 17). As a whole, we confirm the results by Wen and Kobayashi (2001), who found that the most collaborative institutions are the biggest and the most famous and that the proximity to a cluster plays also a role for second rank universities and companies; however, it is important to add that the search for complementary resources or capabilities seems to be also an important motive to collaborate for small or specialized companies.

5.4 The FP type of collaboration

Next, we analyze the FP type of collaboration (between at least one firm and at least one public research institution). In absolute term, the most collaborative public research institutions are (table 12): the AIST (18 cases), Japan Atomic Energy Agency (13) and the National Agriculture and Food Research Organization - NARO (10). The case of AIST is particularly interesting: one of its institutes, the ISRI, is famous as being the leading research institution in the field of next generation robots. Therefore, it is not surprising to find it as the most collaborative institution, in an absolute term perspective. But in a relative perspective the results are less impressive (table 13): in fact, most of the patents applied by AIST have been not collaborative (P type): 77% (77 of 100 patents). As our sample covers the years 1991-2004, it is impossible to check if the former public status of AIST has hindered the collaborations with private companies and if the reform of its status in 2001 and 2005 contributed to change this situation. As for the companies collaborating the most with public research institutions, the most collaborative are respectively Toshiba (21 cases) and Kawasaki Heavy Industries (13). In these two cases, this is clearly the result of the participation of these two companies to many government sponsored collaborative research project, especially through NEDO (the R&D agency of METI) programs.

5.5 The less collaborative players

Then, we try to identify the less collaborative players among the firms with more than 100 patents (table 14). They are Mazda Motor Co. (0.8%, 1 patents related collaboration of 130 total patents), Matsushita Electric Works, Ltd (0.9%, 1 of 115), Ricoh Company, Ltd (1.5%, 2 of 135), Matsushita Electric Industrial Co., Ltd (1.6%, 11 of 707), Fanuc Ltd (1.8%, 8 of 442), Shinko Electric Co (1.8%, 2 of 112), Canon (2%, 3 of 153), Sanyo Electric Co. (2.7%, 4 of 152). This result confirms a great heterogeneity of behavior from the point of view of R&D collaboration. However, at this stage, it is difficult to give a stable interpretation, as our database does not allow us to analyze the individual characteristics of the companies, which may be a part of the explanation.

5.6 Heterogeneity across firms from the point of view of collaboration: a synthesis

The analysis above leads us to explore a structural heterogeneity across firms from the point of view of collaborative R&D. To provide a more complete picture of this stylized fact, we selected 13 major private players and put together their figures in term of F, FF and FU types of patents in absolute term as well as in percentage, for the whole period and by sub-periods (1991-1999 and 2000-2004). The total of patents applied by these 13 companies is 4945, that is 33% of the total patents applied by private firms between 1999 and 2004 (sum of F, FF, FU, FP and FUP types). The percentage of F type patents for the whole period ranges from 98% for Matsushita to 68% for Toyota (on average, the figure is 89%). Companies like Sony Mitsubishi HI or Mitsubishi E are just in the average, whereas companies like Hitachi, Toshiba or Kawasaki HI are much more collaborative and companies like Matsushita EI, Yaskawa, Nissan, Fujitsu, NEC or Honda are much less collaborative (in term of percentage of F patent type). Moreover, the evolution between the two periods is very contrasted: the behavior of a company like Yaskawa has been stable (94% of patents for the two periods), while some companies like Matsushita EI, Hitachi, NEC, Mitsubishi E or Honda R&D have followed the overall trend towards more collaboration and some others like Toshiba, Toyota, Mitsubishi HI, Nissan, Fujitsu, Kawasaki HI have been much less collaborative during the second sub-period. One possible reason of this contrasted evolution is as follows: one can image that companies like Toyota or Nissan, which have been active relatively lately in the RT, have first learned from others through collaboration, because of an initial lack of capabilities, and then developed their capabilities in-house. Of course, this explanation does not hold for companies like Honda R&D or Toshiba. This point requires further investigation.

More generally, based on the theoretical literature (complemented by the results of our interviews), the next part tries to identify some key explanations of these patterns. Especially, we try to explain both the general trend and the differences across the firms.

6 How to explain the patterns of R&D collaboration in the RT and the differences across firms?

6.1 Methodology

In this part, we focus on the last question we addressed in the introduction: what are the factors of / impediments to increasing R&D collaboration? We also try to identify the motives of the firms to collaborate (or not) with specific partners. As noted in the introduction, most of the studies aiming at answering to these questions are based on large scale questionnaire surveys or on very specific case studies limited to few companies (Hagedoorn et alii, 2000). Our perspective is rather different as it is quantitative, based on patents data. These data are objective (they tell us about the outcome of collaboration not about the opinion of an employee of a company) but also incomplete (not all the cases of collaboration are covered) and indirect (the players do not answer about their motives). That is why, to analyze the causes of the increasing collaboration, we complete our study by interviews, that is a more qualitative and interpretative methodology. Between March and December 2006, we have conducted nineteen into-depth interviews with major players involved in the RT (annex 2). Our interviewees are persons involved in the R&D activities in the firms and research institutions, people in charge of policies related to robot industry in the central and local governments, and university professors who are specialized in RT. We use these interviews to interpret our data and to understand more technical issues related to the RT.

Generally speaking, the empirical literature which analyzes the causes of evolution of R&D collaborations mainly try to investigate the motives of the firms in participating such collaborative agreements and their characteristics. Our database as well as the nature of RT related R&D do not allow us to investigate this last point. Our data do not contain any information on firms' characteristics; to analyze them would require merging our database with another one, like the BSBSA, an administrative survey by METI, whose access is strictly limited. Even in this case, we would not have satisfying results as many players are very small, and are obviously not surveyed, even in an extensive administrative survey like the BSBSA. Moreover, as most of the RT related patents do not correspond to a mature technology and to the main business of the largest players (Hitachi, Toshiba, Toyota, etc.), the meaning of general data like the size of the company is doubtful. The most valuable information in this case would be the size of the R&D department involved in this specific research. However, as shown in the first part of this paper, this information is very confidential and only roughly known. Concerning the motives of firms which collaborate with other institutions, the interviews helped us to investigate this point, but of course on a limited scale.

That is why we adopted following perspective. Based on our data (and with the complement of the interviews), we try to investigate the validity of each main theoretical argument. However, it appeared very difficult to empirically test different theoretical explanations. To our limited knowledge, there is no convincing paper providing an empirical method enabling to test one theoretical explanation against one another. For example, Odagiri (2003) tries to test transaction cost theory versus firm's capabilities argument to explain the increasing R&D collaboration in the case of 10 Japanese large pharmaceutical companies. He typically cannot provide a direct test and basically consider the cases of collaboration with foreign firms as a counter-argument to the transaction cost theory. Moreover, the simple opposition between two theories is questionable as other theories are alternative candidates. To overcome this kind of limit, we will rather try to find arguments and counter-arguments supporting or contradicting each theory.

It is even not necessary to mention that what follows is very exploratory. The evidence we show is often based on few examples and according to some criteria, which require further discussions. Doing so, we hope to stimulate further research in this field based on the same type of database.

6.2 From theoretical insights to a new formulation of our question and of the alternative hypotheses

6.2.1 Theoretical arguments

There are three main theoretical explanations for the existence of collaborative R&D, which are transaction cost, strategic management and industrial organization theory. According to the first perspective, transaction costs increase steeply when contracts are incomplete, that is, when they do not fully specify the actions of each party in every contingency. Intangible assets, including technical knowledge, are a primary source of incomplete contracts. Research partnerships are thus explained in transaction cost economics as a hybrid form or organization between the market and the hierarchy to facilitate carrying out an activity specifically related to the production and dissemination of technical knowledge (Ménard, 1996). This argument is particularly useful to understand both the average level of collaboration depending on the type of technology and the choice of one type of partner from the point of view of one particular player.

Among the different variants of the strategic management perspective, the resource-based view of the firm is certainly the most popular[16]. According to this theoretical argument, the access to external complementary resources may be necessary in order to fully exploit the existing resources and develop sustained competitive advantages. Thus, based on this argument, it is possible to understand and to explain heterogeneous behaviors of players, depending on their resources and capabilities. This theory is a basis for the firms' capabilities hypothesis.

Finally, industrial organization theories focus on the potentiality of a failure in the market of scientific and technological knowledge. We do not enter here into the detail of the theory, which analyzes for example the existence of spillovers (at least in its non-tournament variant). Let us just mention that this strand of literature is an incentive to not forget the impact of the industrial structure (and its change) on the innovation process.

6.2.2 Reformulation of the question and of the hypotheses

Based on this very brief survey of the theoretical literature, we can summarize our question as follows: are the patterns of R&D collaboration in the RT between 1991 and 2004 better explained by structural characteristics of the robot technology and industry or by the (occasionally changing) strategies of the firms, which are partly independent from the technology and more related to some firms' characteristics?

The "structural characteristics" refer to various theoretical arguments focusing on classical costs of R&D, transaction costs, the characteristics of the technology (requiring more or less collaboration), the industrial structure in a static and a dynamic perspectives, etc. The argument based on the various strategies of the firms clearly refers to the strategic management perspective, which is the only one able to explain the diversity of behaviors across the firms. The characteristics of the firms are classical (size, level of R&D spending); they could be also idiosyncratic, related to the black box of the internal organization of the firm.

Of course, there is no clear division between these two arguments. For example, with regard to the impact of the industrial structure, in a static perspective, the level of collaboration will depend on

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[16] Other variants are the "competitive force" or the "dynamic capabilities". See Hagedoorn et alii (2000) for a short presentation of each variant and some references.

the proportion of collaborative institutions in a given state. However, in a dynamic perspective, it will increase if the collaborative institutions are developing or entering the market as well as if the non collaborative institutions are changing their strategies. Moreover, the strategies of the companies are affected by changes in the structural environment, so that it could be difficult to distinguish the factors explained by the two arguments.

6.3 The role of science based technologies in the increasing collaboration

Among the structural explanations of the increasing R&D collaboration, the most popular theory is certainly the one focusing on the changing technological paradigm. In general, more collaboration is required when technology is more science-based, more complex. As indicated above, among the 26 sub-types of technology (and the 20 concretely available), the JPO has classified 5 as more science-based (related to the next generation robot): “mobile robots”, “artificial intelligence”, “control of mobile robot”, “image processing”, and “sound recognition”. Are collaborative companies specialized in these technologies? To give a simple answer to this question, we consider the 369 companies of our database with more than five patents (among 1916 firms). The average percentage of collaborative patents for these companies is 19.2%. We define the firms whose percentage of collaborative patents is more (respectively less) than this mean as more (respectively less) collaborative companies. According to this criterion, 121 firms are “more collaborative” and 248 are “less collaborative”. Then, we calculate the percentage of science-based technologies related patent to the total of patents of each firm for these two groups. These percentages are respectively 44.1% and 28%. It means that “more collaborative” companies tend to be specialized in science-based technologies.

However, are the 5 science-based technologies more collaborative than other technologies? If the percentage of collaboration by technology type is calculated and technologies are classified into three categories depending on the degree of collaboration by comparison to the mean for the all patents – collaborative, average and non collaborative, one finds that these science-based technologies are far from being the most collaborative, for the whole period as well as for sub-periods (tables 19). If we consider the whole period and the second sub-period (2000-2004), two of them (“artificial intelligence” and “mobile robots”) are more collaborative than the average. The three others are just in the average during the whole period or a little more for “image processing” and “mobile robots” during the first sub-period. The two most collaborative for the whole period are “chambers provided with manipulation devices” and “micro-robots”. During the second period, we should add “cartesian coordinate type”, “cylinder/polar coordinates type”, “positioning control”, and “safety devices”, which contributed at least as much as some science-based technologies to the increasing trend of collaboration[17]. Therefore, it appears that the collaboration is not directly related to the proximity to science in the robot technology.

However, three factors should be taken into account: the relative importance of each technology in term of patents, the evolution of this relative importance (some average collaborative technologies may represent an important share of the total patents and may have grown faster than other, contributing mechanically to the growth of the collaborations, at least from an absolute perspective) and some specific forms of collaboration, whose growth contributed to the overall growth of joint patent – mainly the FU type. That is why we calculate the contribution (percentage) of each technology to each form of collaboration and non collaboration for three periods - 1991-2004, 1991-1999, 2000-2004 (tables 20a, b & c). From the point of view of this criterion, if one considers the whole period, we find that the share of "mobile robots", "AI", "control of mobile robots" and "image processing" in the collaborative patents (respectively 18, 2.5, 6,14,5) is higher than their average for all the patents (respectively 15.6, 1.9,5.5, 13.6). Moreover, if one compares the two sub-periods (1991-1999 and 2000-2004), one finds that especially in the case of "mobile robots", the contribution to the total collaborative patents has increased drastically (from 11.7% to 27.2%), more than their contribution to the total patents (from 11.1% to 23.9%)[18]. This is *de facto* the highest contribution to the collaboration, the third most important contribution being done by "image processing". However, the contribution of a non-science based technology – "gripping hands" - is the second for the whole period (with 17.8%). This result is not surprising as these three technologies are the top-three in term of the absolute number of patents: 4708 for "gripping hands", 3503 for "mobile robots", and 2894 for "image processing" (the average number of patents by technology being approximately 1100).

