博士論文

Industrial Organization, Innovation, and Public Policy
－A Case Study of Robot Technology in Japan－

横浜国立大学大学院
国際社会科学研究科

池田　幸生
Yukio Ikeda

2009 年 9 月
September. 2009

Introduction

Research objectives

The innovation policy has recently become one of the most important agenda in many developed and developing countries, and one can see a growing public and academic interest in the innovation systems and programs. In Japan, comprehensive innovation policy began with the enactment of Science and Technology Basic Law in 1995, and 40 trillion yen had been invested to R&D activities between 1995 and 2005 by the government.

This paper examines robot technology (RT) in Japan, which is one of the prioritized field in the Science and Technology Basic Plan, as a case study to analyze innovation system and policies. The questions that the paper attempts to answer are as follows.

1) What are the characteristics of innovation activities in this industry?
2) Does market failure exist in this industry? If so, what is the source of market failure and how can it be solved?
3) How can the government policies and supports this industry be evaluated?

To answer these questions, this paper first qualitatively analyzes robot technology and indicates that the lack of corporation among firms in R&D is a bottleneck to the development and the promotion of inter-firm collaboration is a key to the development (Chapter 1). Based on the analysis of Chapter 1, Chapter 2 quantitatively examines the status of inter-firm R&D collaboration of RT in Japan by utilizing patents data. Chapter 3 of this paper, in turn, evaluates the RT-related government sponsored R&D consortia in Japan, which is the major policy instrument to this industry.

Plan of this paper and the background of the analysis

This paper examines characteristics of innovation activities in RT and in turn empirically analyzes collaborative R&D and government sponsored R&D consortia in Japan. These topics have been analyzed extensively in the economic literature, but were examined independently without clear indication of their relation. This paper systematically analyzes these subjects and attempts to contribute to understanding the problems of innovation and the role of government in innovation.

Chapter 1 of this paper qualitatively analyzes the robot technology based on the viewpoint that there is significant variety in technology on which firms and industry are depended. A comprehensive framework that examines the variety in technology among sectors was first suggested by Pavitt (1984). Based on the concept of technological trajectories, which was first introduced by Nelson and Winter (1977) and extended by Dosi (1982), Pavitt (1984) classified industry sectors by the determinants of technological changes and proposed five major technological trajectories. Martin and Scott (2000) extended the framework of Pavitt (1984) and developed typology of innovation modes, sectoral innovation failures, and policy responses.

The analysis of this chapter indicates that the possible source of innovation failure in RT comes from its complexity in technology. Based on the framework of Martin and Scott (2000), it is suggested that the promotion of R&D collaboration among firms is a key to the development of this industry. In Chapter 1, it is also argued there is not enough inter-firm collaboration in RT in Japan and the collaboration among firms should be encouraged for the development of this industry.

Recent work of Malerba (2004) provides another framework to look at innovation in sectors. Malerba (2004) suggests a *sectoral systems of innovation framework* which are affected by three main building blocks (knowledge and technologies, actors and networks, institutions) and analyzed the six main sectors in Europe based on this framework. An important feature of this framework is the inclusion of the network of non-firm agents and the role of institution (such as norms, routines, rules), which had not been paid much attention in the economic literature. The concept of *sectoral systems of innovation*, he claims, plays important role in the relation with *national institutions* as national institutions have different effects in different sectors. The analysis based on sectoral systems, thus, complements other concepts such as *national systems of innovation* and *technological systems*.

Based on the analysis of Chapter 1, Chapter 2 empirically examines the status of inter-firm R&D collaboration of RT in Japan. One can see a remarkable increase in the empirical literature on R&D collaboration in the recent years as the importance of this topic has been recognized[1]. Most of the empirical analysis on R&D collaboration attempts to find one or both of the following issues.

-What are the determinants and motives for firms to engage in R&D collaboration?
-What are the effects of R&D collaboration to participating firms?

The analysis of Chapter 2 of this paper also tries to answer these questions by utilizing the patents data.

One important reason to analyze RT is the fact that there are very few empirical studies that analyzed robot industry as a case study. The examples of such studies include Kondo (1990) and Kumaresan & Miyazaki (1999). Also, Lechevalier, Ikeda, and Nishimura (2007) analyzed the status of R&D collaboration in RT in Japan. This paper utilizes the patents data in RT used by Lechevalier, Ikeda, and Nishimura (2007) and attempts more detailed analysis of collaboration of RT in Japan by classifying various types of R&D collaboration. Analysis of Chapter 2 shows that half of the inter-firm R&D collaboration in RT have been conducted within the group firms

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[1] For the survey of theoretical and empirical literature on R&D collaboration, see Hadedoon et al. (2000).

and this type of collaboration do not exert positive effects on the productivity of participating firms. Also, R&D collaboration with firms which are outside of group have positive effects on the productivity of participating firms, but the rivalry among firms and existence of transaction costs hinder the realization of R&D collaboration of this type.

Chapter 3 of this paper in turn empirically evaluates RT-related government sponsored R&D consortia in Japan, which is the major policy instrument to this industry. There are a number of empirical studies that evaluate the government sponsored R&D consortia. Most of these studies are, however, the case studies on limited number of projects. The examples of such case studies include the research on SEMATCH project of semiconductor in the US (Irwin and Kelnow 1996, Link et al 1996) and fifth generation computer project (Odagiri et al. 1997)[2].

There are a very few studies that empirically analyze this problem using a relatively comprehensive dataset. An example of such studies is Branstetter and Sakakibara (1998), which uses a sample of 145 government-sponsored R&D consortia in Japan to examine the effects of participation to the consortia on the level of research expenditure and research productivity of firms. Lechevalier, Ikeda, and Nishimura (2008) extend the empirical study of Branstetter and Sakakibara (1998). They consider that government sponsored consortia is one form of R&D collaboration and analyzed the effects of government spomsored R&D consortia by comparing market-coordinated R&D collaboration (inter-firm collaborative R&D) and government-coordinated R&D collaboration (government sponsored research consortia). The analysis of Chapter 3 of this paper utilizes the viewpoint that Lechevalier, Ikeda, and Nishimura (2008) proposed and shows that government appear to have played the role of coordinator, helping to realize such R&D collaboration that cannot be undertaken in the market but that have significant effects on research productivity.

The final section gives the summary of this paper. An important feature of this paper is the systematic analysis for the sectoral characteristics in innovation, collaborative R&D, and government sponsored consortia in the field of RT. A motive for the research comes from the viewpoint that the sources of innovation failure are different among industrial sector. The evaluation of government policy should reflect this fact as the expected role of government is also different among industrial sectors. The results of the analysis in this paper can be summarized as follows. Where inter-firm collaboration is required in innovation but the collaboration is hindered by rivalry among firms and transaction costs, the active involvement of the government as a coordinator to conduct large scale projects is necessary.

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[2] See Okada (2006) for the survey of case studies of government R&D projects. Also, for the survey of empirical studies on government R&D project, see David et al. (2000).

Chapter 1:
Market failures in innovation and the case study of robot technology

This chapter attempts to qualitatively analyze robot technology (RT) in Japan and propose policies that are appropriate to the current status of technology and businesses in the robot industry in Japan. In order to achieve this objective, this chapter first review theories on market failures in innovation which justifies the government involvement in innovation. Then, it analyzes the technological characteristics of RT and gives the policy implication based on it.

Analysis of this chapter clarifies that an important feature of RT is its complexity, and the development of robots requires highly specialized technologies in various fields. This implies that the collaboration and cooperation are important for the development of the industry and the policy should be directed to promote the collaboration among firms.

The subsequent sections of this chapter are organized as follows. Section 1 provides a theoretical overview on market failures in innovation, which gives justification of government involvement in this area of economic activities, and discusses policy tools to correct the market failures in innovation. This section also briefly describes the innovation policy in Japan. Section 2 examines the characteristics of robot technology based on the theoretical framework suggested by Martin and Scott (2000). Section 3 depicts the recent movements in robot industry and robot technology in Japan. Section 4 outlines RT related public policies in Japan. The final section gives the conclusion of this chapter

1: Theoretical review on the role of government to innovation

1 -1: Market failure in innovation and the roles of government

One can see the recent increase in public attention to the policies toward science and technologies and the increase of government involvement in promoting innovation activities in many countries. Theoretically, government involvement in economic activities is justified as a correction to various market failures. Market failures in innovation processes involve various kinds of market failures such as public goods, externalities, and risks (Uekusa, 2006).

Goods that are nonrivlrous and unexcludable are called public goods. Ideas, which are necessary elements of technology, are inherently nonrivalrous and at least partially excludable (Romer, 1990). This implies that technologies have important characteristics of public goods. Also, some knowledge and technologies not only impact one sector of the economy but also exert significant externalities to other sectors or the whole economy. In that case the social benefit of innovation is much greater than private benefit accrued by the innovation. Furthermore, incentive for innovation is reduced by the risks that involve it (Uekusa, 2006).

Because of the existence of these market failures, there is no guarantee that market economy produces socially optimum level of innovation activities, and government can play a role in correcting these market failures by supporting R&D activities. The policy methods to support R&D activities can take two approaches. One approach is to encourage public R&D activities thorough public research institutions and universities. The other is to promote R&D in private institutions through tax credits, subsidies, and government sponsored cooperative R&D.

David et al. (2000) points out that there are important differences among these policy tools in their economic impacts. While tax credits directly reduce the marginal cost of R&D, subsidies raises the marginal return on R&D. There is no crowding-out effect of both tax credits and subsidies on industrial R&D. Government sponsored cooperative R&D, however, have the crowding out effect of private R&D in case of inelastic supply of the inputs for R&D (David and Hall, 2000).

1-2: Innovation policy in Japan

Comprehensive innovation policy in Japan has started with the enactment of Science and Technology Basic Law in 1995. Since then, Science and Technology Plan has been implemented every five years. With the first Basic Plan (1996-2000), the government expenditure on R&D has increased to 17 trillion yen (in five years), and the plan attempted to achieve such targets as the increase in post-doctoral fellows, promotion of industry-academia-government collaboration, and implementation of evaluation systems. In 2001, Council for Science and Technology Policy (CSTP) was established in the Cabinet Office. The CSTP has played a coordinating role among the ministries in the science and technology policies. The second Basic Plan (2001-2006) selected life science, IT, environmental science, and nano-technology as primary prioritized areas and budgeted 24 trillion Yen in five years. The third Basic Plan was started to be implemented in 2006. It budgeted 25 trillion yen in five years and selected secondary prioritized areas (energy, MONOZUKURI technology, infrastructure, outer space and oceans) as well as primary prioritized areas listed above. The target of the third plan include the expansion of opportunities of female researchers, increase the attractiveness to work in Japan for foreign researchers, and the promotion of regional innovation activities conducted by local universities.

Along with the various policy measures that are associated with the Basic Plans, there are a couple of policies which worth mentioning. First, there are several tax incentives for experiment researches. In 2003, special tax deduction scheme for experimental research (allowing firms to deduct 8-10% of experimental research spending) was established. Also, even higher tax deduction is allowed for SMEs, for IT related researches, and the collaborative researches among universities, governments, and firms.

Moreover, in 1998, Japanese Small Business Innovation Research (SBIR) was enacted. It allowed ministries to provide subsidy to promote innovation of SMEs. Furthermore, various measures to encourage the collaboration between universities and firms such as TLO act and Japanese Bayh-Dole act have been enacted since 1998.