Then, we focus on the FU type collaboration, because this is potentially the one for which the transfer from science to technology is the highest and because this is the form of collaboration which increased the most (while the share of collaboration between companies tended to decline: see § 3.2). However, if one considers the whole period, one finds roughly, without surprise, the same hierarchy: "mobile robots", "gripping hands" and "image processing" contribute the most to the collaboration, almost 50% if one sums the contribution of the three (tables 20). In the first sub-period (1991-1999), one should add "control of mobile robots", which contributes at the same level than "mobile robots", while in the second sub-period (2000-2004), the highest contribution is "mobile robots (23%).

Summarizing our findings, some specific science-based technology – that is, mainly, "mobile robots" and "sound recognition" - have contributed to the increase of collaboration, especially the collaboration between firms and universities, which contributed in turn to the increase of collaborative R&D (as collaboration between firms tended to decrease). However, as a whole, they are not the most

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[17] However, the numbers of patents for "chambers provided with manipulation devices and "cylinder/polar coordinates type" are very small. Therefore, the percentage of collaboration for these two technologies should be interpreted cautiously.

[18] The same applies for "sound recognition", characterized by a drastic change from the point of view of the contribution to the total collaborative patents (from 0.6% to 5.6%).

collaborative technologies. Therefore an explanation focusing only on the changing technological paradigm is a little short to explain the observed trend. That is why it is necessary to consider other theoretical arguments.

A related argument establishes a link between the level of cooperation and the state of development of the technology. If one follows Tether (2002) or Vonortas (1997), one should expect that the cooperation will be higher in a stage, where uncertainties about the trajectory of the technology as well as the expectations about the future state of the market are high. On may consider that this situation perfectly corresponds to the current state of the RT as a whole. But it is necessary to check into deeper details at the level of the subcategories of technology. We try to test this hypothesis by separating the technologies into three categories: the ones for which the number of patents is increasing, the ones for which it is decreasing and the ones for which it is stable. If one cannot say anything for the last case, one may assume that the first and second ones respectively correspond to the cases of non mature technologies and mature technologies. Then we calculate the average percentage of collaboration by sub-periods: if the argument is true, one should observe an increasing trend of collaboration for non mature technologies and a decreasing trend in the other case. We get mixed results on this (table 21). The hypothesis is always confirmed in the case of non mature technologies (“mobile robots”, “AI”, “sound recognition” and “image processing”) but only very partially confirmed in the case of mature technologies like “master slave type”, “chambers provided with manipulation devices”, “arms” and “program control”. Therefore, at this stage, it is difficult to see the technological cycle as the main determinant of the patterns of collaboration in the case of RT in Japan.

6.4 What does a transaction cost perspective tell us about the level and the evolution of R&D collaboration in the RT?

A transaction cost approach, a typical structural argument, is potentially useful to explain the low level of collaboration in the initial period as well as its increase afterward. The existence of transaction costs tends to curb the likelihood of R&D cooperation (Nakamura and Odagiri, 2004). There are various transaction costs associated with R&D cooperation, two of them seem to be particularly important in the case of RT in Japan. The first one is a simple transaction cost on writing a contract, especially on the property right issue. According to one interviewee (CEO of a start-up): “To cooperate with other firms there are a lot of issues, especially on patents. It is a troublesome task.” There is also a hold-up problem when the assets are relation specific (Williamson, 1979). This seems to be severe for RT as the equipments used are in many cases specific to a buyer’s particular order.

The transaction costs above seem to have been mitigated when the “coordinator” exists, leading to an increase of the cooperation especially among firms. This case includes the strong leadership of a specific company: Hitachi, Toyota, Toshiba and Sony worked with many companies within and outside their group (see above: §5.2 and table 16). It also includes the government-sponsored projects. Government (especially METI but also other ministries) has been deliberately making various institutions (firms and universities) to participate to robot-related projects, organized by research topics for which the participants should work together. The cooperation among firms and between firms and universities has been promoted as a result. According to one interviewee (engineer of a leading company in the RT, which participated to many projects): "For the government projects, the cost incurred by each firms and the patent issues are clearly set, so it is easy to participate." The coordinating contribution of the government is therefore related to the establishment of clear rules and of working groups within its R&D projects[19].

Generally speaking, the limit of a pure transaction cost perspective is that it cannot explain the observed differences across firms. Moreover, it is very difficult to test empirically this argument and to isolate it from other theoretical explanations, like the firms' capabilities argument, as recalled by Odagiri (2003). One way is to consider different forms of collaboration (by types of players involved) and to assume different level of transaction costs by types of collaboration. For example, Odagiri (2003) focuses on collaboration between domestic and foreign companies to test the transaction cost argument, assuming that the transaction cost is higher in this last case: if the number of collaborations is relatively more important with foreign firms than with domestic firms, it invalidates the transaction cost argument and tends on the contrary to support the capability argument. This is of course a very rough test, especially if one considers that competition could be another reason for not collaborating with domestic firms. However, to our limited knowledge, there is no other way to test the transaction cost theory with our database. Instead of focusing on the collaboration with foreign firms, we analyze the share of external and internal collaborations (to be understood as outside and inside the "group" as explained in § 5.2) for a sample of firms, in assuming than external collaboration should be more costly. For this purpose, we refer again to the table 15. The fact that some companies like Sony, Yaskawa and Nissan resorted more often to external collaborations than to internal ones implies that some factors other than transaction cost should be involved in the choice of partners for these companies. In the cases of the companies mentioned above, as well as in the case of firms like Toyota and Toshiba, for which the shares of internal/external collaborations are almost the same, the capability hypothesis could help to explain why some companies choose their partners in spite of the existence of transaction cost (see paragraph 6.6).

6.5 The impact of the changing industrial structure on the evolution of collaboration

The next hypothesis analyzes the impact of the changing industrial structure on the level of collaboration. One can imagine the following changes between the two sub-periods:

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[19] However, a first look at the government sponsored projects (essentially NEDO) related patent shows that most of them include only a single applicant. This is not completely surprising as we know that most of the participants to government-sponsored projects conducted the research in their own laboratory. In these conditions, it is difficult to say if government-supported projects really lead to an increasing trend of collaborative inventions. Further research is required in this field.

- The distribution of collaborative patents by firms may have changed over time;
- The distribution of collaborative players may have changed over time (for example, very collaborative players may have increased their share among all the players);
- In particular, some new players (start-ups) may have entered the market and contributed to change the average results.

We have already indicated the very low (if not inexistent) level of horizontal collaborations, as noticed in the § 5.2. This result is consistent with a discussion of the IO research on R&D cooperation claiming that potential competition among partners *ex post* will reduce the incentive to cooperate. It should be noted that even the final product makers have their own field of strength, indicating the potential complementarity in technology among them and the possibility of cooperation. However, the lack of realized cooperation among the major final product makers indicates that the product market competition plays a significant role to hinder the cooperation. This is probably because the potential benefit of getting ahead of the competitors is quite large. As the current service robot market is very small but the potential demand is thought to be large, there is a chance of monopolization of the market or of getting a large share. One interviewee reacted to our question of the reason for the lack of horizontal cooperation as follows: "The current stage of RT is that firms put new different ideas, paying attention to what other firms are doing, and try to get the *de facto* standard in the future if possible." In this sense, the industrial structure of this emerging sector, dominating by large companies of the electrical machinery and the car industries may have a negative impact on the level of collaboration. However, it should be noted that there is an intense division of work between the suppliers and the final markers (vertical collaboration).

As for the distribution of players by number of collaborative patents, it is difficult to observe any change. This impression is confirmed by two simple distribution tests, the variance ratio test and the two-sample t-test with unequal variances. In both cases, the H0 hypothesis of no difference between the two distributions is confirmed (table 22) [20].

Finally, with regard to the entry of new players, the role of a specific type of companies, the venture type firms, are though to be important factors to explain the increasing R&D collaboration cases in Japan since the beginning of the 1990s (Odagiri, 2004; Motohashi, 2005b). The basic idea is that their size does not allow them to fully internally develop a complete product; it requires collaboration. What can be said about them in the case of the RT? According to some of our interviewees, they seem to be *relatively* more active in collaborating with other firms in their production development. It is probably because they usually focus on the development of relatively narrow-purpose robots. However, the overall number of firms with whom they collaborate is small. It means that, generally speaking, the scope of small firms' activities is limited and one should not expect too much from the startups to increase the level of cooperation in RT as considered as a whole.

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[20] The same applies for the percentage of non collaborative players (defined as players with no collaborative patents, excluded from the figures 11), which is 58.1% for the first period and 57.5% for the second period.

For example, the number of collaborative patents by famous startups like Tmsuk (9), ZMP (2), Kokoro (2) or Vstone (1) are inferior to the number of patents by average collaborative firms, which applied for 6 patents on average (excluding firms with only one or zero patents: see table 22), even if we consider the period during which Tmsuk , ZMP, Kokoro and Vstone are active[21].

To sum-up, the changing industrial structure may have played a negligible role in the overall increasing trend of collaborative patents.

6.6 Explaining the diversity of behaviors in joint patenting: the capability argument, revisited

In the fifth part of this paper, we have shown a considerable heterogeneity across players from the point of view of collaboration. It is natural to consider that this heterogeneity could be explained by a firms' capabilities type of argument. We propose here a simple test of the capability hypothesis (table 23). The test is conducted as follows. For each firm of a sample of 16 firms, we calculate the correlation between the percentage of patents by technological field (micro classification) to the total of patents applied by this company and the ratio of collaborative patents to non collaborative patents by technological field. If the capability hypothesis is true, one should find a negative correlation, in the sense that a lower specialization in a given technological field should lead to higher collaboration (because of lack of capability). There are only 3 cases of positive correlation. (Sony, Mitsubishi Electric and Daihen) For all other companies, the correlation is negative. Of course, it is necessary to check the statistical significance of this correlation. However, a classical T-test can hardly be used here as the sample is very small for each firm (between 20 and 15 points for the two series). That is why we adopt the following rough rule to discriminate between correlation and non correlation: in absolute term, if the correlation index is between 0.2 and 0.4, we consider there is a weak correlation; if it is between 0.4 and 0.6, there is a moderate correlation. According to this criterion, we find that in the cases of seven companies (Toyota, Kawasaki HI, NTT, Kobe Steel, Fujikoshi, ATR and Mitsui Engineering and Shipping) there is a negative correlation. How can we interpret these results? First, for the largest players in RT (defined not by the size of the company but by the number of patents), there seems to be no sign of negative correlation. It indicates that capability hypothesis does not hold for these firms. Second, the frequency of negative relation become higher for firms, which are less specialized in RT (smaller number of patents). It is probably because the range of capabilities in RT of these companies is narrower, requiring more complementary capability. Third, one can find that there is a significant negative correlation for the case of Toyota, and this case seems to strongly support the capability explanation. This is certainly due to the fact that Toyota is a late-comer in RT. Its strategy has been obviously to catch-up with predecessors by collaborating with other players which have technological capabilities that Toyota do not have. As a whole, this very exploratory test is supporting

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[21] Tmsuk is clearly an outlier because it can be defined as a R&D company.

the capability hypothesis for some companies. Therefore, this theory contributes to explain the observed heterogeneity of behaviors.

A related question of this is whether the division of work between companies and universities exists. Are universities specialized in some particular technologies? If so, do the firms collaborate with universities to get access to this specific ability of universities? We can tentatively answer to this question by looking at tables 20 where the contributions of different technologies to different types of patents are summarized. We focus here on F, U, FU and FF patents. If one compares the F and U types for the whole period, one can recognize that universities are specialized in “mobile robots”, “artificial intelligence” and “image processing” (respectively 29.4%, 5.7% and 14.3% of the total of U patents) by comparison to the firms (respectively 15%, 1.8% and 12.8%) and to the average (15.6%, 1.9% and 13.1%). On the contrary, universities do not engage at all in “cartesian coordinate type”, “cylinder/polar coordinate type” and “chambers provided with manipulation devices” and are not specialized (by comparison to firms) in “gripping hands”, “safety devices” and “positioning control”. It is important to note that the firms collaborate with universities for “artificial intelligence” and “image processing” (4.1% and 15.7%), more than with other firms (1.7% and 13.4%). Therefore, we can conclude that the companies which collaborate with universities look for the capabilities that they cannot find internally or within other companies. This result has been confirmed by some interviewees: the merit of the researches in universities for firms is to broaden their choices of institutions to cooperate with. One advantage of the researches in the universities is that some of them have much longer history of researches in the robot technology than many firms. Thus, there is considerable accumulation of data in the universities, which are quite useful for the firms to conduct empirical tests. Also, the level of technology between the university labs and those of private firms depends clearly on the technological field (higher in universities for artificial intelligence for example and much lower in hardware related technological fields). This fact supports the capabilities argument. This study could be completed by an analysis of the patent quality by technology and by type of patent; however, the part on quality showed us that we need a more stable methodology to say something on it (§ 4). That is why we renounce here to go further on this point.

Finally, based on interviews, there are a couple of other results on the firms’ motivation for collaboration (and non collaboration). In the literature on R&D collaboration, the question on the motives of the collaboration is still an object of debates. What is clear is that it varies across the firms. It could be therefore an explanation of the observed heterogeneity in the collaborative behavior (Hagedoorn et alii, 2000). In the case of the RT, the choice between collaboration and non collaboration for firms is directly related to the strategic goal to go ahead in developing the successful application and to get the *de facto* standard. The collaborative R&D definitely involves a trade-off between the speed of invention (potentially higher with collaboration) and the risk of being ahead by partners. Based on the interviews, we found that the most important incentive for firms to cooperate appear to be technological complementarity, seeking the technology or know-how (both tangible and intangible) they do not have. Cost minimization is also important for some firms to participate to the government projects. Therefore, we confirm the heterogeneity of the motives of collaboration across firms, as documented by Sakakibara (1997). We also find that the inquiry on them generally supports also partly the capability argument.

Conclusion

In this paper, we have investigated the collaborative R&D pattern in the case of the robot technology in Japan from the 1990s. We have used RT-related patents data to examine the evolution of collaboration as well as the impact of collaboration on the quality of invention. We have also investigated the heterogeneity in the strategies of the firms. We have supplemented the quantitative research with a qualitative analysis based on interviews and references to the literature on R&D collaboration in an attempt to explain the observed pattern.

We can summarize our findings as follows:

- The level of collaboration was initially very low but has increased between 1991 and 2004.
- Among the collaborative cases, the collaboration between firms is the most common case. This is followed by the case of collaboration between firms and universities, which has increased recently, and that between firms and public research institutions;
- Generally speaking, from the point of view of firms, the collaboration in patenting seems to lead to a higher level of quality of the invention; however, our method to estimate the quality of patents needs to be improved;
- The practice of collaborations as well as the form of collaborations (external/internal, short-term/long term) is very diverse across firms;
- These patterns are tentatively explained by the structural characteristics of the RT (by reference to a transaction cost argument and to the role of science-based technologies) as well as by firms' capabilities hypothesis; however, it was not possible to rigorously demonstrate that one argument better explains the observed patterns than one another.

This study can be improved and complemented by further researches especially in the three following directions. First we have found that firms are heterogeneous in their R&D strategy, even for a very narrowly defined technology like the RT, and even if they belong to a same sector (automotive industry for example). However, our results are only exploratory, based on few examples; they should be systematized with larger samples of companies. Second, we have mentioned that the government – local and central, ministries and related agencies – have been very active to promote collaboration in the RT. A study is needed to evaluate the efficiency of the government policies using the same patents data, which should be divided into the ones related to government sponsored programs and the others. It requires a complete list of government projects and of all patents for each project. However, we have only the list for METI-NEDO projects at this stage. Third, another important issue is the impact of clusters on R&D collaboration; this is related to the general question of geographical proximity (Giuri & Mariani, 2005). This question has been especially investigated in the literature on spillovers. For example, Giuri & Mariani (2005) use a specific question of PatVal survey this investigate this question. In our database, we have the address of the inventors. So it is practically possible to investigate this point. It will be the object of further research.

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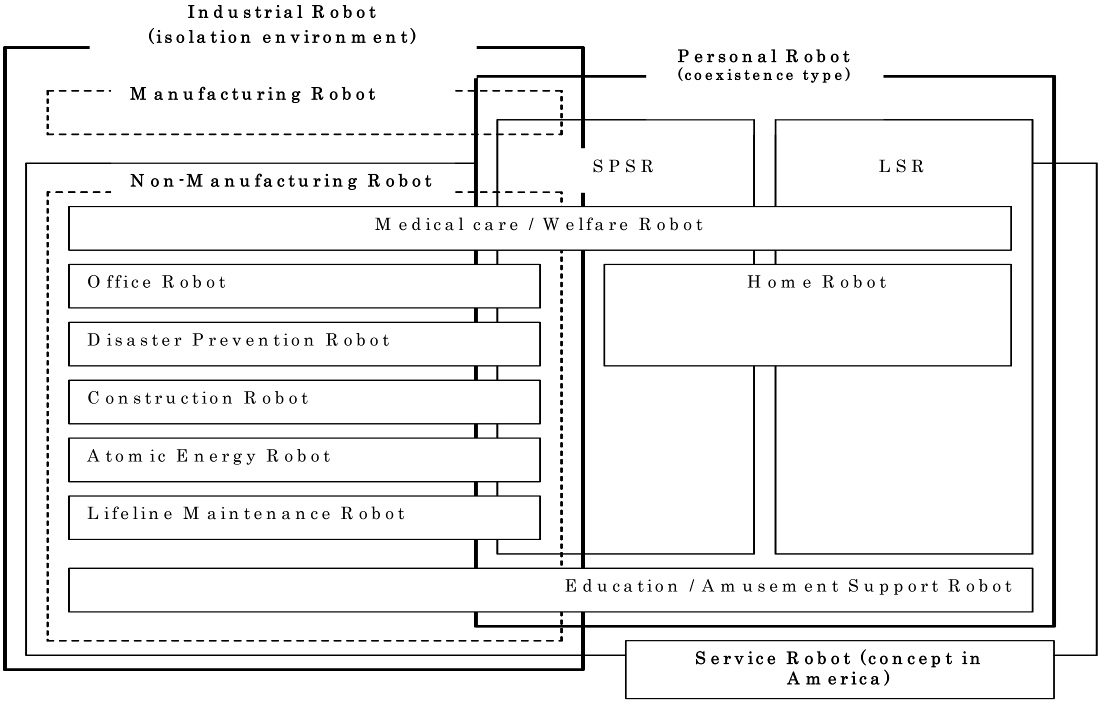
Figures & tables

Figure 1: Definition of robots



Source: Jara (2001)
Note: SPSR: Social Participation Support Robot, LSR: Life Support Robot

Figure 2: The gap between "Collaborative invention" and "Collaborative R&D"

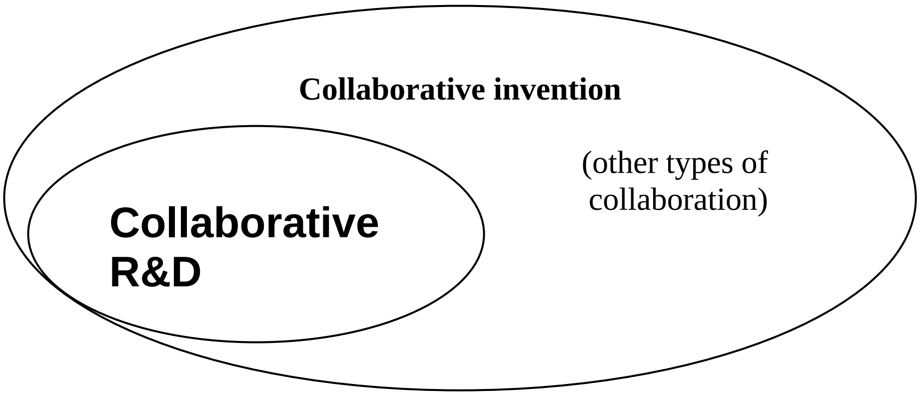
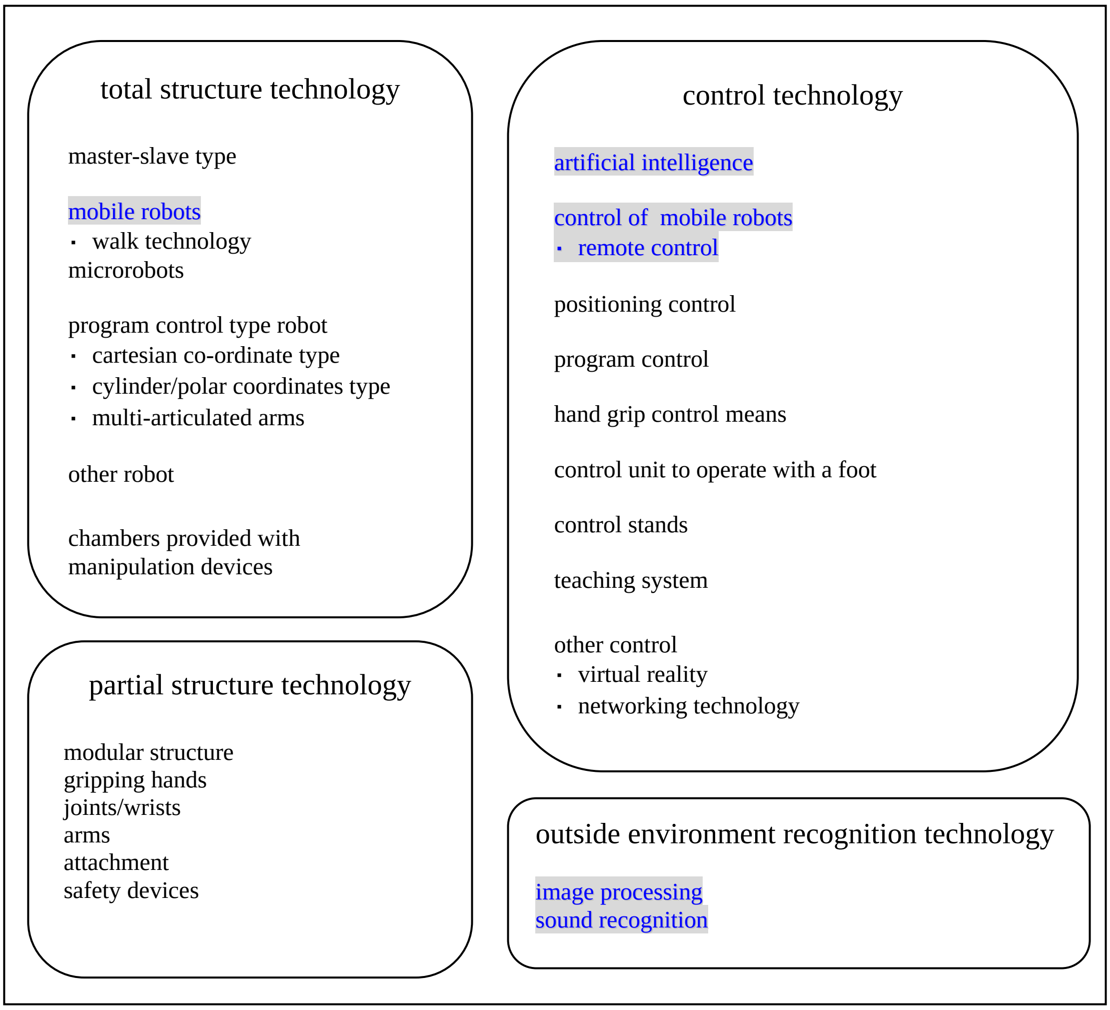