2: Sectoral difference in innovation

2-1: Theoretical review

Section 1 of this chapter formulates the theoretical explanation to the government involvement to innovation from the neoclassical point of view. As early as 1980s, however, there was a wide range of dissatisfaction to the representation of technological change in the neo-classical economic model. One of such dissatisfaction comes from the fact that the neo-classical model fails to capture the considerable variety in innovation process which was revealed by empirical studies (Nelson 1981, Rosenberg 1982). Since then, a number of industrial economists have tried to generalize sectoral patterns of innovation. The analysis of Sherer (1982) was one earliest attempt of such generalization. He looked at the generation and use of patents and constructed an intersectoral matrix of the origin and use of R&D in the U.S economy.

It is, however, the work of Pavitt (1984) which first present a comprehensive framework of the diversity of innovation process. An important feature of the analysis of Pavitt (1984) is the utilization of the notion of "technological trajectories" which was first proposed by Nelson and Winter (1977) and elaborated by Dosi (1982). According to Dosi (1982), a technological trajectory is "the pattern of normal problem solving activity (i.e. of progress) on the ground of a technological paradigm", where technological paradigm is defined as "model and a pattern of solution of selected technological problems". Pavitt (1982) uses the data on about 2000 significant innovations in Britain since 1945 and classified them into four groups (science based, supplier dominated, scale intensive, specialized intensive) based on the determinants of technological trajectories.

Martin and Scott (2000) extended the analysis of Pavitt (1982) and developed a typology of innovation modes, sectoral innovation failures, and policy responses (Table 1-1). A significance of their analysis is the combination the framework of Pavitt (1982) and the notions of market failures in innovation which is articulated in the neo-classical economic theories. The analysis of the following sections of this chapter is based on the framework suggested by Martin and Scott (2000).

2-2: Characteristics of innovation in RT

One important feature of the development of robots is its complexity. It involves various kinds of highly specialized technology such as censor, powertrain, intelligence, and control technologies which are the objects of various industries. Thus, any single company is not

Table 1-1 : Innovation modes, sources of sectoral innovation failure, and policy responses
Source: Martin and Scott (2000)

	Main Mode of innovation	**Sources of sectoral innovation failure**	**Typical sectors**	**Policy instrument**
1)	Development of inputs for using industries	Financial market transactions cost facing SMEs; risk associated with standards for new technology; limited appropriability of generic technologies	Software, equipment, instruments	Support for venture capital markets; bridging institutions to facilitate standards adoption
2)	Application of inputs developed in supplying industries	Small firm size, large external benefits; limited appropriability	Agriculture, light industry	Low-tech bridging institutions to facilitate technology transfer
3)	Development of complex systems	High cost, risk, limited appropriability	Aerospace, electrical and electronics technology, telecom/computer	R&D cooperation, subsidies; bridging institutions to facilitate infra-structure technology
4)	Application of high-science-content technology	Knowledge base originates outside commercial sector	Biotechnology, chemistry, materials science, pharmaceuticals	High-tech bridging institutions to facilitate diffusion of advances in big research

capable of dealing with all aspects of robots systems (JARA, 2001). Similar characteristics can be found in the analysis of Wengel and Shapira (2004) on the sector of machine tools-an important part of RT. They state that the sectoral scope of innovation in machine tools has been expanded and the sectoral system involves extensive innovation networks of various kinds of institutions with complementary skills. This indicates that the RT is classified into the type 3) in the table 1-1. For this kind of industry, market failure in innovation arises because the R&D projects require costs and technologies that cannot be dealt with by any single firm. Also the high risk involved in the R&D activities limit expected private gains; thus, the equilibrium level of R&D is deemed to be significantly lower than the socially optimum level.

3: Overview of robot industry and RT in Japan[3]

The Japanese robot industry has grown significantly in the 1990s mainly due to the boost of plant and equipment investment in the fast-growing IT industry. Japanese robot manufactures' production values exceed 600 billion Japanese Yen in the early 2000s, ranking the first in the world in production. There have also been a series of new movements in R&D and dramatic technological advances in robotics technologies since the early 1980s. Namely, many firms have invested a lot of effort developing "next generation robots" which consist of new types of industrial robots and service robots. Service robots are the ones that are used outside factories, in places such as households and public areas.

The leaders in the development of "new generation industrial robots" are mainly composed of robot makers with long tradition. They include "biggest four" in the robot industry (FANUC, Yasukawa, Kawasaki Heavy Industry, Fujikosi), Denso, largest small type robot maker, Mitsubishi Electric, and Cannon. Among them, FANUC leads in the development of artificial intelligence in robotics, and several robot cells that use its state-of-art intelligent robots are currently in operation. Yasukawa leads in the development and production of arm robots, and started to produce a new generation industrial robot which have two hands and seven pivots in 2006. Also, Canon utilizes its knowledge in image processing and censor as a precision machinery maker and has been conducting researches on elements technologies of robotics that can be applied to its production lines.

One significant feature in the recent movements of RT is the development of service robots and it has gone hand in hand with the entry of many firms in various industries into the robot industry. Examples are some electric appliance makers (such as Sony, Fujitsu, NEC, Matsushita, Omron), automotive makers (such as Honda and Toyota), general machinery makers (such as Fuji Heavy Industries and Mitsubishi Heavy Industries), securities companies (such as SECOM

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[3] This section is based on Lechevalier, Ikeda, and Nishimura (2007), JARA (2001), and Ishihara and Gonaikawa (2007).

and ALSOK), and venture firms that specialize in RT (such as Tmsuk, Viston, and ZMP). There are a number of service robots which have been put into the markets. They include business-use cleaning robot, "RFS", by Fuji Heavy Industry, home robot, "Wakamaru", by Mitsubishi Heavy Industry, hobby robot "Tetsujin" by Viston, and reception robot, "Ridic", by Tmsuk.

In spite of the considerable efforts of these firms of R&D on service robots, they are still at the dawn of market cultivation and there is not such robot that is successful on the market where AIBO by Sony is an exception. Indeed, many point out that the lack of cooperation among firms is a major bottleneck for the development in RT.[4] Lechevalier, Ikeda, and Nishimura (2007) empirically analyzed the condition of R&D collaboration in RT in Japan and finds that the level of collaboration is quite low even though the engagement in R&D collaboration has positive impact on firms' research productivity. During the interviews we conducted with a number of related firms, most of the interviewees claim that there is less collaboration in R&D among firms than there should be. Thus, it is clear that the current status of RT in Japan is characterized as a low degree of collaboration and the collaboration among firms should be encouraged for the development of this industry.

4: Public policies in the field of robot technology

The new development in the R&D activities of "next generation robots" has attracted a great deal of public attention, and a number of central and local governments have been involved with supporting this industry. The public involvements on RT have been extended to the domain of various ministries in the central government. However, only the Ministry of Economy, Trade, and Industry (METI) and Ministry of Internal Affairs and Communication (MIC) have had relatively comprehensive views on the industry-wide technological development, and their budgets on RT related projects are the biggest among these ministries. The involvements of other ministries (Ministry of Education, Culture, Sports, Science and Technology, Ministry of Health Labor and Welfare, Ministry of Land, Infrastructure and Transport, Ministry of Agriculture, Forestry and Fisheries) are more focused on very specific issues which relates to RT.

The following parts of this section briefly describe the involvements of each ministry on RT.[5]

Public policies of METI on RT

METI has been engaged in the RT related commissioned R&D projects since the early 1980s, and most of the such projects are carried out by its R&D agency, NEDO. By the late 1990,

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[4] This kind of claim can be found in JARA (2001), Tanie(2004), and Nakayama(2006)

[5] The following parts of this section is based on Lechevalier, Ikeda, and Nishimura (2008) and Kansai Jisedai Robot Suishin Kaigi (2006).

METI had not have a general strategy on the development of the industry, and the topics of RT related projects of NEDO in the 1980s and 1990s were focused to very specific fields. These projects include "Robot for Hazardous Zone" (1983-1991), "R&D on the Micromachine Technology" (1991-2000), "Mobile Meal Delivery Robot for Aged and Disabled People" (1995-1999), "The Surgery Support System for Brain Tumors" (1998-2000).

In 1998, NEDO started to carry out the Humanoid Robotics Project (HRP). HRP project was the first project which had an industry-wide strategic view, and the projects was aimed at developing humanoid robots, which was thought to bring about a significant technological breakthrough and various commercial applications. Various manufacturing firms participated to this project, including Honda which was considered to be the leading firm in this field. The achievements of the projects include the development of a comprehensive hardware (HRP-2) and comprehensive software (OpenHRP). However, it actually did not generate any commercial outcomes. Some criticize that the goal of the project was too vague without any clear views on connecting to the R&D to commercial applications.

Since the early 2000s, METI started to formulate the comprehensive strategy for the promotion of robotics research, and the implementation of post-HRP projects has reflected the criticism on the HRP project and was more focused on problem solving and on practical uses of robot technologies. In 2002, the 21st Century Robot Challenge Program was established. It connected all the related robot projects, and its main objective is to research on the common and basic technologies necessary for the development of robots.

In 2003, the first meeting of Robot Vision KONDANKAI (committee) was held, where important figures in the academics and businesses discuss the problems they faced.[6] The committee published a report in 2004, and the report indicated some points that the government should follow for the development of the industry. These points include the promotion of collaboration among firms and universities to complement technologies, the support for the modulerizaion and standardization of technologies, and to build up the safety standard for the uses of robots. In 2006, METI proposed New Industries Creation Strategy (NICS), and RT was selected as one of the priority industry. The recent RT projects have been implemented based on the proposals of the committee reports and the action plan in the NICS, and the themes of the projects are grouped into systematization technology, base technology, and elements technology, and the targets of each theme and the relation between them is clearly specified.

Also, subsidies have been provided to several RT related ventures companies and SMEs through NEDO and Development Bank of Japan.

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[6] Another committee for the RT related project (Robot Policy KENKYUKAI) was established in 2005.

Public policies by MIC.

MIC has been supporting the development of network robots, which uses communication and network technologies. As it has overall responsibilities on communication related policies, MIC is the sole administrator for the policies for the network robots at the central government level. The public policies on network robot first appeared in the R&D projects on the Network Human Interface (NHI), and "Network Robot where Ubiquitous Network Technologies and Robot Technologies" was carried out between 2004 and 2008 as one topic of NHI projects. This was a commissioned R&D project, and its target is to establish the necessary component technology to materialize network robot. The project was carried out by National Institute of Information and Communications Technology (NICT), an incorporated administrative agency of MIC.

MIC also conducted an empirical test on network robot in cooperation with electric firms at the 2006 CEATEC (Combined Exhibition of Advanced Technologies). Furthermore, MIC has been working with Network Robot Forum on the standardization of technology in the field of network robots.

Public policies by MEXT (Ministry of Education, Culture, Sports, Science and Technology).

MEXT funded two RT related projects: "MEXT Special Project for Earthquake Disaster Mitigation in Urban Area" (DDT Project) and "Bio-Mimetic Control Research". DDT Project is a commissioned R&D to research the disaster mitigation in urban area, and one of its programs includes robotics related technology. This program was administrated by an NGO, IRS, and is carried out between 2002 and 2007. Bio-Mimetic Control Research was conducted by Riken, an Independent Administrative Institution (IAI) subordinated to MEXT. The project aims to create advanced engineering systems such as soft human interactive robot. Also, some RT related small research program has been funded through JST, a project-oriented funding agency (IAI) under MEXT.

Public projects by other ministries

Ministry of Land Infrastructure and Transport has carried out two projects involved robotics technologies in the fields of construction and infrastructure building. These two projects are "The Development of IT Construction System by Robotics" and "The Research on the Operation and Surveillance by Underwater Robots". Ministry of Health, Labour and Welfare (MHLW) funded a research grant, "R&D for Human Body Analysis, Support, and Substitution Instrument" (2003-2008). The aim of the project is to promote the new medical instruments to substitute and support human body. The Ministry of Agriculture, Forestry and Fisheries (MAFF) funded "The Emergent Development of Next Generation Agricultural Machines Project", which aims to develop the high quality agricultural machines that will save energy, cost, and environmental damage.

Inter-ministerial coordination and involvement of the CSTP

Like the other R&D policies, the RT related public policies described above have been implemented independently by each of the ministry without inter-ministerial coordination. In the mid-2000s, the Council for Science and Technology Policy (CSTP) started to work on promoting the cooperation among the ministries in the important technological fields. In 2004, CSTP adopted "Reform on Science and Technology related budget for fiscal year 2005". Based on this plan, it appointed the coordinators to remove the duplicated projects and promote coordination among policies of ministries for respective technological fields. Next generation robot was selected as one of these technological fields, and four RT related public projects were carried out in 2004 and 2005 through the funding of MEXT to complement the existing projects.

CSTP has recently launched a program that evaluates the technology policies of the various ministries in the important technological fields which include RT. The administrative works for this program is commissioned to JST, and the coordination program for RT is led by Dr. Kazuo Tanie.

5: Summary

This chapter examined the robot technology (RT) and RT-related government policies in Japan by closely looking at the market failures in innovation of this industry. An important characteristic of RT is its complexity. The source of innovation failure in this industry is likely to be resulted from the fact that R&D projects require costs and technologies that cannot be dealt with by any single firm and the high risk involves in R&D. According to the framework of Martin and Scott (2000), the most effective way to solve this market failure is to promote R&D collaboration among firms. The current status of RT in Japan, however, is characterized as a low degree of collaboration.

The policy instruments to support this industry in Japan include the tax incentive for SMEs and formation of a committee (*kenkyukai*), however the major public support for RT is materialized in the form of government sponsored R&D consortia. It is obvious that the major figures and policy maker recognized nature of RT discussed in the preceding section (complex system that require various specific technologies and the development involve high cost and risk) and the implementation of these consortia was an attempt by the government to mitigate the market failure in innovation of this sector[7]. As R&D collaboration is an important issue for

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[7] Many RT-related committee reports states the needs for various types of collaboration in R&D such as the collaboration with systems integrators, parts makers, and users and also the collaboration with universities. These

the development of robot industry and government has been actively involved with supporting this industry in the form of government research consortia, RT should provides a very valuable case study for collaborative R&D and the issue of the government's role in innovation.

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claims have been reflected to the implementation of RT-related projects of METI.

Chapter 2: Empirical studies on R&D collaboration in RT in Japan

The analysis of previous chapter of indicates that the promotion of R&D collaboration as a key to the development of robot industry. This chapter in turn empirically analyzes collaborative R&D in robot industry in Japan. An important feature of the empirical analysis of this chapter is the consideration for the difference in the benefits and determinants for R&D collaboration among the types of partners.

Economic literature has indicated several factors that lead to the heterogeneity in the benefits of R&D collaboration depending on the type of partner. For example, Katz (1986) states that, if a firm tries to conduct R&D collaboration with a partner that competes in the market, part of the rent born out of the collaborative R&D can be lost in the subsequent market competition. This follows the argument that benefits of horizontal cooperation (cooperation between competing firms) are vitiated by the ex post market competition, while there is no such detrimental effect for vertical cooperation (cooperation with suppliers or customers) (De Bondt et at.,1992). The same logic can be applied to inter-industry cooperation versus intra-industry cooperation (Steurs, 1995). Another important factor would be transaction costs. Where uncertainty over specifying and monitoring performance of partner is higher, firms will face higher opportunistic risk when they are engaged in collaborative R&D. In-house R&D tends to be more advantageous in this case. These transaction costs are likely to be lower for the collaboration among the firms with close relations such as those with affiliated firms.

Even though a large volume of theoretical literature has been developed on this subject so far, most of the empirical studies on R&D collaboration do not distinguish R&D cooperation by type of partner. The exceptions to this include Leiponen (2001), who distinguishes R&D cooperation with competitors, customers, suppliers, and universities using 1997 CIS data for Finnish manufacturing firms, and Belderbos et al. (2004), who differentiate these four types of cooperative partners using survey data of Dutch firms.

The chapter examines the heterogeneity in R&D collaboration by differentiating types of collaboration (in-group, non-group, inter-industry, and intra-industry collaboration).[8] In-group collaboration represents the collaboration among the firms in the same company group, and non-group collaboration represents collaboration with firms which are outside of the group. The analysis based on this categorization make it possible to see the effects of market competition and transaction costs described above on collaborative R&D among firms.

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[8] Another important distinction is differentiation of the collaboration with firm, university, and public institution. Yet this paper focuses on inter-firm collaboration and does not consider the collaboration with university and public institution. For the investigation on this topic, see Lechevalier, Ikeda and Nishimura (2007).

While most of previous studies use questionnaire survey data, which inevitably encounter the problem of sampling biases, I use patent data for empirical tests. As the patent data contains data on smaller firms, so the sample is less biased than questionnaire surveys in terms of the size of institutions. Moreover, patent data contain information such as the number of claims, citations, inventors, and technological fields, which can be used as indicators of the quality of the R&D. This makes it possible to measure the benefits of collaboration as well as the determinants for collaboration, while the previous studies investigate only one of the two issues at a time.[9]

The subsequent sections are organized as follows. Section 1 describes the dataset. Section 2 empirically analyzes the benefits of collaborative research distinguishing the type of collaboration. Section 3 examines the motives and determinants for firms to engage in R&D collaboration.

This study shows that the benefits of and determinants for R&D collaboration differ significantly across types of partner. One finding is that transaction costs which relate to appropriability play an important factor for non-group collaboration but do not affect the in-group collaboration. This implies that the boundaries of firms within a group are not detrimental for in-group collaboration in terms of appropriability and monitoring costs. The analysis of this chapter also shows that in-group R&D collaboration does not exert any impact on research productivity of participating firms, whereas non-group R&D collaboration is associated with higher research productivity of participating firms. Within non-group collaboration, the impact of intra-industry collaboration on research productivity is greater than inter-industry collaboration, which suggests that rivalry among participating firm do not have negative impact on the benefits of participating firms, contrary to the prediction of theoretical studies on R&D collaboration. Even though intra-industry collaboration is most "beneficial" to the firms, it is realized in only a few occasions. This generates important implication for the nature of and development of the industry. Finally, Section 4 provides a summary of the analysis and policy implications.

1: Dataset

The dataset used in this chapter is drawn from two complementary data sources: Industrial Property Digital Library or IPDL ("koho text kensaku") and Standardized Data ("Seiri-Hyojyunka Data"). The IPDL data enable us to clearly classify 4 macro- and 26 micro-technological fields of RT. However, for some unknown reason, the JPO (Japan Patent Office) does not provide information on 6 categories ("other robots," "modular structures,"

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[9] See Lechevalier, Ikeda and Nishimura (2006) for the discussions on the merits and demerits of using patent data for the analysis on collaborative R&D.

"attachments," "control units operated by foot," "virtual reality," and "networking technology").[10] Thus, the analysis in this chapter is limited to 20 technological fields. Moreover, the IPDL only covers the patents from around 1991 and does not contain information on citations. On the other hand, the Standardized Data do include such information. Yet we cannot clearly identify the RT-related patents, and it covers patents until around 2001. Therefore, these two data were merged to get a more complete dataset for the empirical analysis in this chapter.

By doing this, 16,736 patent numbers were collected through the IPDL (12,863 patents of the total are matched with the Standardized Data). Then, unbalanced panel data which were organized by company and year were created.[11] Within these data, many firms have only a small number of patents. As it is difficult to assess the R&D productivity (quality of patents) for these firms, the firms which have less than five patents were excluded. In sum, our sample includes 316 companies and 13,711 patents,[12] with a sample period between 1991 and 2004.

As a next step, I identified the patents that derived from inter-firm collaboration using the information on the inventors of patents. The patents whose inventors belong to more than one are considered to be inter-firm collaborative patent.[13] The collaborative patent is used as proxy to measure collaborative R&D activity, and non-collaborative patent is used to measure in-house R&D activity.[14]

These inter-firm collaborative patents are further divided depending on the type of partners. The collaborative R&D between the firms in the same company group is labeled as in-group collaborative R&D, while the collaboration with the firm(s) outside of the group is labeled as non-group collaborative R&D.[15] Moreover, within non-group collaborative R&D, collaboration between the firms in the same industry is labeled as intra-industry collaborative R&D, and collaboration between firm(s) in different industries is labeled as inter-industry collaborative R&D.[16]

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[10] We did not receive a satisfying answer from the JPO as to why they are not available. This is probably due to identification problems for these six technologies.

[11] See Lechevalier, Ikeda, and Nishimura (2007) for more details on the creation of dataset.

[12] Among these patents, some patents overlap because some are collaborative patents.

[13] As this paper focuses on the analysis of inter-firm collaboration, the collaboration with university or public institution is not considered to be collaborative patents.

[14] Patents data are often used in many empirical studies on innovations as proxy for innovative activities. However, according to Jaffe and Trajtenberg (2002), there are two types of limitations in using them. 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 "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.

[15] 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. I used this definition because the relevant information is readily available at the company homepages, and these are the companies that firms subjectively recognize they are closely related.

[16] The classification of industries is based on '*Shikiho*'.

2 Impact of engagement on R&D collaboration

In this section, I try to examine if R&D collaboration exert benefits to the participating firms and if it differs depending on type of partners. To do this, I conduct economic estimation to see if collaborative research will affect research productivity of participating firms, by using quality indicators of patents such as the number of claims and inventors. Before describing the empirical model, brief reviews on the theoretical and empirical literature on this topic are provided.

2-1: Review on theoretical and empirical literature

The theoretical explanation to justify collaborative R&D is originated from the pioneering study by Spence (1984).[17] Spence indicates that R&D activities are involved with two types of market failures which counteract each other. The existence of knowledge spillovers leads to incomplete appropriability of the R&D results, and thus the equilibrium level of R&D is deemed to be significantly lower than the socially optimum level. The enhancement of intellectual property rights corrects the incentive problem of R&D. Yet this will create the duplication of R&D activities and hence leads to an excessive level of R&D. Under these circumstances, R&D collaboration can mitigate the tradeoff between the incentives for appropriation and the duplication of R&D and can provide a solution for the dilemma. Collaborations enable the participating firms to internalize the externality created through spillovers, and the spillovers which are internalized constitute the benefit for these participating firms.

The level of spillovers that collaborating firms can internalize depends on number of elements, and economic literature has suggested two main factors for it: the level of ex post market competition and technological proximity among participating firms. For example, Katz (1986) states that the incentive to form R&D collaboration can be affected by the states of the ex post market competition. If a firm tries to conduct R&D collaboration with a partner that competes in the market, part of the rent born out of the research can be lost in the subsequent market competition. Thus, if the market competition among the collaborating firms is intense, welfare gain of single participating firm is offset by the fall in costs of its rivals that come with collaboration. Anticipating this effect, firms set their R&D activity levels lower than they would achieve in equilibrium without research collaboration. Steurs (1995) uses this idea and shows that equilibrium ex post R&D investment level is lower for intra-industry cooperation than inter industry cooperation. Attallah (2002) uses the same logic and indicates that horizontal cooperation may decrease R&D investment level while vertical cooperation with suppliers is not affected by such detrimental effect.