Figure 3: Classification of the inventions by type of collaboration

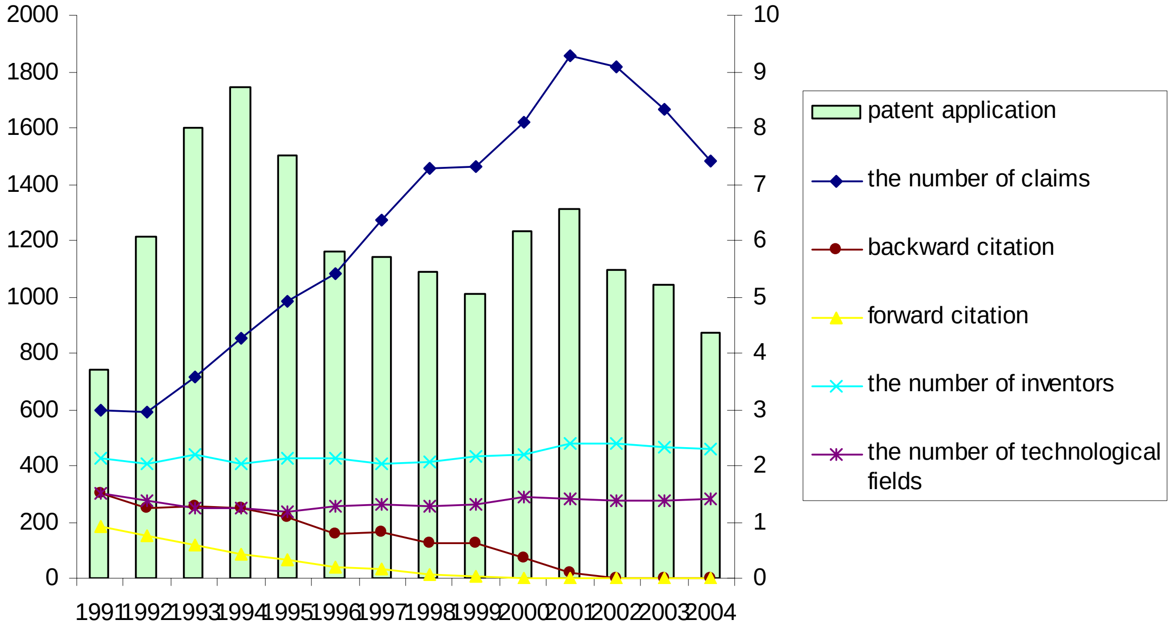
F	invention by one firm
U	invention by one university
P	invention by one public research institution
FU	collaboration between firm(s) and university (ies)
FP	collaboration between firm(s) and public research
FF	collaboration between firms
UP	collaboration between university (ies) and public research institution(s)
UU	collaboration between universities
PP	collaboration between public research institutions
FUP	collaboration between firm(s), university (ies) and public research instiution(s)

Figure 4: 4 macro classifications and 20 micro classifications of RT



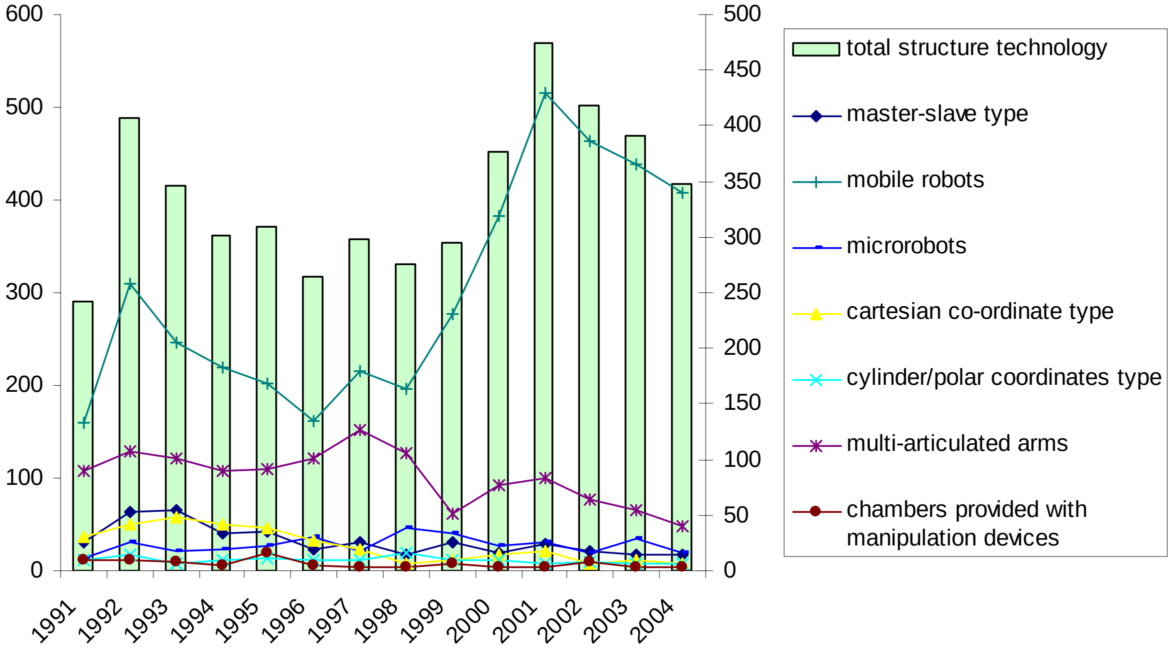
Source: JPO (2002)
Note: The technologies shaded are closely related to the technology of next generation robots

Figure 5: Characteristics per patents



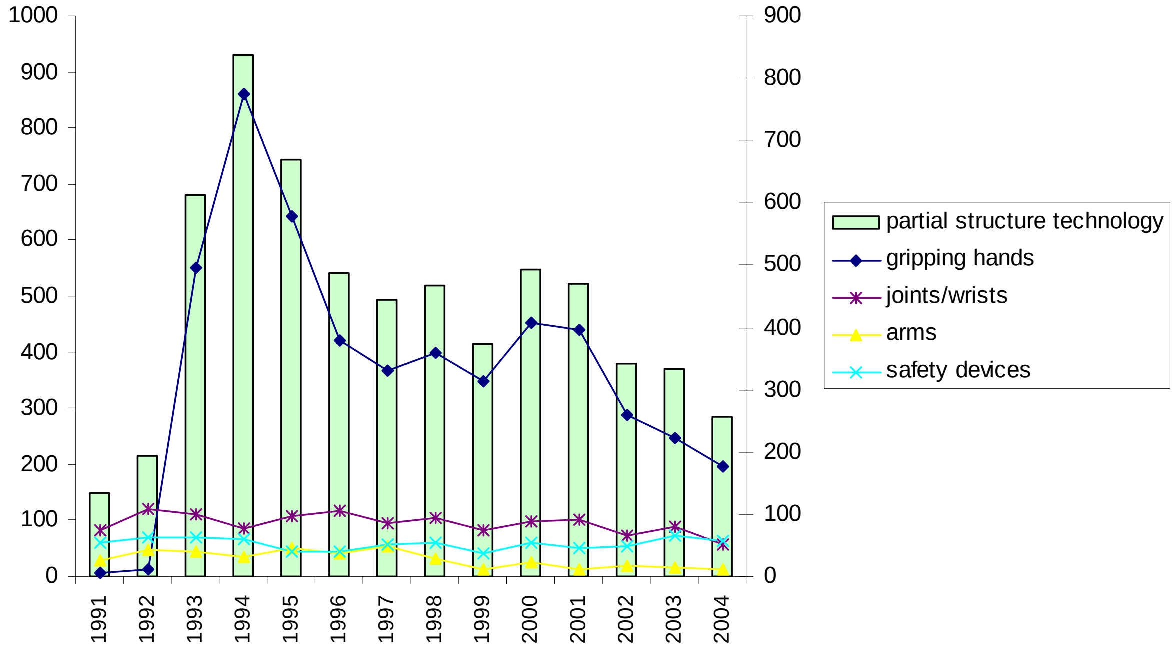
Note: patent applications should be read on the left axis, other items on the right axis

Figure 6: Number of patent applications in total structure technology



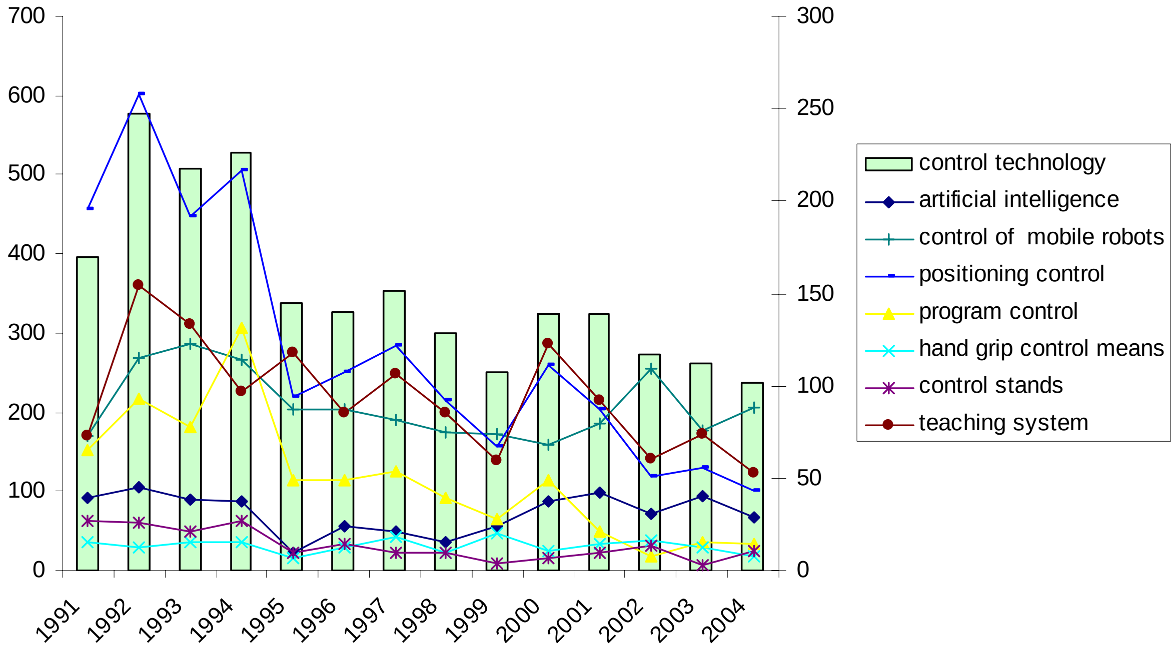
Note: the number of total structure technology patents should be read on the left axis, other items on the right axis

Figure 7: Number of patent applications in partial structure technology



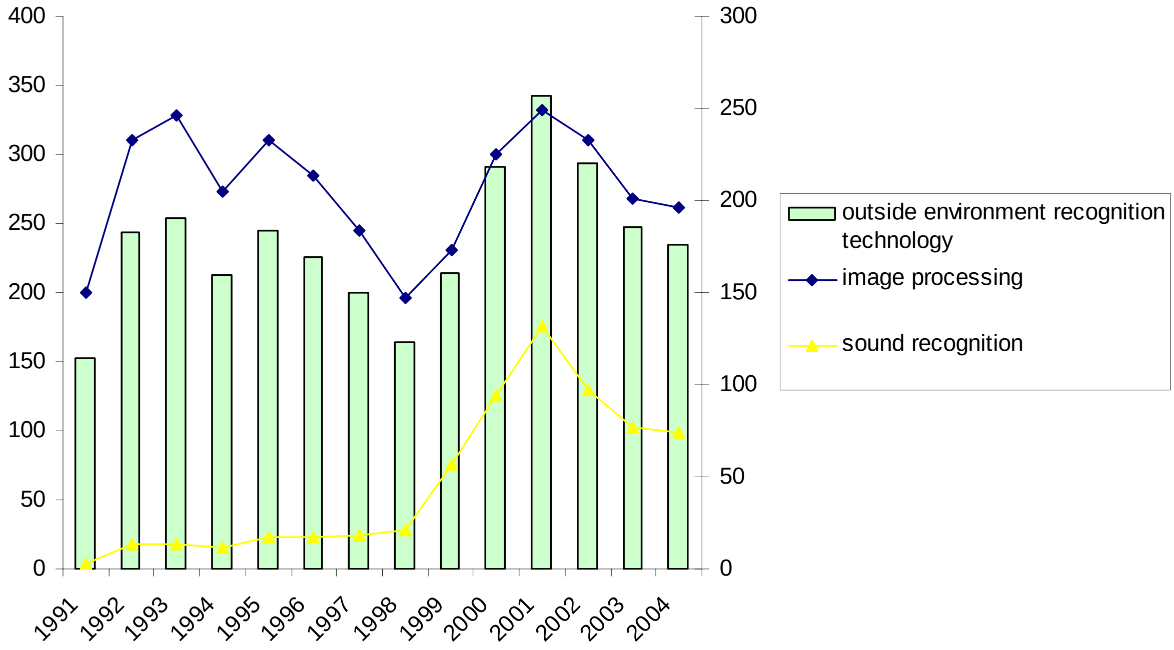
Note: the number of partial structure technology patents should be read on the left axis, other items on the right axis

Figure 8: Number of patent applications in control technology



Note: the number of control technology patents should be read on the left axis, other items on the right axis

Figure 9: Number of patent applications in outside environment recognition technology



Note: the number of outside environment recognition technology patents should be read on the left axis, other items on the right axis

Table 1: Evolution of the number of RT related patents by types of collaborations and non collaborative institutions (absolute numbers)

Types of patents	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
F	634	1066	1326	1483	1232	954	948	870	804	961	1024	821	853	726	13702
U	2	3	4	11	5	4	6	7	12	21	31	35	29	34	204
P	6	3	10	7	6	10	5	7	14	14	25	25	19	9	160
FU	8	15	17	16	24	10	13	14	13	16	22	19	34	23	244
FP	6	5	16	6	9	11	3	8	8	9	9	10	4	4	108
FF	37	61	121	94	119	84	50	50	42	81	77	73	36	50	975
UP	0	0	1	1	0	6	1	5	6	4	8	6	3	4	45
UU	0	1	1	0	0	0	0	0	0	0	1	4	1	2	10
PP	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
FUP	0	0	0	0	0	0	0	0	1	1	0	4	0	2	8
Total	693	1154	1496	1618	1395	1079	1026	962	900	1107	1197	997	979	854	15457
% of F patents	91.49	92.37	88.64	91.66	88.32	88.42	92.40	90.44	89.33	86.81	85.55	82.35	87.13	85.01	88.65
% of collaboration	7.36	7.11	10.43	7.23	10.90	10.29	6.53	8.11	7.78	10.03	9.77	11.63	7.97	9.95	9.00

Note: % of collaboration includes all the cases of collaboration (FU, FF, FP, FF, UP, UU, PP, FUP).