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[17] This paragraph is based on Lechevalier, Ikeda, and Nishimura (2008)

Branstetter and Sakakibara (2002) is an example of the empirical studies that considers the relation between benefits of collaboration and rivalry among participating firms. They uses the a sample of 145 government-sponsored R&D consortia in Japan and finds that the outcomes of the consortia are (weakly) negatively related to the degree of product market competition among participating firms, as Katz model predicts.

Also, a number of economic researches point to the relation between the welfare impact of collaborative research and technological proximity among the participating firms, yet there are two countervailing arguments. On the one hand, there is an argument based on the concept of "absorptive capacity" of firms. According to this type of argument, the level of incoming spillovers to participating firms is higher if their absorptive capacities are higher, and the absorptive capacity of a firm is higher when the technological proximity among the collaborating firms is higher. For example, Cohen and Levinthal (1989) claims that, for the collaborative research to be successful, the prior knowledge of a firm must be similar to the new knowledge on the basic level.

On the other hand, resource-based strategic management theory (also known as "capability theory") suggests that benefits of collaboration for a participating firm is accrued from its access to complementary knowledge. Thus, the effect of collaboration is greater if the partner firms have different technological orientation.

The empirical studies on this issue provide diverse results. On the one hand, Branstetter and Sakakibara (2001) uses a sample of Japanese government-sponsored R&D consortia involving 213 firms and find that diversity in technological fields among the participating firms is associated with greater R&D expenditure by participating firms. On the other hand, Banstetter and Sakakibara (2002) used the same dataset and find that level of similarity in technology among participating is associated with higher outcomes of consortia.

2-2: Empirical model and variables

A simple model of research productivity is specified for estimation. I assume that productivity of the R&D activities is a function of firm level R&D spending and the intensity of engagement in collaborative R&D.

$$Ni = f\ (Ri,\ Ci,\ Zi) \qquad (1)$$

where Ni is innovation, Ri is R&D spending, Ci is intensity of engagement in collaborative R&D, and Zi is other factors that affects the innovative level of firm i.

To estimate this model, I use the number of claims for patents as a proxy measures for the unobservable "innovation". The claims in the patent specification delineate the property rights protected by the patent. The larger the number of claims, the broader and the greater the expected profitability of an innovation is. While the number of patents has often been used as a proxy for "innovation" (for example, Sakakibara & Branstetter, 2002; Darby et al., 2003), the number of claims is considered to be proxy to measure "quality-adjusted R&D productivity" and has recently been alternatively used as proxy for the outcome of innovation activities.[18]

Concerning R&D spending, ideally it would be desirable to collect data on R&D expenses in the RT field by each firm. It is, however, extremely difficult to obtain such data; thus, the number of inventors of patents is used as a proxy for R&D expenses. This variable is considered to measure the scale of a research project and the accumulation of human capital. Goto et al. (2006) and Mariani and Romanelli (2006) use the number of inventors as a proxy for R&D expenses and find that this variable has a significant and positive impact on R&D productivity.

The model is based on firm level observation. Estimation based on firm level data is expected to capture the spillover effects of collaboration to the collaborating firms rather than direct impact of collaboration on the quality of its research (patents).

The equation I seek to estimate is based on the (1) and takes the form of

$$N_{it} = \beta_0 + \beta_1 Intra_{it} + \beta_2 Inter_{it} + \beta_3 Ingroup_{it} + \beta_4 R_{it} + \beta_5 Tech\_Proximity_{it} + \beta_6 Scicence_{it} + \mu_{it} \tag{2}$$

where

N_{it} = the number of claims of patents generated by firm i in time t;

$Intra_{it}$ = the number of intra-industry collaborative patents for firm i in time t
$Inter_{it}$ = the number of inter-industry collaborative patents by two or more firms for firm i in time t
$Ingroup_{it}$ = the number of in-group collaborative patents by two or more firms for firm i in time t

The coefficients of these three variables indicate the impact of each type of collaboration on research productivity. As the degree of competition is greater for intra-industry collaboration then inter-industry collaboration, the coefficient of *Inter* is expected to be higher than that for *Intra*. Also, the coefficient for *Ingroup* is expected to be higher than that for *Inter* for the same reason.

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[18] The numbers of forward and backward citations of patents are also often used as proxies to measure research productivity of firms. Yet the data of citation is included only up to 1997 in the dataset, so the number of citations is not used for the estimations in this paper.

R_{it} = the number of inventors for the patent

$Tech\_Proximity_{it}$ = the index of technological proximity for the collaborative partners. The proximity between two firms is calculated based on the framework suggested by Jaffe (1986). This variable measures the similarity in technological fields among firms which engaged in collaborative R&D. Negative coefficients for this variable will indicate that the result is consistent with capability theory, whereas a positive coefficient will indicate the consistency with absorptive capacity argument.

$Science_{it}$ = the number of patents in the "science-based" technologies among the sub-types of RT technologies.[19] R&D activities in science-based technology are more complex and exert more uncertainty, thus more collaboration is expected.

The dependent variable of the models (the number of claims) is a count variable that takes on nonnegative integer values and its distribution does not follow normal distribution. Poisson Regression and Negative Binomial Regression models are the two common estimators for count data. Yet one assumption of the Poisson Regression model is that its mean is equal to its variance. As the variance of dependent variable is greater than its mean in the dataset, it does not appear to satisfy this assumption. Thus, the estimation of Poisson Regression model seems to lead to over-dispersion. Accordingly, Negative Binomial Regression model will be used in the estimation of the model (2).

2-3: Sample statistics

Table 2-1 gives descriptive statistics for each type of collaborative R&D. Among 13,707 RT related patents during the sample period, inter-firm collaborative patents are only 976 (7%). Thus, the amount of inter-firm collaboration is quite limited. Of the total inter-firm collaborative patents, 490(50%) are in-group collaborative R&D, indicating that many of the inter-firm collaboration are conducted within a relatively small extent of networks. One can notice that intra-industry collaborative patents are only 39 (4% of total inter-firm collaborative patents), and it is a surprisingly small number. During the interviews I conducted with the key players in this industry, most of the interviewees state that horizontal cooperation with competitors is quite few. If we assume that intra-industry collaborative R&D is very close concept to horizontal collaboration R&D, this evidence is consistent with the comments of these interviewees.

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[19] I follow the classification defined by JPO to identify the science-based technologies. According to JPO, science-based technologies in RTs include five sub-types of 26 sub-types of all RT.

Table2-1: Summary statistics for each type of R&D collaboration

	Total Number	Backward citation	Forward citation	Claims	Inventors	Technological Proximity
In-group collaborative Patents	490	1.07	0.20	5.24	5.24	0.67
Inter-industry collaborative patents	447	1.22	0.56	2.55	3.90	0.70
Intra-industry collaborative patents	39	0.43	0.96	3.65	5.39	0.73
Total Inter-firm collaborative patents	976	1.12	0.39	3.95	4.63	0.69
Non collaborative patents	12,731	0.71	0.25	5.55	2.20	
Total Patents	13,707	0.74	0.26	5.44	2.37	

The table also gives the data on the indicators of the quality of research (patents) for each type of collaboration: the number of citations, claims, and inventors. One can notice that the number of inventors is much larger in the case of inter-firm collaborative patents than non-collaboration patents. This indicates that the scale of R&D is greater for inter-firm collaboration than in-house R&D. Also, number of claims and inventors are smaller for inter-industry collaboration than other types. Yet there is not much difference in the number of technological fields among these. Technological proximity among the participating firms is greater for intra-industry collaborative R&D than inter-industry collaboration; it is consistent with our intuition as technological orientations tend to be similar among the firms in the same industry. Also, technological proximity is smaller for in-group collaboration than other types of collaboration, which suggests that the technological orientation among firms tend to be different for in-group collaboration. It may suggest that the specializations in technological fields are built up among the group firms in RT.

2-4: Estimation results

The Table 2-2 shows the results of the estimations with fixed effects and random effects. Hausman specification test suggests that fixed model is appropriate, even though the results of both models are quite similar. The coefficient for *Tech_Proximity* is positive and significant, indicating that the level of similarity in technology among participating is associated with higher positive effects of R&D collaboration on participating firms. Thus, the argument of "absorptive capacity" rather than capability theory is relevant in this case.

If we look at the coefficients for the three types of collaboration, a very interesting variation appears. The coefficients on *Intra* and *Inter* are positive and significant whereas that on *Ingroup* is insignificant. It indicates that the non-group R&D collaboration has positive impact on the research productivity of participating firms (by spillover effects), but the in-group collaboration, which constitute more than half of the total inter-firm collaboration, does not lead to the increase in research productivity of the participating firms. Thus, while non-group collaborative R&D generates positive spillovers to participating firm in a way that Spence model suggest, in-group collaboration do not exert spillovers to participating firms. It may suggest that the motives and expected outcomes to engage in in-group collaboration are different from Spence model indicates, or it can be considered to be quasi-internal R&D.

Table 2-2: The effect of collaborative patents on R&D productivity of firms (Negative Binomial Estimation)

Variable	***Dependent variable: N (number of claims)***	
	Fixed Effects	Random Effects
Intra	0.1214*** (0.0397)	0.1424*** (0.0360)
Inter	0.0224*** (0.0094)	0.0236*** (0.0089)
Ingroup	-0.0070 (0.0156)	-0.00767 (0.0148)
R (Inventors)	0 .0087*** (0.0007)	0.00943*** (0.0006)
Tech_Proximity	0.3711** (0.2051)	0.3461** (0.1786)
Science	0.00005 (0.1110)	0.0203 (0.0969)
Constant	0.1291 (0.20882)	0.1598 (0.1898)
Year Dummies	yes	yes
Number of samples	521	582
Number of groups	118	179
Log likelihood	-1587.8787	-2522.3756
Hausman Specification test	chi2(19) = 44.63	Prob>chi2 = 0.0008

*Significant at the 10% level

** Significant at the 5% level

*** Significant at the 1% level

Moreover, the coefficient on *Intra* is much larger than that on *Inter*. This indicates that, within non-group collaboration, intra-industry type collaboration has more significant impact on research productivity than inter-industry type collaboration. These results are inconsistent with the predictions of Katz model. Thus, we can infer that rivalry is not relevant to determine the impact of collaboration on research productivity in this case. It is, however, not clear why the impact of intra-industry collaboration on research productivity is greater than that of inter-industry collaboration. One possible explanation would be that the difference in the impact between two types of collaboration may come from the degree of similarity in organizational context. Knoben and Oerlemans (2006) argue that inter-organizational collaboration is more efficient and lead to better outcomes when the organizational context of interacting firms is similar, as similarity promotes mutual understanding. Corporate culture, customs, norms, and routines tend to be similar among the firms in the same industry than with the firms in different industry, therefore transfer of knowledge may be easier for intra-industry collaboration and thus it might result in greater spillover effects than inter-industry collaboration.

To sum up, the estimation in this section suggests that the impact of R&D collaboration on research productivity significantly differ depending on the types of partners in a contradicting way to Katz model. There is no evidence that in-group collaboration has any impact on research productivity of participating firms, yet the engagement in non-group collaboration is associated with the increase in research productivity of the firms. Also, within the non-group type collaboration, the intra-industry collaboration, in which the degree of competition among the participants is higher, exerts greater effect on research productivity than inter-industry collaboration. Thus, the degree of rivalry is not relevant factor to determine the degree of impact on the research productivity of participating firms.