Table 2: Evolution of the number of RT related patents by types of collaborations (percentages)

Types of patents	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
FU	15.7	18.3	10.9	13.7	15.8	9.0	19.4	17.9	18.6	14.4	18.8	16.4	43.6	27.1	17.5
FP	11.8	6.1	10.3	5.1	5.9	9.9	4.5	10.3	11.4	8.1	7.7	8.6	5.1	4.7	7.8
FF	72.5	74.4	77.6	80.3	78.3	75.7	74.6	64.1	60.0	73.0	65.8	62.9	46.2	58.8	70.1
UP	0.0	0.0	0.6	0.9	0.0	5.4	1.5	6.4	8.6	3.6	6.8	5.2	3.8	4.7	3.2
UU	0.0	1.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	3.4	1.3	2.4	0.7
PP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1
FUP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.9	0.0	3.4	0.0	2.4	0.6

Note: The denominator is the total number of patents of collaboration (FU+FP+FF+UP+UU+PP+FUP)

Figure 10: Evolution of the cases of collaborations involving at least one firm (percentage)

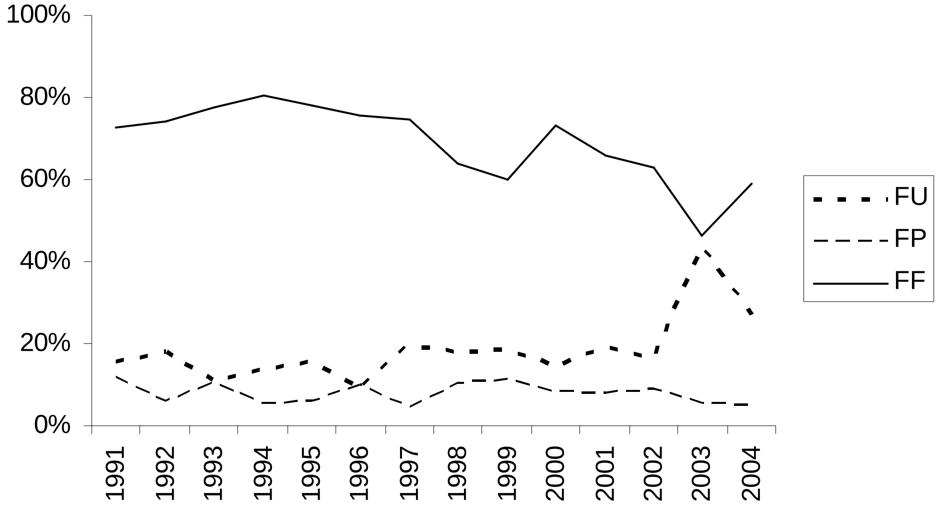


Table 3: Evolution of the number of claims per patent by type of collaboration and non collaborative institution

Types of patents	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
F	2.56	2.52	3.13	3.93	4.34	4.66	5.01	5.64	6.19	7.20	8.29	8.12	7.72	7.13	5.30
U	6.50	10.67	7.00	4.45	6.60	5.25	4.67	6.86	6.50	7.52	6.61	7.49	6.97	7.12	6.86
P	2.17	11.00	1.40	4.43	1.83	3.50	6.20	3.86	5.50	6.00	6.60	7.32	8.32	5.33	5.69
FU	1.88	2.47	4.00	5.19	6.46	5.30	3.62	4.43	6.92	15.63	8.36	8.79	8.59	9.83	7.09
FP	1.33	3.40	3.19	5.00	3.56	4.64	5.00	6.25	4.63	9.67	7.44	5.20	4.75	8.50	5.09
FF	3.03	3.25	2.96	3.29	3.98	4.02	5.40	6.62	6.79	7.86	9.00	10.93	10.33	8.46	5.74
UP	ND	ND	1.00	2.00	ND	6.83	10.00	6.20	2.83	6.50	8.00	13.33	12.67	7.75	7.58
UU	ND	6.00	3.00	ND	ND	ND	ND	ND	ND	ND	6.00	6.00	57.00	6.00	10.80
PP	ND	ND	ND	ND	ND	ND	ND	2.00	ND	ND	ND	ND	ND	ND	2.00
FUP	ND	ND	ND	ND	ND	ND	ND	ND	4.00	2.00	ND	7.75	ND	6.50	6.25

Note: ND means "NO DATA". NO DATA means that there is no sample data

Table 4: Evolution of the backward citations

Types of patent	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
F	1.54	1.24	1.26	1.28	1.08	0.84	0.81	0.57	0.58	0.30
U	0.50	1.33	4.25	1.91	0.80	0.75	1.83	0.86	0.00	0.14
P	1.50	2.33	1.40	2.00	1.00	0.70	2.20	2.57	1.79	1.86
FU	0.75	0.73	1.94	1.38	1.33	1.00	1.00	1.71	0.38	1.56
FP	1.83	1.00	1.69	1.00	1.00	1.45	0.33	1.38	0.50	3.11
FF	1.89	1.02	1.19	0.93	1.32	0.58	0.94	0.84	0.38	0.43
UP	ND	ND	0.00	1.00	ND	0.67	1.00	0.80	2.00	0.50
UU	ND	4.00	0.00	ND	ND	ND	ND	ND	ND	ND
PP	ND	ND	ND	ND	ND	ND	ND	0.00	ND	ND
FUP	ND	ND	ND	ND	ND	ND	ND	ND	0.00	0.00

Note: ND means "NO DATA". NO DATA means that there is no sample data

Table 5: Evolution of the forward citations

Types of patent	1991	1992	1993	1994	1995	1996	1997
F	0.93	0.74	0.62	0.45	0.32	0.21	0.15
U	1.00	0.33	0.00	0.00	0.80	0.00	0.00
P	2.00	1.00	1.00	0.29	0.50	0.00	0.60
FU	1.13	0.87	0.53	0.50	0.50	0.20	0.23
FP	1.00	1.60	0.44	0.50	0.00	0.09	0.67
FF	1.00	0.69	0.50	0.35	0.30	0.21	0.22
UP	ND	ND	0.00	1.00	ND	0.83	0.00
UU	ND	1.00	0.00	ND	ND	ND	ND
PP	ND	ND	ND	ND	ND	ND	ND
FUP	ND	ND	ND	ND	ND	ND	ND

Note: ND means "NO DATA". NO DATA means that there is no sample data

Table 6: Evolution of the number of inventors per patent

Types of patents	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
F	2.00	1.91	2.02	1.89	1.90	1.92	1.95	1.87	2.04	2.08	2.24	2.14	2.14	2.06	2.00
U	2.00	2.00	1.00	1.27	2.40	1.75	1.67	1.43	2.33	1.57	1.81	2.06	2.03	2.18	1.91
P	1.83	2.00	2.10	2.57	2.17	2.40	1.60	2.43	2.29	1.79	2.84	3.56	2.79	2.78	2.58
FU	3.00	3.33	3.35	3.13	3.42	3.40	3.23	3.57	3.38	2.88	4.09	3.68	4.12	4.17	3.59
FP	3.50	3.20	4.94	3.83	4.33	4.45	3.33	4.50	3.88	6.00	5.00	4.40	4.25	5.75	4.51
FF	3.73	3.80	3.92	3.81	4.23	3.77	3.60	4.00	3.43	3.33	3.77	3.71	4.11	4.08	3.82
UP	ND	ND	3.00	5.00	ND	9.00	3.00	3.00	3.33	3.25	3.50	4.83	2.67	4.00	4.31
UU	ND	2.00	4.00	ND	ND	ND	ND	ND	ND	ND	2.00	3.00	2.00	2.50	2.70
PP	ND	ND	ND	ND	ND	ND	ND	5.00	ND	ND	ND	ND	ND	ND	5.00
FUP	ND	ND	ND	ND	ND	ND	ND	ND	5.00	3.00	ND	6.25	ND	4.00	5.13
F (excluding only one inventor case)	3.00	2.91	3.05	2.83	2.86	2.88	2.77	2.78	3.05	3.03	3.19	3.03	2.94	2.99	2.95
U (excluding only one inventor case)	3.00	2.00	ND	4.00	4.50	2.50	2.33	2.00	3.00	2.50	2.92	2.95	2.76	2.82	2.81
P (excluding only one inventor case)	2.67	2.00	3.20	3.20	3.33	2.56	2.50	3.50	3.00	2.83	3.88	4.05	4.40	4.20	3.50

Note: ND means "NO DATA". NO DATA means that there is no sample data

Table 7: Evolution of the number of technological fields per patent

Types of patent	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
F	1.52	1.40	1.25	1.26	1.18	1.30	1.33	1.26	1.29	1.45	1.41	1.37	1.33	1.40	1.33
U	1.00	1.00	2.00	1.36	1.20	1.00	2.00	1.43	1.17	1.19	1.35	1.49	1.31	1.41	1.37
P	1.17	1.33	1.40	1.57	1.17	1.20	1.60	1.57	1.79	1.57	1.28	1.44	1.68	1.33	1.46
FU	1.38	1.47	1.29	1.25	1.29	1.30	1.38	1.29	1.38	1.56	1.41	1.53	1.56	1.39	1.41
FP	1.67	1.40	1.25	1.00	1.11	1.00	2.00	1.38	1.00	1.33	1.22	1.30	1.75	2.25	1.31
FF	1.38	1.33	1.21	1.18	1.21	1.23	1.20	1.30	1.33	1.30	1.44	1.40	1.36	1.58	1.30
UP	ND	ND	1.00	1.00	ND	1.33	1.00	1.20	1.00	2.25	2.63	1.00	3.00	1.75	1.67
UU	ND	1.00	1.00	ND	ND	ND	ND	ND	ND	ND	1.00	1.00	1.00	1.50	1.10
PP	ND	ND	ND	ND	ND	ND	ND	1.00	ND	ND	ND	ND	ND	ND	1.00
FUP	ND	ND	ND	ND	ND	ND	ND	ND	1.00	2.00	ND	2.00	ND	1.50	1.75

Note: ND means "NO DATA". NO DATA means that there is no sample data

Table 8: Composite Index 1 (5 components)

Types of pat	1991	1992	1993	1994	1995	1996	1997	Total
F	−0.065	−0.082	−0.079	−0.047	−0.105	−0.083	−0.063	−0.075
U	0.063	0.698	0.760	−0.203	0.443	−0.355	0.106	0.128
P	0.142	1.314	−0.010	0.385	−0.139	−0.281	0.753	0.160
FU	0.025	0.238	0.468	0.491	0.677	0.377	0.442	0.440
FP	0.326	0.630	0.651	0.526	0.258	0.583	0.889	0.537
FF	0.523	0.454	0.272	0.295	0.556	0.256	0.542	0.393
UP	ND	ND	−0.684	0.811	ND	2.354	0.237	1.609
UU	ND	1.138	−0.256	ND	ND	ND	ND	0.441

Note 1: ND means "NO DATA". NO DATA means that there is no sample data

Note 2: Backward citations, forward citations, claims, the number of inventors and the number of technological fields are utilized to construct this composite index. (According to the tables (backward and forward citations), I excluded the data from 1998 to 2004.