These facts exert important implication for the nature of and development of the industry. The estimation results suggest that among these inter-firm collaborations, in-group collaboration, which is composed of more than half of the total number of inter-firm collaboration, does not have any impact on research productivity of the participating firms. Furthermore, intra-industry collaboration, which can be found in only a few cases, is proved to be most "beneficial" type of collaboration to participating firms. It is puzzling to see that the intra-industry collaboration is "beneficial" to the firms, yet it is realized in only a few occasions. This makes us to wonder if there may be some factors that hinder such beneficial cooperation. For example, some of the interviewees state that rivalries among firms on the market and high coordination costs prevent the likelihood of cooperation among firms. These two factors may play critical roles in firm's decision to conduct (and not to conduct) collaborative R&D with other firms.

3: Determinants and motives for collaborative R&D

This section empirically examines the determinants and motives of collaborative R&D distinguishing them by type of partner. Before describing the empirical test, brief review on the theoretical and empirical literature on this topic is provided.

3-1: Theoretical Perspective

There is a vast literature that attempts to theoretically explain the motives for firms to conduct collaborative R&D. One can group them, however, into three main categories: industrial organization theory, transaction cost theory, and strategic management theory (Kogut, 1988; Hagedorn et al., 2000; and Belderbos et al., 2004)[20].

Industrial Organization Theories:

Industrial organization literature has claimed that knowledge spillover plays an important role as an incentive and disincentive for the engagement to collaborative research. On the one hand, firms try to make use of external information flow (or *incoming spillovers*) for their innovation process, and thus incoming spillovers are major incentives for collaborative research. On the other hand, firms often attempt to avoid information flows out of the company (or *outgoing spillovers*), and thus outgoing spillovers may decrease the attractiveness of cooperation. Recent studies on this topic emphasize that firms in fact have ability to control spillovers, minimizing outgoing spillovers while maximizing incoming spillovers. A key factor for firm's ability to control spillovers is the level of its absorptive capacity. Firms can increase their ability to utilize external knowledge more effectively by increasing absorptive capacity through investments in internal R&D efforts. Thus, it is necessary for firms to engage in a certain level of in-house R&D, and a key issue is to determine relative level of in-house R&D activities and the utilization of outside knowledge. Also, the concept of absorptive capacity is closely related to the technological proximity among the collaborating institutions, as the prior knowledge which is similar to the new knowledge will enhance the absorptive capacity of firms in collaborative research (Cohen and Levinthal, 1989).

Strategic Management theories

Resource based view of strategic management perspective - also known as capability theory – considers "firm" as a unit of analysis and the boundaries and structure of firms are dependent on their unique capabilities or core competences. Given that it is costly to create and maintain capabilities and is difficult for its competitors to imitate them, cooperation can be seen as a

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[20] Transaction cost theory and strategic management theory constitute the two major streams of institutional theories of firms. For the overview of the institutional theories of firms, see Langlois and Robertson (1995) and Isogai (2004).

means to effectively combine the capabilities of other firms by utilizing their complementarities. According to this argument, institutions will have an incentive to collaborate when their capabilities are different and potentially complementary. Yet, as discussed in section 2-1, this argument contradicts with the concept of absorptive capacity which claims that the similarities in technology among partners are important for successful collaboration.

Transaction Costs Theories

Transaction costs approach originates Williamson (1979), and this approach uses "transaction" as a unit of analysis. According to this branch of thought, entrepreneurs choose an institutional organization between arm's length transaction in the market and vertically integrated ownership in a way to minimize the sum of transaction costs and integration costs. On the one hand, if the costs of investing and managing different activities (integrating costs) are high, market transaction is more advantageous than integrated ownership. On the other hand, under uncertainty, asymmetric distribution of information, and bounded rationality, entrepreneurs face high opportunity risk and thus high cost of transaction in the market. Integrated ownership is preferable to market transaction in such environment.

The choice between R&D collaboration and in-house R&D can be explained in the same logic. If the participants to collaboration are likely to behave in opportunistic manner, firms tend to avert collaboration with others and in-house R&D tends to be selected rather than collaborating with others. Thus, the formation of R&D collaboration is discouraged where transaction costs are high.

The level of transaction costs which arises from opportunistic risk depends on many elements, but one main factor is the degree of definability and enforceability of property rights. When one tries to transact intangible assets such as technology, he usually faces a difficulty in specifying the range of technology to be transacted. Accordingly, each party has incentive to interpret it in a favorable to them, and this increases the opportunistic risks and decrease the incentives for transacting technology (such as R&D collaboration). The intellectual property rights system, such as patent system, mitigates the problem of these opportunistic risks as the range of relevant technology is specified in a patent.

In reality patents do not guarantee the inventor to fully appropriate profits from the invention. Also, it is suggested that the extent of such appropriability is different across industries (Nakamura and Odagiri , 2005). I will include the effects of appropriability and the differentiation across industries in the subsequent empirical analysis in this chapter.

In addition to these three major theoretical explanations, there are some other factors that may affect the probability of collaborations[15]. First, it is claimed by many that the more science based the research is, the more complex it is, and the more collaboration is required. This aspect, which is partly related to the capability argument, is suggested to be important factor for the increasing trend of collaboration in the world since the 1970s (Hagedoorn, 2002). Second, past experience of collaboration can be thought to be am important factor to affect the probability of collaboration (Hagedoorn et al., 2003). These factors are also included in the econometric models.

3-2: Empirical literature:

There are growing numbers of empirical literature on the determinants and motives of R&D collaboration. Yet these studies produce contradicting results, which imply that the nature of R&D collaboration is quite complex and it is dependent on number of factors. For example, Nakamura and Odagiri (2005) support absorptive capacity and transaction theory as the determinants for R&D collaboration based on the survey data of 14,000 manufacturing firms in Japan. Yet the empirical study of Odagiri (2003) indicates that complementarity is a major determinant for collaboration among major pharmaceutical firms in Japan, but does not support transaction costs theory as a determinant for it.

Even though it is widely recognized that the determinants for cooperation differ depending on type of partner, very few empirical studies has explore the differentiation by type of partner. Examples of these empirical studies include Leiponen (2001) who considers four types of cooperation (competitors, suppliers, customers, and universities) and shows that firm size and membership of larger group increase the likelihood of these four types of R&D cooperation. Also, Nakamura and Odagiri (2005) indicates that the level of approbiliability by patents has positive impact on the likelihood of non-group R&D collaboration but do not affect in-group R&D collaboration. One can also find some contradicting results among these empirical studies that consider the heterogeneity in determinants by type of partner. For example, Fritsch and Lukas (2001) uses sample of 1,800 German manufacturing enterprises and indicates that there is not much difference in determinants among the types of cooperation. However, Belderbos et al. (2004) argue that the determinants of R&D cooperation significantly differ across the different types of cooperation: for example, the positive impact of firm size and R&D intensity is weaker in the case of cooperation with competitors.[21]

3-3: Empirical models and variables:

Based on the theoretical discussion on collaboration above, the empirical model to examine the determinants of R&D cooperation is specified here. The estimation model is based on firm-level data and is in the form of:

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[21] This sentence is based on Lechevalier, Ikeda, and Nishimura (2007).

$$Coinv_{it} = \beta_0 + \beta_1 Appro_i + \beta_2 Spillpool_{it} + \beta 3_2 PatStock_{it} + \beta_4 Tech\_Proximity_{it} + \beta_5 Science_{it} + \beta_6 Coinvstock_{it} + \mu_{it}$$

where

$Coinv_{it}$ = the number of collaborative patents by firm *i* in year *t*.

$Appro_i$ = Industry level survey data collected by Nakamura and Nagata (2005)[22] is used for this variable. It measure firms subjective judgment as to how much patent application is effective in protecting competitive advantages from innovation, and so it is considered to measure extent of appropriability of patents. As discussed earlier, higher appropriability of patents decrease the transaction costs in the transaction of technology and encourage inter-firm collaboration. A positive coefficient for this variable is consistent with the prediction of transaction costs theory.

$Spillpool_{it}$= the spillover pool of firm *i* in year *t*. To calculate this variable, the framework suggested by Jaffe (1986) is used. This variable measures the potential level of opportunity for firm *i* to take advantage of outside knowledge at *t*. A positive coefficient for this variable is consistent with the prediction of industry organization theory, as this variable indicates potential incoming spillovers when R&D collaboration is conducted.[23]

Pat_Stock_{it} =the accumulated number of patents applied by firm *i* at year *t* with the depreciation rate of 10%. This variable is considered to measure the knowledge stock that firm *i* has accumulated by year *t*, so it is thought to be a proxy to measure absorptive capacity of the firm.

$Tech\_Proximity_{it}$ = the index of technological proximity for the collaborative partners. The proximity between two firms is calculated based on the framework suggested by Jaffe (1986). This variable measures the similarity in technological fields among firms which engaged in collaborative R&D. A negative coefficient for this variable will indicate that firms collaborate in order to obtain access to complementary knowledge, which is

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[22] The survey by Nakamura and Nagata (2005) extends only to 23 sectors, and some industries such as service industry and electric power industry. Twenty-one cases of collaborative R&D of the firms in these two industries in the sample data are exclude in the estimation.

[23] The derivation of spillover pool is presented in Appendix.

consistent with capability theory. Yet a positive coefficient for this variable will indicate that the similarities in technology are associated with the likelihood to realize R&D collaboration, which is consistent with absorptive capacity argument.

$Science_{it}$ =the number of patents in the "science-based" technologies among the sub-types of RT technologies. R&D activities in science-based technology are more complex and exert more uncertainty, thus more collaboration is expected.

$Coinvstock_{it}$= the accumulated number of collaborative patents of firm i before year t. This variable is used to test if past collaborative experience affects the tendency of collaboration in the future.

I also consider the heterogeneity in the determinants of collaboration among the different types of collaboration: in-group and non-group types of collaboration. In other words, the following models are estimated to see if and how the determinants of collaboration differ among these cases.

$$Nongroup_{it} = \beta_0 + \beta_1 Appro_i + \beta_2 Spillpool_{it} + \beta 3_2 Pat\_Stock_{it} + \beta_4 Tech\_Proximity_{it} + \beta_5 Science_{it} + \beta_6 Nongroup\_Sstock_{it} + \mu_{it}$$

$$Ingroup_{it} = \beta_0 + \beta_1 Appro_i + \beta_2 Spillpool_{it} + \beta 3_2 Pat\_Stock_{it} + \beta_4 Tech\_Proximity_{it} + \beta_5 Science_{it} + \beta_6 Ingroup\_Stock_{it} + \mu_{it}$$

where

$Nongroup_{iti}$ = number of non-group type collaborative patents of firm i and time t.
$Ingroup_{i\,t}$ = number of in-group type collaborative patents of firm i and time t.
$Nongroup\_Stock_{it}$ = the accumulated number of non-group type collaborative patents applied by firm i at year t with the depreciation rate of 10%.
$Ingroup\_\ Stock_{it}$ = the accumulated number of patents applied by firm i at year t with the depreciation rate of 10%.

The last two variables are included to see if the past experiences in the same type of collaboration will affect the likelihood of that type of collaboration.

3-4: Estimation Results

The estimation results are reported in table 2-3. Random Effect Tobit estimation is used for the estimation, as the dependent variables have many zero values and they appear to be left censored.

Results show that the coefficient for *Appro* is statistically significant with expected sign in model 3-1 where *Coinv* is dependent variable. It indicates that higher appropriability of patents reduces transaction costs in conducting inter-firm collaboration. There is, however, clear difference in result for this variable between model 3-2 and 3-3. While Appro is statistically significant in the case of model 3-2 where *Nongroup* is dependent variable, it is not significant in the case of model 3-3 where *Ingroup* is dependent variable. This suggests that in-group type of collaborative research can be considered to be quasi-internal R&D and thus the issue of monitoring costs and approbiliability do not emerge.