Table 9: Composite Index 2 (3 components)

Types of pat	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
F	−0.090	−0.115	−0.112	−0.091	−0.144	−0.134	−0.087	−0.169	−0.133	−0.086	−0.116	−0.156	−0.131	−0.108	−0.118
U	0.148	0.996	0.784	−0.157	0.310	−0.383	0.316	−0.118	−0.110	−0.402	−0.394	−0.139	−0.252	−0.067	−0.150
P	−0.430	1.292	−0.198	0.506	−0.344	−0.178	0.036	0.221	0.302	−0.189	−0.118	0.298	0.403	−0.098	0.085
FU	0.069	0.452	0.446	0.548	0.744	0.410	0.414	0.436	0.453	0.822	0.476	0.503	0.787	0.841	0.583
FP	0.352	0.511	0.770	0.572	0.543	0.441	0.993	0.974	0.145	1.361	0.580	0.317	0.638	1.816	0.672
FF	0.492	0.655	0.393	0.470	0.660	0.345	0.486	0.737	0.417	0.296	0.434	0.563	0.791	0.805	0.516
UP	ND	ND	−0.339	0.577	ND	2.421	0.272	0.241	−0.167	0.777	1.108	0.790	1.722	0.826	0.898
UU	ND	0.215	0.240	ND	ND	ND	ND	ND	ND	ND	−0.616	−0.302	3.893	−0.010	0.250
PP	ND	ND	ND	ND	ND	ND	ND	0.589	ND	ND	ND	ND	ND	ND	0.589
FUP	ND	ND	ND	ND	ND	ND	ND	ND	0.482	0.234	ND	1.610	ND	0.532	1.028

Note 1: ND means "NO DATA". NO DATA means that there is no sample data

Note 2: Claims, the number of inventors and the number of technological fields are utilized to construct this composite index.

Table 10: Estimations

	Quality1 (composite index1)	Quality2 (composite index2)	Quality3 (composite index3)	
		OLS Estimation Fixed Effects Model		
U	0.074	-0.262	-0.401	-0.393
	(0.143)	(0.363)	(0.346)	(0.357)
P	-0.555	-0.054	0.317	0.262
	(0.214)***	(0.393)	(0.437)	(0.423)
FU	0.615	0.467	-0.062	0.067
	(0.093)***	(0.204)**	(0.198)	(0.206)
FP	0.32	0.291	0.023	0.115
	(0.141)**	(0.282)	(0.344)	(0.333)
FF	0.541	0.432	-0.192	-0.035
	(0.036)***	(0.049)***	(0.056)***	(0.051)
UP	0.269			
	(0.205)			
UU	0.257			
	(0.618)			
FUP	0.628			
	(0.224)***			
BackwardC	0.046			
	(0.006)***			
ForwardC	0.07			
	(0.013)***			
Ninventors			0.089	
			(0.011)***	
Techscope			0.036	0.035
			(0.019)*	(0.019)*
year1992	0.015	0.047	0.068	0.063
	(0.042)	(0.049)	(0.049)	(0.050)
year1993	0.097	0.086	0.06	0.075
	(0.041)**	(0.049)*	(0.049)	(0.049)
year1994	0.166	0.147	0.125	0.127
	(0.042)***	(0.050)***	(0.049)***	(0.050)***
year1995	0.151	0.089	0.073	0.08
	(0.041)***	(0.049)*	(0.050)	(0.050)
year1996	0.147	0.099	0.098	0.103
	(0.043)***	(0.050)**	(0.050)*	(0.051)**
year1997	0.232	0.136	0.085	0.095
	(0.042)***	(0.050)***	(0.050)*	(0.051)*
year1998	0.200			
	(0.044)***			
year1999	0.133			
	(0.047)***			
year2000	0.219			
	(0.048)***			
year2001	0.167			
	(0.046)***			
year2002	0.152			
	(0.048)***			
year2003	0.18			
	(0.048)***			
year2004	0.242			
	(0.052)***			
constant	-0.302	-0.159	-0.328	-0.159
	(0.036)***	(0.040)***	(0.050)***	(0.050)***
N	15461	8453	8453	8453
Number of groups	1762	1094	1094	1094
F-test	F(1761,13676)= 2.77(P>F=0.000)	F(1093,7347)=1.89 (P>F=0.000)	F(1093,7346)=1.51 (P>F=0.000)	
AIC	35390	21054	21564	21680
Hausman test	chi2(23)=633.26 (P>chi2 =0.000)	chi2(11)=1072.75 (P>chi2=0.000)	chi2(13)=66.01 (P>chi2=0.000)	
BP LM test for random effects	chi2(1) =75359.22 (P >chi2=0.000)	chi2(1)=7143.48 (P>chi2=0.000)	chi2(1)=1525.41 (P>chi2=0.000)	

*Note: Robust standard errors in parentheses. * p<.1; ** p<.05; *** p<.01. The type of "PP" is excluded in the equation of quality1 because there is only one observation. The type of "UP", "UU", "PP" and "FUP" are excluded in the equation of quality2 and 3 because there are small observations. Quality3 (composite index3) is newly constructed by utilizing the data on claims, backward citations and forward citations.*

Table 11: Ranking of the most active players in patenting

F	U	P
Matsushita Electric Industrial Co., Ltd (694 patents)	University of Tokyo (24)	AIST (77)
	Tokyo Institute of Technology (19)	JST (21)
Sony (686)	Waseda University (9)	JAXA (9)
Yaskawa Electric Co. (468)	Gifu University (8)	Japan Atomic Energy Agency (4)
Fanuc (434)	Kyoto University, Kinki University, Kyushu Tokai University, Tokyo University of Science (6)	
Toshiba (367)		
Mitsubishi Heavy Industries (335)		
Mitsubishi Electric Co. (292)	Keio University, Ritsumeikan University (5)	
Honda R&D Co.,Ltd. (272)		
Hitachi (255)		
Fujitsu (215)		

Table 12: Ranking of the most collaborative players by type of collaboration (absolute numbers)

FF	FU	FP
Hitachi (86 cases)	University of Tokyo (33)	Toshiba (21)
Toyota, Toshiba (78)	Tokyo Institute of Technology (23)	AIST (18)
Sony (75)		Kawasaki Heavy Industries, Japan Atomic Energy Agency (13)
Yaguchi Robotics Institute (42)	Waseda University (17)	
Mitsubishi Electric Co. (37)	Nagoya University (11)	
Mitsubishi Heavy Industries, Toyoda Machine Works, Ltd (now JTEKT Corporation) (32)	Toyota, Tohoku University (10)	National Space Development Agency of Japan (now merged into JAXA), 生物系特定産業技術研究推進機構 (now merged into NARO) (10)
	Nihon University (9)	
	Osaka University (8)	
Hitachi Keiyo Engineering (31)	RHYTHM WATCH CO., LTD., Tmsuk, Hokkaido University, Okayama University (7)	
Yaskawa Electric Co., Toyota Central R&D Labs., Inc. (28)		Hitachi (9)
KYUSHU ELECTRIC POWER CO., INC, TOSHIBA MACHINE CO.,LTD (23)	Sony, Iseki ? Co, Fuji TechExperts, SHINRYO CO., Tokyo University of Agriculture and Technology, Tsukuba University, etc (6)	The New Industry Research Organization, Technical Research and Development Institute (8)
Kawasaki Heavy Industries (22)		

Table 13: Ranking of the most collaborative players by type of collaboration (percentage)

FF	FU	FP
Yaguchi Robotics Institute, CHUBU Electric Power Co., East Japan Railway Company (100%)	Nihon University (75%)	National Space Development Agency of Japan (now merged into JAXA) (83%)
	RHYTHM WATCH CO., LTD (70	
	Tohoku University (67%)	
	University of Electro-Communications (60%)	The New Industry Research Organization (80%)
Tokyo Electric Power Co. (94%)		
KYUSHU ELECTRIC POWER CO., INC (92%)	Tsukuba University (54%)	Technical Research and Development Institute (73%)
	Tokyo University (52%)	
Hitachi Keiyo Engineering (91%)	Tokyo Institute of Technology (51%)	Japan Atomic Energy Agency (72%)
TOKICO GIKEN LTD (81%)		
Tochiba Machine Techno (70%)	Osaka University, Tokai University, Ritsumeikan University (50%)	生物系特定産業技術研究推進機構 (now merged into NARO) (67%)
Toshiba Engineering Co. (67%)		
YANMAR Co., Ltd (60%)		
OBAYASHI Co., Toyota Central R&D Labs. (58%)	Keio University, Tmsuk (41%)	Japan Aviation Electronics Industry, Ltd. (27%)
	THK Co. (38%)	
Komatsu Machinery Co. (50%)	Kyoto University (35%)	AIST (18%)

Note: We have selected the players in FF, FU and FP which have totally more than 10 patents, because players which have few patents artificially show high percentage.

Table 14: Ranking of the less collaborative players by type of collaboration (absolute numbers)

Non-Collaborative Firms (more than 100 patents)
Mazda Motor Co. (0.8%)
Matsushita Electric Works, Ltd (0.9%)
Ricoh Company, Ltd (1.5%)
Fanuc Ltd, Matsushita Electric Industrial Co., Ltd, SHINKO ELECTRIC CO., LTD (1.8%)
CANON (2%)
SANYO Electric Co. (2.7%)
Kubota Co. (4.7%)

Table 15: Share of external and internal collaborations for some companies (FF type)

HITACHI	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
Internal	8	13	9	8	15	10	7	5	0	2	12	89
External	0	1	0	0	0	0	0	0	0	0	3	4
Total	8	14	9	8	15	10	7	5	0	2	15	93

TOSHIBA	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
Internal	4	4	5	12	4	3	4	2	0	5	0	43
External	1	9	9	11	6	4	0	0	0	2	0	42
Total	5	13	14	23	10	7	4	2	0	7	0	85

TOYOTA	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
Internal	3	3	9	5	5	3	2	3	3	0	2	3	2	0	43
External	3	1	5	2	5	1	2	4	0	0	2	3	1	6	35
N/K	0	0	3	1	1	0	2	0	1	0	3	1	0	0	12
Total	6	4	17	8	11	4	6	7	4	0	7	7	3	6	90

SONY	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
Internal	0	0	0	2	0	1	0	0	0	16	0	19
External	1	0	1	0	0	0	0	0	3	39	5	49
N/K	0	0	0	0	0	0	0	0	0	4	0	4
Total	1	0	1	2	0	1	0	0	3	59	5	72

MitsubishiHI	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	Total
Internal	0	2	3	4	4	3	4	2	0	0	0	4	26
External	0	0	2	2	1	0	2	0	0	0	0	2	9
Total	0	2	5	6	5	3	6	2	0	0	0	6	35

MitsubishiElectric	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
Internal	0	4	5	1	5	2	4	1	1	2	0	25
External	0	0	0	0	0	1	0	1	3	7	0	12
N/K	0	0	2	0	0	1	0	0	1	2	0	6
Total	0	4	7	1	5	4	4	2	5	11	0	43

Yaskawa	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	Total
Internal	0	0	0	1	0	0	0	0	1	2	0	1	0	5
External	0	1	4	2	7	2	0	0	1	0	1	2	1	21
N/K	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Total	0	1	4	3	7	2	0	0	3	2	1	3	1	27

Nissan	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
Internal	0	0	0	0	0	0	0	0	0	0	0	0
External	0	0	14	0	3	0	0	1	0	0	1	19
N/K	0	0	0	0	0	1	0	0	0	0	0	1
Total	0	0	14	0	3	1	0	1	0	0	1	20

Note: N/K indicated that the (external/internal) status of the collaborator could be established.