The coefficients for *Pat_Stock* and *Spillpool* are insignificant for all of three models, indicating that the level of spillover pool and the accumulated knowledge stock do not affect the likelihood of inter-firm collaboration. Thus, we cannot see support for the industrial organization arguments in this case.

Tech_proximity is positive and significant in model 3-3, indicating that similarity in technology is positively associated with the likelihood of in-group collaboration. However, it is statistically insignificant in the model 3-2 where *Nongroup* is dependent variable. The positive coefficient for this variable in model 3-3 may indicate the support for absorptive capacity argument, yet, if we assume so, it is hard to interpret why absorptive capacity matter only for in-group collaboration but not for non-group collaboration. In any case, strategic management theory which claims the importance of the access to complementary capabilities is not supported in this case.

Science is insignificant in all of the models, indicating the research themes do not affect the probability of R&D collaboration.

Finally, the coefficient of *Ccoinv_stock* is positive and significant in model 3-1, indicating that past experience in collaboration affects the probability of future collaboration. *Nongroup_Stock* and *Ingroup_stock* are also positive and significant in the model 3-2 and 3-3 respectively, showing that past experiences in particular type of collaboration increases the likelihood of the same type of collaboration.

To sum up, the estimation results indicates that appropriability reduces transaction costs, which is consistent with the hypothesis of transaction costs theory. Yet this is not applicable to in-group collaboration where the opportunistic risk appears to be not relevant. There is, however, no evidence to support the hypothesis of industrial organization and resource based argument, except for that absorptive capacity argument may relevant for the case of in-group collaboration.

Table 2-3: Determinants for R&D collaboration (RE Tobit Estimation)

Variable	3-1	3-2	3-3
	Dependent variable: Coinv	Dependent variable: Nongroup	Dependent variable: Ingroup
App	6.055* (3.463)	6.34* (3.505)	-4.173 (6.959)
Spillpool	-0.0002 (0.0008)	1.0001 (0.0002)	0.0004 (0.0014)
Pat_Stock	0.0016 (0.0036)	0.00416 (0.0039)	-0.1053 (0.0064)
Tech_Proximity	1.625*** (0.64106)	0.106 (0.6917)	3.185*** (1.147)
Science	0 .0408 (0.3095)	0.3444 (0.3576)	-0.5934 (0.5361)
Coinv_Stock	0.090*** (0.0146)		
Nongroup_Stock		0.1588*** (0.027)	
Ingroup_Stock			0.2983*** (0.0346)
Constant	-1.1538 (1.1512)	-2.111 (1.762)	-2.864 (3.533)
Number of observations	404	404	404
Number of groups	151	151	151
Log likelihood	-842.25245	-665.85766	-519.77995
Likelihood-ratio test comparing model against pooled tobit model	Prob > chi2 = 0.0000	Prob > chi2 = 0.0000	Prob > chi2 = 0.0173

* Significant at the 10% level

** Significant at the 5% level

*** Significant at the 1% level

It is not really clear why these theories do not hold in this case. One possibility is the existence of transaction costs prevent firms from conducting even though it would generate incoming spillovers and give access to complementary technology. Finally, we find that the past experience in collaboration increase the probability to conduct collaborative R&D in the future, and the past experiences in particular type of collaboration increases the likelihood of the same type of collaboration.[24]

4: Concluding discussion

4-1: Summary of findings

This chapter examines the benefits of and determinants for inter-firm R&D collaboration in RT in Japan by focusing on the differentiation between types of cooperation partners. The analysis of this chapter shows that there are substantial differences in the determinants and benefits of the different type of cooperation.

The main findings of the analysis can be summarized as follows.

-Inter-firm cooperation is not conducted frequently, and more than half of inter-firm collaboration is in-group cooperation.

-Among the non-group collaboration, most of them are inter-industry collaboration. Intra-industry collaboration is very few.

-In-group R&D collaboration do not exert any impact on research productivity of participating firms, whereas non-group R&D collaboration has positive impact. Within non-group collaboration, intra-industry collaboration exerts greater positive impact on research productivity than inter-industry collaboration. These results suggest that, contrary to the prediction of Katz model, rivalry among participating firm do not have negative impact on the benefits of participating firms.

-As to the determinants and motives for R&D collaboration, transaction costs theories appear to hold in the case of non-group collaboration. Yet, in the case of in-group collaboration, transaction cost theories do not hold. This suggests that transaction costs play the role to hinder the likelihood of collaboration for the non-group collaboration, while groups can be thought of quasi-internal organization and thus the problem of monitoring costs and approbiliability do not

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[24] The determinants for the inter-industry collaboration and intra-industry collaboration would be potentially very interesting topic. Yet this issues are not considered here as the regression against these types of collaboration did not generate any meaningful results (most of the variables are indicated to be insignificant). It may be resulted from the fact that the numbers of these two types of collaboration is quite small in the sample data and there are a lot of zeros in the dependent values in these regressions.

emerge. We can infer that the boundaries of firm in terms of financial relation matter for the determinants for R&D collaboration.

-The estimation results do not support industrial organization theory and capability theory. Incoming spillover and access to complementary technology are not important factors in the determinants of R&D collaboration in RT in these period.

-Past experiences in particular type of collaboration increases the likelihood of the same type of collaboration.

4-2: Policy Implications

Based on the analysis of this chapter, some implications can be addressed. First, as non-group collaborative R&D has positive impact on research productivity of participating firms but it is actually conducted in very few occasions, the research partnership among firms which are not financially related should be more encouraged. The analysis of this chapter shows that there are a couple of factors that affects the likelihood of R&D collaboration. First, the level of transaction costs that relates to monitoring and appropriability. Second, even though this chapter does not directly investigate this, rivalry among firms seems to play a major role for firms' decision to and not to conduct collaborative R&D and appear to be a reason that intra-industry collaboration is quite rare even though it is the most 'beneficial' type of collaboration. During the interview we conducted, most of the interviewee agree that the inter-firm collaboration is not enough and suggest that rivalry among the firms are preventing the realization of inter-firm collaboration. One interviewee, reacting to our question of the reason for the lack of horizontal cooperation, stated that "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 fact standard in the future if possible." Thus, the market condition of robot industry has been such that potential benefit of getting ahead of the competitors is quite large and there is a chance of monopolization of markets or of getting large share, as the current service robot market is very small but the potential demand is thought to be large.

Under these conditions, government involvement to promote inter-firm R&D collaboration or formation of government sponsored R&D consortia might be justified. And the discussion above indicates that, in conducting R&D consortia, the government should select research themes in the way that common interests of main producers in this industry are reflected in order to mitigate their rivalry. Also, we have to pay attention to the agreements on intellectual property rights and monitoring to mitigate the problem of appropriability and opportunistic risks.

Chapter 3: Empirical studies on RT-related government sponsored consortia

This chapter empirically analyzes the impact of public policy on robot industry, focusing on the RT related government consortia. The starting point of the analysis is Lechevalier, Ikeda, and Nishimura (2008) which finds that government sponsored R&D consortia has a non-negligible impact in the field of RT in Japan. They did not, however, examine what factors make government sponsored R&D collaboration have positive impact on research productivity. To see what factors affect the impact of participation to public projects, I classify the RT related project into three groups--the ones that involve more than ten participants, those of intra-industry collaboration type (whose participating firms belong to the same industry), and other projects.

The empirical result of this chapter show that impact of the government sponsored research consortia significantly differ depending on the types of projects, and thus there is no evidence that public projects intrinsically have positive impact on research productivity. Yet the reason that government sponsored R&D consortia have positive impact on research productivity is that they tend to have a large number of participants and the participants tend to belong to the same industry. These kinds of R&D collaboration are in fact difficult to be realized by market coordination. Thus, government appears to have played the role of coordinator, helping to realize such R&D collaboration that cannot be undertaken by the market coordination.

The subsequent sections are organized as follows. Section 1 briefly reviews the theoretical justification of government support for innovation in the form of R&D consortia. Section 2 describes the dataset. Section 3 empirically examines the benefits of RT-related government research consortia in Japan. Finally, Section 4 provides a summary of this chapter.

In this chapter, I define the government sponsored consortia as government coordinated R&D collaboration and define R&D collaboration which is engaged by firms without government involvement as market coordinated R&D collaboration.

1: Theoretical overview on government R&D consortia

The economic literature identifies several potential channels whereby government R&D projects benefits private R&D. For example, David et al. (2000) indicates the following three mechanisms through which public R&D encourage complementary private R&D expenditures:

1) Publicly supported R&D generates learning effects which enhance the ability of private firms to obtain the latest scientific and technological knowledge. (*Absorptive capacity*)
2) Using public funds to enable the use of experimental facilities and research facilities and having the government assume the fixed costs for establishing specific R&D projects allows private firms to start projects with low additional costs. This increases the expected return

on R&D investment. (*Cost sharing*)

3) Commissioned R&D signals future demand in the public sector and demand for goods and services diverted to the private sector. Accordingly, this increases the expected return on R&D investment. (*Pump-priming effect*).

Also, Lechevalier, Ikeda, and Nishimura (2008) states that the government sponsored R&D collaboration tend to have greater positive impact on participating firms than R&D collaboration among firms without government involvement. They list the following possible reasons which explain the difference. First, themes of government R&D consortia tend to be closer to the technological frontier, and their goals tend to be more ambitious. This kind of research is likely to generate significant spillover effects and the learning effects tend to be bigger, but it is often inappropriate to the R&D of private firms as it is potentially more risky.

Second, there is less risk of opportunistic behavior and necessity of bargaining over the research outcome is low, as participation in public projects goes with an *ex ante* agreement on the ownership of research output. Also, having monitoring and evaluation by a public institution promotes trust among the participants (*institutional-building trust*). This encourages the participants to collaborate with other which will promote knowledge sharing and more knowledge spillovers

Third, the scale of research of the government sponsored R&D tends to be bigger. Larger the number of participating firms is, the greater the accumulated level of knowledge of the participants. There will be more chances for each participating firm to access complementary technology; thus, the spillover effects tend to be larger. The obstacles for the formation of such large scale collaborative research includes the coordination costs such as search costs to find a proper partner, the cost of negotiations on the allocation of the research results, and the management costs for the projects. By bearing these costs, the government plays a role of coordinator making it possible to realize large scale R&D collaboration that cannot be undertaken by the coordination of markets.

2: Dataset

The main purpose of the subsequent sections is to empirically assess various types of RT-related government sponsored consortia. For this purpose, I utilize information about patents that derived from the government consortia. The dataset used for the analysis in this chapter is the same as the one used in Chapter 2, which includes 13,711 patents of 316 firms, with a sample period between 1991 and 2004.

Among these patents data, I identified the patents that are derived from inter-firm collaboration using the information on the inventors of patents. The patents whose inventors belong to more than one are considered to be inter-firm collaborative patents. Inter-firm collaborative patents are used as proxy to measure market-coordinated collaborative R&D activity, and non-collaborative patent is used to measure in-house R&D activity.

As a next step, we identified the patents that are related to government sponsored R&D projects out of these patents. By referring to the official reports of the 12 projects by NEDO and NICT which are listed in Table 3-1, we found that there are 94 such patents in the dataset.[25] I define these patents as G1 patents. However, the number of G1 patents is quite small relative to non-G1 patents (13,711-94=13,617). We then borrowed the methodology used by Branstetter & Sakakibara (2002) and consider the patents applied for by participating firms in the targeted technologies during and after consortia as the outcomes of these consortia. We define these patents as G2 patents and the sum of the G1 and G2 patents as government (G) patents. G patents are used as proxy to measure government-coordinated collaborative R&D in the subsequent section.