Table 16: Measuring the fidelity of the R&D collaborative relationship (1)

Firms	*Total number of FF type collaborating patents*	*Total number of col. Firms*	*Average number of collaborating patents by partner*	*Number of partners collaborating only once*
HITACHI	93	36	2.6	24
TOSHIBA	85	30	2.8	23
TOYOTA	90	35	2.6	25
SONY	72	20	3.6	11
Mitsubishi HI	35	19	1.8	14
Mitsubishi Electric	43	18	2.4	10
Yaskawa	31	15	2.1	12
Nissan	20	10	2.0	9
Average	59	23	2.5	16

Table 17: Measuring the fidelity of the R&D collaborative relationship (2)

Firms	*Collaborating Companies*	*Number of collaborating patents/total number of collaborating patents for the firm*	*Number of years for which joint application occurred*	*Importance*	*Main field of business (collaborating companies)*	*Comment*
HITACHI	日立京葉エンジニアリング株式会社 (Hitachi Keiyo Engineering&Systems, Ltd.)	33.3%	7	**	Robot, mechatornics	Originally established to engage in robot business, RT has been one of the main business of them.
TOYOTA	豊田工機株式会社 (Toyota Kouki)	27.8%	10	**	Steering system, powertrain.	
Mitsubishi HI	西菱エンジニアリング株式会社 (SEIRYO ENGINEERING CO., LTD)	28.6%	5	**	Energy Plant Engineering firm.	Probably relating to the R&D in nuclear power plant robots.
Mitsubishi Electric	三菱電機メカトロニクスソフトウェア株式会社 (Mitsubishi Electric Mechatronics Software Corporation.)	23.3%	5	*	CNC, Robot, Laser	
Mitsubishi Electric	三菱電機エンジニアリング株式会社 (Mitsubishi Electric Enginering Company Ltd.)	16.3%	4		Energy control system, mechatronics, medical system	
Yaskawa	株式会社安川テクノサポート (Yaskawa Techno Support)	16.1%	4		Intellectual Property business	
TOYOTA	株式会社豊田中央研究所 (Toyota Central R&D Labs.,Inc.)	14.4%	7		Central R&D lab of Toyota.	
Mitsubishi HI	高菱エンジニアリング株式会社 (Koryo Engineering Co., Ltd)	11.4%	3		Turbin, Plant Enginering	
TOSHIBA	東芝エンジニアリング株式会社 (ES Toshiba Engineering)	12.9%	6		Energy Plant Engineering firm.	Probably relating to the R&D in nuclear power plant robots.
SONY	ヤマグチロボット研究所 (Yamaguchi Robotics Institute)	58.3%	3			
Nissan	株式会社明電舎 (Meidensha Corporation)	55.0%	3		Energy, Solution business, IT, Auto Parts etc	
Yaskawa	九州電力株式会社 (Kyushu Electric Power Co. Inc)	22.6%	4			
Yaskawa	トヨタ自動車株式会社 (Toyota Motor Corporation)	16.1%	3			Yasukawa is a main supplier of industrial robots used in Toyota plant

Table 18: Heterogeneity across firms from the point of view of collaboration - examples

	Type of patents	Year Average 1991-1999	Year Average 2000-2004	Grand Tota	Percentage 1991-1999	Percentage 2000-2004	Percentage 1991-2004
HITACHI	F	23	10	255	73	70	72
	FF	8	3	86	25	23	24
	FU	0	0	0	0	0	0
	Grand Total	31	14	352	100	100	100
TOSHIBA	F	32	17	367	76	86	78
	FF	8	2	78	19	10	17
	FU	0	0	4	1	2	1
	Grand Total	42	19	470	100	100	100
TOYOTA	F	12	16	188	64	74	68
	FF	7	4	78	35	18	28
	FU	0	2	10	1	7	4
	Grand Total	19	22	277	100	100	100
SONY	F	31	81	686	95	85	89
	FF	1	13	75	4	14	10
	FU	0	1	6	1	1	1
	Grand Total	33	95	769	100	100	100
MITSUBISHIHI	F	26	21	335	89	92	90
	FF	3	1	32	10	5	9
	FU	0	0	3	1	1	1
	Grand Total	29	23	375	100	100	100
YASKAWA	F	33	35	468	94	94	94
	FF	2	2	28	5	6	6
	FU	0	0	2	1	0	0
	Grand Total	35	37	499	100	100	100
NISSAN	F	17	9	198	92	98	93
	FF	2	0	15	8	2	7
	Grand Total	19	9	213	100	100	100
Matsushita EI	F	50	49	694	99	97	98
	FF	0	0	6	1	1	1
	FU	0	1	5	0	2	1
	Grand Total	51	50	707	100	100	100
FUJITSU	F	21	4	215	95	100	95
	FF	0	0	4	2	0	2
	FU	1	0	6	3	0	3
	Grand Total	23	4	226	100	100	100
KAWASAKIHI	F	12	19	203	79	92	85
	FF	2	1	22	12	6	9
	FU	0	0	1	1	0	0
	Grand Total	15	21	239	100	100	100
NEC	F	18	7	197	97	90	96
	FF	1	1	9	3	8	4
	FU	0	0	1	0	3	0
	Grand Total	18	8	207	100	100	100
MITSUBISHIE	F	28	9	292	88	84	88
	FF	3	1	37	11	12	11
	FU	0	0	2	0	2	1
	Grand Total	32	10	334	100	100	100
HONDA R&D	F	13	31	272	98	91	94
	FF	0	2	13	2	6	4
	FU	0	0	1	1	0	0
	Grand Total	13	34	290	100	100	100
All	F	1035	877	13702	90	85	89
	FF	73	63	975	6	6	6
	FU	14	23	244	1	2	2
	Grand Total	1147	1027	15457	100	100	100

Tables 19: Percentage of collaborative patents by technologies (micro classification)

Ranking of technologies (1991-2004)	Percentage of collaborative patents	Total number of patents
control stands	2.7	185
hand grip control means	4.8	167
cartesian co-ordinate type	6.1	297
teaching system	6.1	1276
program control	7.4	661
gripping hands	7.6	4338
positioning control	7.8	1595
multi-articulated arms	8.2	1074
sound recognition	8.3	576
safety devices	8.5	705
control of mobile robots	9.9	1135
image processing	10.0	2683
joints/wrists	10.1	1086
mobile robots	10.4	3208
artificial intelligence	12.1	388
arms	12.3	341
cylinder/polar coordinates type	12.8	117
master-slave type	13.1	344
microrobots	18.6	295
chambers provided with manipulation devices	21.9	73
total	9.0	20544

Note: the 5 science-based technologies are shaded.

Ranking of technologies (1991-1999)	Percentage of collaborative patents	Total number of patents
control stands	2.1	146
cartesian co-ordinate type	4.5	246
sound recognition	5.0	140
hand grip control means	5.3	114
teaching system	6.0	896
safety devices	6.3	442
positioning control	6.6	1279
gripping hands	7.5	2959
multi-articulated arms	8.1	791
program control	8.2	560
mobile robots	8.8	1481
image processing	9.4	1675
control of mobile robots	9.7	762
joints/wrists	9.9	738
artificial intelligence	11.1	235
microrobots	12.2	196
cylinder/polar coordinates type	12.8	86
arms	13.2	273
master-slave type	13.7	263
chambers provided with manipulation devices	23.6	55
total	8.3	13337

Note: the 5 science-based technologies are shaded.

Ranking of technologies (2000-2004)	Percentage of collaborative patents	Total number of patents
program control	2.0	100
hand grip control means	3.8	53
control stands	5.1	39
teaching system	6.3	380
gripping hands	7.8	1377
multi-articulated arms	8.5	284
arms	9.0	67
sound recognition	9.6	437
control of mobile robots	10.2	373
joints/wrists	10.7	346
image processing	11.1	1010
master-slave type	11.1	81
mobile robots	11.8	1725
safety devices	12.2	263
positioning control	12.3	317
cylinder/polar coordinates type	12.9	31
cartesian co-ordinate type	13.7	51
artificial intelligence	14.2	155
hambers provided with manipulation device	16.7	18
microrobots	31.3	99
total	10.4	7206

Note: the 5 science-based technologies are shaded.

Tables 20: Contribution of the different technologies to the different form of patents (collaborative and non collaborative)

a. 1991-2004

Types of patents	master-slave type	mobile robots	microrobots	cartesian co-ordinate type	cylinder/polar coordinates type	multi-articulated arms	chambers provided with manipulation devices	gripping hands	joints / wrists	arms	safety devices	artificial intelligence	control of mobile robots	positioning control	program control	hand grip control means	control stands	teaching system	image processing	sound recognition
F	1.5	15.0	1.2	1.5	0.6	5.3	0.3	21.8	5.3	1.6	3.5	1.8	5.5	8.0	3.3	0.8	1.0	6.5	12.8	2.8
U	5.7	29.4	6.8	0.0	0.0	3.6	0.0	9.0	5.0	1.4	1.8	5.7	4.7	3.6	1.8	1.4	0.7	3.2	14.3	1.8
P	3.9	26.2	3.9	0.0	0.0	3.0	1.3	8.2	3.0	0.9	2.1	2.1	6.9	5.6	2.6	2.6	0.0	6.0	16.7	5.2
FU	4.9	15.7	8.4	0.0	0.9	3.2	0.3	13.1	6.4	1.7	2.9	4.1	7.3	4.4	1.7	0.6	0.0	3.8	15.7	4.9
FP	0.0	16.3	5.7	0.0	0.0	3.5	4.3	8.5	7.1	0.7	2.1	5.0	8.5	7.1	4.3	0.0	1.4	6.4	18.4	0.7
FF	2.0	17.9	0.7	1.3	0.9	5.6	0.7	21.0	5.9	2.8	3.6	1.7	5.5	7.3	2.9	0.5	0.2	4.1	13.4	1.9
UP	4.0	29.3	10.7	1.3	0.0	1.3	0.0	2.7	2.7	0.0	1.3	5.3	6.7	8.0	0.0	0.0	0.0	4.0	16.0	6.7
UU	0.0	18.2	9.1	0.0	0.0	0.0	0.0	27.3	9.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.3	9.1
PP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
FUP	0.0	42.9	0.0	0.0	0.0	0.0	0.0	7.1	7.1	0.0	0.0	7.1	0.0	7.1	0.0	0.0	0.0	7.1	21.4	0.0
Collaborative	2.4	18.0	3.0	1.0	0.8	4.8	0.9	17.8	5.9	2.3	3.2	2.5	6.1	6.7	2.6	0.4	0.3	4.2	14.5	2.6
Non collaborative	1.6	15.4	1.3	1.5	0.5	5.3	0.3	21.4	5.2	1.6	3.5	1.8	5.5	7.9	3.3	0.9	1.0	6.4	12.9	2.8
Total	1.7	15.6	1.4	1.4	0.6	5.2	0.4	21.1	5.3	1.7	3.4	1.9	5.5	7.8	3.2	0.8	0.9	6.2	13.1	2.8

Note: the 5 science-based technologies are shaded.

b. 1991-1999

Types of patents	master-slave type	mobile robots	microrobots	cartesian co-ordinate type	cylinder/polar coordinates type	multi-articulated arms	chambers provided with manipulation devices	gripping hands	joints / wrists	arms	safety devices	artificial intelligence	control of mobile robots	positioning control	program control	hand grip control means	control stands	teaching system	image processing	sound recognition
F	1.8	11.0	1.3	1.9	0.6	6.0	0.3	22.5	5.4	1.9	3.4	1.7	5.6	9.8	4.2	0.9	1.2	6.9	12.4	1.1
U	4.1	13.5	13.5	0.0	0.0	5.4	0.0	12.2	6.8	1.4	2.7	6.8	2.7	6.8	4.1	0.0	0.0	4.1	14.9	1.4
P	3.0	18.2	7.1	0.0	0.0	4.0	1.0	14.1	4.0	2.0	1.0	2.0	7.1	6.1	5.1	3.0	0.0	10.1	11.1	1.0
FU	6.4	8.1	7.5	0.0	1.7	3.5	0.6	14.5	6.4	2.3	2.9	4.0	8.1	5.2	3.5	1.2	0.0	5.8	17.9	0.6
FP	0.0	10.1	2.2	0.0	0.0	3.4	6.7	11.2	6.7	1.1	1.1	4.5	9.0	7.9	6.7	0.0	2.2	9.0	18.0	0.0
FF	2.8	12.6	0.5	1.2	1.0	6.6	0.7	22.6	6.6	3.8	2.7	1.6	6.1	8.4	4.2	0.5	0.1	4.3	12.9	0.7
UP	8.7	17.4	21.7	4.3	0.0	4.3	0.0	4.3	4.3	0.0	0.0	8.7	8.7	0.0	0.0	0.0	0.0	4.3	13.0	0.0
UU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
FUP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Collaborative	3.3	11.8	2.2	1.0	1.0	5.8	1.2	20.1	6.6	3.3	2.5	2.4	6.7	7.7	4.2	0.5	0.3	4.9	14.2	0.6
Non collaborative	1.9	11.1	1.4	1.9	0.6	5.9	0.3	22.4	5.4	1.9	3.4	1.7	5.6	9.8	4.2	0.9	1.2	6.9	12.4	1.1
Total	2.0	11.1	1.5	1.8	0.6	5.9	0.4	22.2	5.5	2.1	3.3	1.8	5.7	9.6	4.2	0.9	1.1	6.7	12.6	1.0

Note: the 5 science-based technologies are shaded.