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[25] It would be desirable to include the patents that are born out of all the RT-related public projects into the empirical analysis. Yet, due to lack of information on the patents that are related to public projects, I focus on 12 projects listed in table 2.

Table 3-1: List of the 12 government projects related to the robot industry studied in this chapter (source: Lechevalier, Ikeda, and Nishimura, 2008)

Name of the program	**Period**	**Participants (firms)**	**Name of the program**	**Period**	**Participants (firms)**
1)R&Don Micromachine Technology	1991 — 2000	Around 30 firms (the participants changed over time), including Mitsubishi Electric, Yaskawa, Fanuc, Toshiba, Hitachi	7) Key Technology Research and Development for Humanoid Robots Operating in Actual Environments	2002 — 2007	2 (Kawada Industries, Kawasaki Heavy Industries) in collaboration with AIST
2) Mobile Meal Delivery Robot for Aged and Disabled People	1994 — 1998	2 (Yaskawa & Fujitsu)	8) Project for the Practical Application of Next-Generation Robots	2004 — 2005	Around 40 (including Matsushita Electric Works, Mitsubishi Heavy Industry, ALSOK, Tmsuk, NEC) in collaboration with many universities
3) Surgery Support System for Brain Tumors	1995 — 1999	3 (Hitachi, Toshiba, NHK Engineering Services)	9) R&D on Medical Welfare Machinery Technology	1999 — 2003	6 (including Hitachi, Yaskawa Electric, Daihen Tec, Sanyo Electric)
4) Humanoid Robot Project	1998 — 2002	12 (including ALSOK, Hitachi, Kawasaki Heavy Industries, Yaskawa Electric, Kawada Industries, Honda, Fanuc) in collaboration with universities and AIST	10) Epigenetic Interface for Appropriating Social Communication Skills	2002 — 2004	1 (ATR) in collaboration with universities
5) Advanced support system for endoscopic and other minimally invasive surgery	2000 — 2004	2 (Toshiba & Asahi Optical)	11) R&D on Human Information Communication	2002 — 2006	1 (ATR) in collaboration with universities
6) Development of a Software Infrastructure for Robot Systems (RT Middleware Project)	2002 — 2004	1 (Matsushita Electric Works) in collaboration with AIST and JARA	12) R&D on Network Human Interface (Network Robots)	2004 — 2008	5 (ATR, Toshiba, NTT, Mitsubishi Heavy Industries, Matsushita Electric Industries)

3: Impact of engagement on R&D collaboration

In this section, I try to empirically examine the factors that affect the impacts of the participation to government consortia on research productivity, by using quality indicators of patents such as the number of claims and inventors. Before describing the empirical model, I provide brief reviews on the empirical literature on which the study of this chapter is based.

3-1: Overview on past empirical literature

There are a number of empirical studies that examine the effects of government consortia on research capabilities of firms. Most of these studies are, however, the case studies on limited number of projects, and a very few studies empirically analyze this problem using a relatively comprehensive dataset. One of the examples that systematically analyze it with a large number of data is Branstetter and Sakakibara (1998). They uses a sample of 145 government-sponsored R&D consortia in Japan and finds that frequent participation in these consortia has a positive impact on the level of research expenditure and research productivity. Lechevalier, Ikeda, and Nishimura (2008) extend the empirical study of Branstetter and Sakakibara (1998) by comparing market-coordinated R&D collaboration and government-coordinated R&D collaboration and find that the market-coordinated R&D collaboration has a limited impact on firms' research productivity, whereas government-coordinated R&D has a non-negligible impact in the field of RT in Japan. One of the grounds of this conclusion is that past experiences of market-coordinated R&D collaboration do not exert any impact on firms' research productivity while those of government-coordinated R&D collaboration have positive impact on research productivity.

Lechevalier, Ikeda, and Nishimura (2008) do not examine what factors make government sponsored R&D collaboration have greater impact on research productivity but postulate some possible explanations, which include greater scale of research, a greater number of participants, and choice of research themes. Among these possible explanations, this chapter tries to examine if the number of participants affects the impact of government research consortia on firms' research productivity. Indeed, some of the RT related government research consortia involve a large number of participants, which cannot be seen in the case of market-coordinated R&D collaboration in RT. This characteristic seems to be resulted from the existence of coordination costs (such as search costs and the cost for negotiation) which are necessary to form R&D collaboration.[26] As these coordination costs will become larger as the number of participants becomes larger, the government might have played the role of coordinator, bearing these costs

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[26] Many of the interviewees we met have confirmed this claim. See Lechevalier, Ikeda, and Nishimura (2008) for the detail.

and helping to realize larger scale R&D collaboration that cannot be undertaken by the coordination by markets.

To see if the number of participants affects the impact of participation to government research consortia on research productivity, I will classify the RT related public projects into those with more than ten participants and those with less than ten participants and then will see if and how the impacts of these types of projects differ.

Also, government consortia are further classified into intra-industry collaboration (whose participating firms belong to the same industry) and inter-industry collaboration (whose participating firms belong to different industries). This classification is based on an empirical finding Chapter 2 of this paper. By classifying market-coordinated R&D collaboration into "in-group collaboration"(between the firms in the same company group), "intra-industry collaboration" (between the firms in the same industry), and "inter-industry collaboration" (between firm(s) in different industries), the analysis of Chapter 2 finds that intra-industry collaboration are rarely realized probably due to rivalry among firm.[7] Yet intra-industry collaboration exerts greater positive impact on research productivity than other types of collaboration, probably because the similarity in technology and organizational structure between the partners make the participants firms easier to learn each other.

Thus, to examine the impacts of these types of R&D collaboration, inter-firm collaborative patents and G patents are divided into six categories as depicted in Table 3-2. In the Table 3-2, *G_10* is defined as the public projects which involve more than 10 participants, and which include projects 1, 4, and 8 in the table 2. *G_Intra* is defined as the public projects in which participating firms belong to the same industry (intra-industry type) and those with less than ten participants. Even though the project 1, 4, and 8 are also intra industry type projects, these are excluded from *G_Intra* to avoid overlap. Thus, the G_Intra includes the project 3, 6, 9, and 12 in the table 2. *G_Other* is the projects that are not intra-industry type and has less than ten participants (projects 2, 5, 6, 10, and 11 in the table 2).

Ingroup is the market-coordinated R&D collaboration between the firms in the same company group. Among the collaboration with the firm outside of the group, I divide them into intra-industry collaboration (*Intra)* and inter-industry collaboration (*Inter*). Thus, these six groups are mutually exclusive.

Table 3-2: Types of R&D collaboration (variable in parentheses)

R&D Collaboration	Government Coordinated R&D Collaboration	Intra-Industry Type (*G_Intra*)	"Intra-Industry Type" and "Collaboration with More Than 10 Participants (*G_Intra_10*)
		Collaboration with More Than 10 Participants (*G_10*)	
		Other Government Collaboration (*G_Other*)	
	Market Coordinated R&D Collaboration (*Firms*)	Intra-Industry R&D Collaboration (*Intra*)	Non-gruop R&D Collaboration
		Inter-Industry R&D Collaboration (*Inter*)	
		In-Group R&D Collaboration (*Ingroup*)	

3-2: Empirical model and variables

A simple model of research productivity is specified for estimation. The model is based on the assumption that productivity of the R&D activities is a function of firm level R&D spending and the intensity of engagement in collaborative R&D.

$$Ni = f(Ri, Ci, Zi) \tag{1}$$

where Ni is innovation, Ri is R&D spending, Ci is intensity of engagement in collaborative R&D, and Zi is other factors that affects the innovative level of firm i.

To estimate this model, I used the number of claims as a proxy measure for innovation in the same way as in Chapter 2. Also, I use the number of inventors of patents is used as a proxy for R&D expenses.

Concerning the intensity of engagement in collaborative R&D, I use collaborative patents and G patents as a proxy to measure firms' engagement in collaborative R&D. These collaborative and G patents are divided into six categories as depicted in Table 3, depending on the type of partners and nature of collaboration. This will enable us to examine the difference in the impact among these types of R&D collaboration.

As for the other factors that affect firms' research productivity, I include spillover pool of each firm, which is suggested by Jaffe (1986). The spillover pool measures the potential level of opportunity for a firm to make use of outside knowledge at a given time, and spillover pool for the firm i in time t is formularized as

$$K_{it} = \sum_{i \neq j} T_{ij} R_{jt} \qquad (2)$$

where Rj is the number of patent application of firm j , and Tij is the "technological distance" between the firm i and j. It can be thought as the sum of knowledge stock of other firms weighed by the technological distance to the firm j

Also, the number of patents in the "science-based" technologies is included as independent variable. R&D activities in science-based technology are more complex and exert more uncertainty, thus more collaboration is expected.

The model is based on firm level observation. Estimation based on firm level data is expected to capture the spillover effects of collaboration to the collaborating firms rather than direct impact of collaboration on the quality of its research (patents).

The estimation model takes the form of

$$N_{it} = \beta_0 + \beta_1 R_{it} + \beta_2 G\_Intra_{it} + \beta_3\, G\_10_{it} + \beta_4\, G\_Other_{it} + \beta_5 Intra_{iy} + \beta_6 Inter_{iy} + \beta_7 Ingroup_{iy} + \beta_8 Spill\_Poolp_{it} + \beta_9 Scicence_{it} + \mu_{it} \qquad (3)$$

where

N_{it} = the number of claims of patents generated by firm i in time t;

R_{it} = the number of inventors for the patent

G_Intra_{it} = the number of patents that are born out of public projects in which participating firms belong to the same industry for firm i in time t (which corresponds to project 3, 6, 9, 12 in the table 2)

G_10_{it} = the number of patents that are born out of public projects with more than ten participants for firm i in time t (which corresponds to project 1, 4, 8 in the table 2[27])

G_Other_{it} = the number of patents that are born out of other public projects for firm i in time t (which corresponds to project 2, 5, 6, 10, 11 in the table 2)

$Spillpool_{it}$ = the spillover pool of firm i in year t

$Intra_{it}$ = the number of intra-industry collaborative patents for firm i in time t

$Inter_{it}$ = the number of inter-industry collaborative patents by two or more firms for firm i in time t

$Ingroup_{it}$ = the number of in-group collaborative patents by two or more firms for firm i in

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[27] Indeed, these projects (1,4,8) are also intra-industry type collaboration. Yet the patents of these projects are excluded from *G_Intra* to avoid overlap.

time t

$\mathit{Science}_{it}$ = the number of patents in the "science-based" technologies among the sub-types of RT technologies. R&D activities in science-based technology are more complex and exert more uncertainty, thus more collaboration is expected.