c. 2000-2004

Types of patents	master-slave type	mobile robots	microrobots	cartesian coordinate type	cylinder/polar coordinate type	multi-articulated arms	chambers provided with manipulation devices	gripping hands	joints / wrists	arms	safety devices	artificial intelligence	control of mobile robots	positioning control	program control	hand grip control means	control stands	teaching system	image processing	sound recognition
F	0.9	23.0	0.9	0.7	0.4	4.1	0.2	20.4	4.9	0.9	3.7	1.9	5.1	4.4	1.6	0.7	0.6	5.7	13.7	6.2
U	6.3	35.1	4.4	0.0	0.0	2.9	0.0	7.8	4.4	1.5	1.5	5.4	5.4	2.4	1.0	2.0	1.0	2.9	14.1	2.0
P	4.5	32.1	1.5	0.0	0.0	2.2	1.5	3.7	2.2	0.0	3.0	2.2	6.7	5.2	0.7	2.2	0.0	3.0	20.9	8.2
FU	3.5	22.9	9.4	0.0	0.0	2.9	0.0	11.8	6.5	1.2	2.9	4.1	6.5	3.5	0.0	0.0	0.0	1.8	13.5	9.4
FP	0.0	26.9	11.5	0.0	0.0	3.8	0.0	3.8	7.7	0.0	3.8	5.8	7.7	5.8	0.0	0.0	0.0	1.9	19.2	1.9
FF	0.4	27.6	1.1	1.6	0.9	3.8	0.7	18.0	4.4	0.9	5.3	2.0	4.4	5.1	0.4	0.4	0.4	3.8	14.4	4.2
UP	1.9	34.6	5.8	0.0	0.0	0.0	0.0	1.9	1.9	0.0	1.9	3.8	5.8	11.5	0.0	0.0	0.0	3.8	17.3	9.6
UU	0.0	22.2	11.1	0.0	0.0	0.0	0.0	22.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.3	11.1
FUP	0.0	46.2	0.0	0.0	0.0	0.0	0.0	7.7	7.7	0.0	0.0	7.7	0.0	7.7	0.0	0.0	0.0	7.7	15.4	0.0
Collaborative	1.2	27.2	4.2	0.9	0.5	3.2	0.4	14.3	5.0	0.8	4.3	2.9	5.1	5.2	0.3	0.3	0.3	3.2	15.0	5.6
Non collaborative	1.1	23.6	1.1	0.7	0.4	4.0	0.2	19.7	4.8	0.9	3.6	2.1	5.2	4.3	1.5	0.8	0.6	5.5	13.9	6.1
Total	1.1	23.9	1.4	0.7	0.4	3.9	0.2	19.1	4.8	0.9	3.6	2.2	5.2	4.4	1.4	0.7	0.5	5.3	14.0	6.1

Note: the 5 science-based technologies are shaded.

Table 21: Confronting the collaboration to the technological cycles

	Average of collaborative patents 1991-1999	Average of collaborative patents 2000-2004
master-slave type (manipulator)	13.2%	11.7%
cartesian co-ordinate type	6.4%	13.9%
cylinder / polar coordinates type	13.8%	13.2%
multi-articulated arms	8.4%	8.3%
chambers provided with manipulation devices	31.4%	20.0%
gripping hands	7.2%	7.6%
joints/wrists	9.8%	10.8%
arms	12.8%	8.1%
control of mobile robots	9.5%	10.5%
positioning control	6.3%	12.6%
program control	8.5%	1.5%
control stands	2.3%	4.0%
teaching system	6.8%	6.5%
mobile robots	9.0%	11.6%
artificial intelligence	12.2%	14.0%
image processing	9.4%	11.0%
sound recognition	5.4%	9.4%

Table 22: Results of two simple statistical tests of comparison between the distribution of collaborative patents in 1991-1999 and 2000-2004 (excluding 0 and 1patent cases)

Variable	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
var1(1991-1999)	250	6.044	0.598	9.461	4.866	7.222
var2(2000-2004)	153	5.144	0.587	7.262	3.984	6.304
combined	403	5.702	0.433	8.693	4.851	6.554
diff		0.900	0.838		-0.748	2.548

Variance ratio test

ratio = sd(var1) / sd(var2)		f = 1.6970
Ho: ratio = 1		degrees of freedom = 249, 152
Ha: ratio < 1	Ho:ratio = 1	Ha: ratio > 1
Pr(F < f) = 0.9998	2*Pr(F> f) = 0.0004	Pr(F > f) = 0.0002

Two-sample t test with unequal variances

diff = mean(var1) -mean(var2)		t = 1.0739
Ho: diff = 0		Satterthwaite's degrees of freedom = 380.886
Ha: diff < 0	Ha: diff = 0	Ha: diff > 0
Pr(T < t) = 0.8582	Pr(T > t) = 0.2836	Pr(T > t) = 0.1418

Table 23: A simple test of the capability hypothesis – correlation between the specialization and the percentage of collaboration by technology (micro classification)

	Correlation	# of Patent	Degree of Correlation
Sony	0.11	772	
Yaskawa	-0.14	501	
Toshiba	-0.04	475	
MHI	-0.06	375	
Mitsubishi Electric	0.38	336	
Toyota	-0.46	277	**
Hitachi	-0.18	255	
Kawasaki HI	-0.21	239	*
NTT	-0.36	205	*
Meidensha	-0.09	180	
Kobe Steel	-0.39	130	*
Fujikoshi	-0.32	115	*
Daihen	0.31	97	
ATR	-0.23	64	*
Fuji Electric	-0.05	53	
Mitsui Engineering and Shipping	-0.35	42	*

*Note: As for the degree of correlation, * indicates a weak correlation and ** a moderate correlation (if one considers that 0.2-0.4=weakly correlated, 0.4-0.6=moderately correlated, 0.6-1=highly correlate). We also made a T-test of correlation, according to which only in the case of Toyota, NTT and Kobe Steel one can reject the null hypothesis of absence of correlation at 10%. However, this test is not reported here as its significance should be considered with caution: for each firm the sample of observations is between 20 and 15, which is too small to conduct rigorously a T-test.*

ANNEX 1: Major Players in the robot industry

Final Product Makers:

Industrial robots: Fanuc, Yaskawa Electric Corp., Kawasaki Heavy Industries, Kobe Steel, Daihen Corporation, Toyota Kohki Co.Ltd., Nachi-Fujikoshi, Mitsubishi Electric Corp., Yamaha Motor Co. Ltd., etc.

Non-Industrial robots: Honda Motor Co. Ltd., Toyota Motor Corporation, Fuji Heavy Industries Ltd., Mitsubishi Heavy Industries Ltd., Sony Corporation, Fujitsu Ltd., NEC Corporation, Matsushita Electric Works Ltd., Hitachi Ltd., Ishikawajima-Harima Heavy Industries Co. Ltd., Kawada Industries Inc., Bandai Co. Ltd., Megahoues Corporation (palbox; former Tsukuda-original), Omron Corporation, Sougo Security Services Co. Ltd., Secom Co. Ltd., Tmsuk, Japan Logic Machine, ZMP Inc., etc.

Component Makers:

<u>Censor System</u>

Visual Censor

CCD: Sony Corporation, Matsushita Electric Works Ltd., Sharp Corporation, Fuji Film Microdevices Co. Ltd., Hamamatsu Photonics K.K., etc.

CMOS: Mitsubishi Electric Corp., Toshiba Corporation, Olympus Corporation, Hitachi Ltd., Fujitsu Ltd., etc.

Supoersonic Waves Censor: Nippon Ceramic Co. Ltd., Murata Manufacturing Co. Ltd.,

Power Censor: Nitta Corporation, BL Autotec, Ltd., etc.

Gyro Censor: Mitsubishi Electric Corp., NEC Tokin Corporation, Panasonic Electronic Devices Co. Ltd., Tokimec Inc., etc.

<u>Powertrain (actuator, modulator)</u>

Linear Motor: Yaskawa Electric Corp., Sodick Plustech Co. Ltd., Hitachi Ltd., Yokogawa Electric Corporation, etc.

Servo Motor: Yaskawa Electric Corp., Mitsubishi Electric Corp., Matsushita Electric Industries Co. Ltd., Fanuc, Tamagawa Seiki Co. Ltd., Omron Corporation,

Linear Guide, XY Table: THK Co. Ltd., NSK Micro Precision Co. Ltd., Nippon Thomson Co. Ltd., Union Tool Co., Central Motor Wheel Co. Ltd., etc.

Modulator: TS Corporation, Harmonic Drive Systems Inc., Sumitomo Heavy Industries Ltd., etc.

<u>Mechanical Brain, Control Systems</u>

Walking with two feet technology: Honda Motor Co. Ltd., Sony Corporation, Kawada Industries Inc., Fujitsu Automation Ltd., General Robotix Inc., etc.

Face expression control technology: AGI Inc., Kokoro Co. Ltd.,

Voice recognition technology: Asahi Kasei Corporation (Voice Inerface Project), NEC System Technologies Ltd.,

Mechanical Brain: InterRobot Inc., CAI Inc., AGI Inc.,

Governments

Central government

Ministry of Economy, Trade, and Industry (METI)

Ministry of Education, Culture, Sports, Science and Techonology (MEXT)

Ministry of Internal Affairs and Communications

Related organizations (Independent Administrative institutions)

New Energy and Industrial Technology Development Organization – NEDO (METI)

Advanced Industrial Science and Technology – AIST (METI)

RIKEN (MEXT)

Japan Science and Technology Agency – JST (MEXT)

Japan Society for the Promotion of Science – JSPS (MEXT)

Local governments

Fukuoka Prefecture

Fukuoka City

Kitakyushu City

Osaka Prefecture

Gifu Prefectue

Public Research Institutes

Kitakyushu National College of Technology, Human Media Creation Center,Industrial Technology Center of Nagasaki

Fukuoka Industrial Technology Center

IRS

Gifu National College of Technology (Control Engineering Lab)

Universities

Aichi Institute of technology (Tetsujin Project)

Chiba university (Control and Robotics Lab)

Chuo University (Osumi Lab)

Cranfield University

Fukuoka Institute of Technology

Hiroshima University (Robotics Laboratory)

Kanto Gakuin University

Kumamoto University (Uchimura Lab.)

Kyoto University (Sato Laboratory)

Kyshu Sangyo University
Kyushu Institute of Technology (Ishikawa Lab.)
Kyushu Institute of Technology (Kitamura Lab.)
Kyushu Institute of Technology, (LSSE, Ishii lab)
Kyushu Polytechnic College
Kyushu Tokai University
Nagasaki University (Ishimatsu Lab.)
Nara Institute of Science and Technology (Information Science)
Nippon Bunri University,
Okayama university (Department of Systems Engineering Intelligent Machine Control Laboratory)
Osaka University (Ishiguro Lab.)
Robot Research Club Tokyo Univ. of A&T
Robotics Research Institute
Saga University (Watanabe Lab.)
Saitama University
Shizuoka University, (OIWA Laboratory)
The University of Electro-Communications (Nakano Lab.)
The university of Kitakyushu (faculty of environmental engineering)
Tohoku University (Uchiyama Lab.)
Tokyo university (Tachi lab.)
Tottori University (Department of Electrical and Electronic Engineering.)
Waseda University (Takanishi Lab.)
Yamaguchi University
Yamanashi University (Kiyohiro Lab.)

Miscellaneous

Trade Association

Japan Robot Association (JARA)

Academic Society

Robot society of Japan (RSJ)

Annex 2: List of the 19 interviewees (March - December 2006)

Public institutions

- CSTP – JST: Mr Tanie (section of the CSTP in charge of the evaluation of the public policy in the robot technology field);
- METI: Mr. Tsuchiya (Economic Industrial Policy Bureau, Industrial Revitalization Division;
- Ministry of Public Management, Home affairs, Posts and Telecommunications: Ms Otsuka (Research Promotion Office);
- NEDO: Mr. Manabe;
- AIST – JRL – ISRI, Mr. Matsuo, Mr. Hirukawa and Mr. Kheddar (CNRS – Toulouse);
- Kenkyukai: Mr Gonaikawa (CEO of UNI-FI Research Institute)
- Fukuoka Prefecture government & RIDC: Mr FUKUMOTO

Private firms

- Mitsubishi MHI: Mr Murata
- Yasukawa: Mr Fujiishi and Mr Yokoyama
- Toyota: Mr Takagi
- Yamaguchi robotics institute: Mr Yamaguchi
- ZMP: Mr Taniguchi (CEO)
- Tmsuk : Mr Takamoto,CEO

Universities

- Dr. Oguro Ryuichi, associate professor at Kyushu Institute of Technology Faculty of Computer Science and Systems Engineering Department of Systems Innovation and Informatics

-Prof. Hasegawa Tsutomu, Kyushu University, Faculty of Information Science Electrical Engineering, Department of Intelligent Systems, & member of RDIC (Fukuoka)

-Prof Yamamoto Motoji, Kyushu University, Faculty of Engineering, Departments of Mechanical Engineering Science and Intelligent Machinery and Systems, Control Engineering Lab.

Other

- Robosquare: Mr Shinkawa
- JARA: Mr Yanai (general affairs)
- International Rescue System Institute (NPO): Mr. Ishiguro