I also estimate the following models by grouping *Intra, Inter,* and *Ingroup* into the all inter-firm collaborative patents (*Firms*); also grouping *G_Intra* and *G_10* into *G_Intra_10.*

$$N_{it} = \beta_0 + \beta_1 R_{it} + \beta_2 \mathit{G\_Intra\_10}_{it} + \beta_3\ \mathit{G\_Other}_{it} + \beta_4 \mathit{Firms}_{it} + \ + \beta_5 \mathit{Spill\_Poolp}_{it} + \beta_6 \mathit{Scicence}_{it} + \mu_{it} \quad (4)$$

where

Firms_{it} = inter-firm collaborative patents for firm i in time t $(\mathit{Intrat}_i + \mathit{Inter}_{it} + \mathit{Ingroup}_{it})$

$\mathit{G\_Intra\_10}_{it}$ = the number of patents that are born out of public projects in which participating firms belong the same industry and projects with more than ten participants for firm i in time t $(\mathit{G\_Intra}_{it} + \mathit{G\_10}_{it})$

The model (2) and (3)will only capture the impact of current collaborative R&D on the research productivity of firms at that time. To examine the impact of past experience of R&D collaboration on firms' research productivity, I also estimate the following model, adding the stock variables of collaborative and G patents to model (3).

$$N_{it} = \beta_0 + \beta_1 R_{it} + \beta_2 \mathit{G\_Intra}_{it} + \beta_3\ \mathit{G\_10}_{it} + \beta_4\ \mathit{G\_Other}_{it} + \beta_5 \mathit{G\_Intra\_Stock}_{it} + \beta_6\ \mathit{G\_10\_Stock}_{it} + \beta_7 \mathit{G\_Other\_Stock}_{it} + \beta_8 \mathit{Firms}_{it} + \beta_9 \mathit{Firm\_Stocks}_{it} + \beta_{10} \mathit{Spill\_Poolp}_{it} + \beta_{11} \mathit{Scicence}_{it} + \mu_{it} \quad (5)$$

where

$\mathit{G\_Intra\_Stock}_{it}$= the accumulated number of G_Intra patents for firm i applied before time t with a depreciation rate of 10%

$\mathit{G\_10\_Stock}_{it}$ = the accumulated number of G_10 patents for firm i applied before time t with a depreciation rate of 10%

$\mathit{G\_Other\_Stock}_{it}$ = the accumulated number of G_Other patents for firm i applied before time t with a depreciation rate of 10%

$\mathit{Firm\_Stocks}_{it}$= the accumulated number of inter-firm collaborative patents for firm i applied before time t with a depreciation rate of 10%

The coefficients of these four variables will indicate the impact of past participation to each type of collaboration on firms' research productivity.

The dependent variable of the models (the number of claims) is a count variable that takes on nonnegative integer values and its distribution does not follow normal distribution. Poisson Regression and Negative Binomial Regression models are the two common estimators for count data. Yet one assumption of the Poisson Regression model is that its mean is equal to its variance. As the variance of dependent variable is greater than its mean in the dataset, it does not appear to satisfy this assumption. Thus, the estimation of Poisson Regression model seems to lead to over-dispersion. Accordingly, Negative Binomial Regression model will be used in the estimation of the model (2).

3-3: Sample statistics

Table 3-3 gives descriptive statistics of the quality of patents for each type collaborative patents. One can notice that the average numbers of citations (backward and forward) are much higher for inter-firm collaborative patents than government patents. However, the number of claims is much higher for G patents than inter-firm collaborative patents. This may be due to the fact that the data on citations are available only up to 1997. Indeed, Lechevalier, Ikeda, and Nishimura (2008) finds that the impact of participation to RT related public projects are statistically significant only after 1997.

Table 3-3: Summary statistics for each type of R&D collaboration (per patent)

	Total Number	Backward citation	Forward citation	Claims	Inventors
In-group collaborative Patents	490	1.07	0.20	5.24	5.24
Inter-industry collaborative patents	447	1.22	0.56	2.55	3.90
Intra-industry collaborative patents	39	0.43	0.96	3.65	5.39
Total Inter-firm collaborative patents	976	1.12	0.39	3.95	4.63
G_In Patents	98	0.35	0.10	7.59	3.54
G_10 Patents	830	0.44	0.12	7.21	2.65

G_Other Patents	337	0.21	0.08	6.45	2.53
Total G Patents	1,265	0.41	0.13	6.94	2.63
Non collaborative patents	11,466	0.74	0.26	5.40	2.15
Total Patents	13,707	0.74	0.26	5.44	2.37

3-4: Estimation results

The Table 3-4 shows the results of the estimations. Hausman specification test suggests that for all the models fixed effects models are appropriate, thus the results of fixed effects models are presented.

The results show that there are significant variations in the coefficients for each type of collaborative patents. If we look at the results of Model (2), the coefficients for *G_Intra* and *G_10* are significant and positive, whereas that for *G_Other* is not statistically significant. This implies that the participation for the public projects has positive impact on firms' research productivity only if the participants of the project belongs to the same industry or if it is big enough to have more than ten participants. The coefficients for *intra* and *inter* are positive and significant, but that of *Ingroup* is not significant, indicating that intra-industry and inter-industry types of inter-firm collaboration have positive impact on research productivity while *ingroup* type of collaboration do not have impact on it. This result is consistent with a finding of Chapter 2.

The results also show that the scale of impact on research productivity differ among the G patents. The elasticity of *G_10* is 0.185 (=[exp(0.0169)-1]×0.495), which is much higher than that of *G_Intra* patent on the number of claims (0.015). Yet the elasticity for these two types of G patents is still lower than that of *Firms* (=0.23). This implies that the impact of any kind of public projects on research productivity is lower than market-coordinated collaboration.

It is important to note that, however, the results of model (2) and (3) only capture the impact of participation on current research activity of firms. Indeed, one of the findings of Lechevalier, Ikeda, and Nishimura (2008) is that past experiences of market-coordinated R&D collaboration do not exert any impact on firms' research productivity while those of government-coordinated R&D collaboration have positive impact on research productivity. The empirical analysis of Model (4) extends this finding. The results of Model (4) show that that all of the coefficients for stock variables are statistically insignificant except for the *G_10_Stock*. This implies that only the government-coordinated R&D collaboration which are big enough to have more than ten participants have lasting impact on firms' research productivity, while the impact of any other types of R&D collaboration dissipate quickly overtime. It is indicative to see that there is no inter-firm collaboration with more than ten partners in our dataset.

Table 3-4: Estimation of Research Productivity Function

Variables	Dependent variable: N (number of claims)		
	Model (2)	*Model (3)*	*Model (4)*
R (Inventors)	0.0096*** (0.0005)	0.0093*** (0.0004)	0.0093*** (0.0004)
G_Intra	0.0364** (0.0169)		0.0432*** (0.0164)
G_10	0.0169*** (0.0035)		0.0124*** (0.004)
G_Intra_10		0.0163*** (0.027)	
G_Other	0.003 (0.006)	0.0095 (0.0052)	0.0079 (0.0063)
G_Intra_Stock			-0.01 (0.0121)
G_10_Stock			0.0038* (0.002)
G_Other_Stock			0.0079 (0.0063)
Intra	0.1100*** (0.0417)		
Inter	0.02524*** (0.0078)		
Ingroup	-0.0123 (0.0138)		
Firms		0.0131** (0.007)	0.0129* (0.0069)
Int_Firms_Stock			0.0018 (0.0034)
Spill_Pool	0.0008*** (0.0002)	0.0008*** (0.0002)	0.0008*** (0.0002)
Science	0.0599 (0.04769)	0.0591 (0.0477)	0.0589 (0.0479)
Number of observations	2324	2324	2324

*Significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level

To sum up, the estimation in this section suggests that the impact of the participation to public projects on research productivity significantly differ depending on the types of projects. Thus, we cannot find the evidence that public projects intrinsically have positive impact on research productivity or exert greater impact than market-coordinated R&D collaboration. Yet the reason that government consortia (government-coordinated collaboration) on average exert greater impact than market-coordinated collaboration is that government consortia tend to have more participants and its participants tend to belong to the same industry. These kinds of R&D collaboration are in fact difficult to be realized by market coordination. Intra-industry R&D collaboration is quite rare probably due to the rivalry among the firms even though it exerts significant positive effects on research productivity. Also, R&D collaboration with more than ten participating firms (without government involvement) has not been realized yet. It is probably because coordination costs to engage in such collaboration are quite large. Thus, government appear to have played the role of coordinator, helping to realize such R&D collaboration that cannot be undertaken by the coordination by markets but that have significant effects on research productivity.

4: Summary

This chapter qualitatively analyzed RT-related government consortia in Japan by comparing the inter-firm R&D collaboration without government involvement. The analysis of Chapter 1 indicates that the source of innovation failure in robot industry is resulted from the fact that the robots are complex systems and the development requires various kinds of highly specialized technology. R&D projects require costs and technologies that cannot be dealt with by any single firm, and the high risk involved in the R&D activities limit expected private gains. R&D collaboration will solve this innovation failure, but the lack of coordination among firms hiders the realization of R&D collaboration at the sufficient level. Under these conditions, appropriate policy instrument appear to be the promotion of cooperation among firms. Recognizing the technological status of robot industry, central governments of Japan have implemented many government sponsored R&D consortia as the main policy instrument to support this industry.

The empirical analysis on the RT related government sponsored R&D consortia in this chapter extends the analysis of Lechevalier, Ikeda, and Nishimura (2008) which showed that government sponsored R&D consortia have positive impact on the research productivity of participating firms and the impact is on average greater than market coordinated R&D collaboration. The empirical results show that impact of the government sponsored research consortia on firms' research productivity significantly differ depending on the types of projects, and thus there is no evidence that public projects intrinsically have positive impact on research productivity or exert greater impact than market-coordinated R&D collaboration. The reason that government sponsored R&D consortia exert greater impact than market-coordinated collaboration is that government consortia tend to have more participants and its participants tend to belong to the same industry. These kinds of R&D collaboration are in fact difficult to be realized by market coordination. Thus, government appear to have played the role of coordinator, helping to realize such R&D collaboration that cannot be undertaken by the coordination by markets but that have significant effects on research productivity.

Conclusion

This paper examines characteristics of innovation activities in RT and in turn empirically analyzes collaborative R&D and government sponsored R&D consortia in Japan.

Chapter 1 of this paper qualitatively analyzed robot industry based on the viewpoint that there is significant variety in technology on which firms and industry are depended. The analysis of this chapter indicates that the possible source of innovation failure in RT comes from its complexity in technology. Based on the framework of Martin and Scott (2000), it is suggested that the promotion of R&D collaboration among firms is a key to the development of this industry. Yet the robot technology in Japan is characterized as a low degree collaboration among firms and thus inter-firm collaboration should be encouraged for the development of this industry.

Based on these results, the subsequent chapters empirically analyze the status of inter-firm collaboration and government sponsored consortia. The analysis in Chapter 2 shows that more than half of inter-firm collaboration is in-group cooperation and this type of R&D collaboration do not exert any impact on research productivity of participating firms. Also, the results of estimation for the benefits of collaboration indicate that the type of R&D collaboration with higher the degree of competition among the participants exerts greater effect on research productivity. This result actually contradicts the prediction of Katz model. These results suggest that the rivalry among firms hinders the realization of R&D collaboration in RT, whereas in the Katz model rivalry reduces the benefits of collaboration to the participating firms.

As to the determinants and motives for R&D collaboration, the estimation results do not support industrial organization theory and capability theory. Transaction costs theories appear to hold in the case of non-group collaboration and thus play the role to hinder the likelihood of collaboration for this type of collaboration. However, transaction costs do not exert any impact in the case of in-group collaboration. This suggests that transaction costs that arise from monitoring costs and approbiliability is not a problem for in-group collaboration and groups can be thought of quasi-internal organization. This result is consistent with the empirical results of Nakamura and Odagiri (2005) which analyzes the determinants of R&D collaboration based on the sample of 1400 Japanese firms.

The results of empirical analysis in Chapter 2 indicate that only the non-group R&D collaboration has positive impact on the research productivity of participating firms and, for this type of collaboration, the existence of transaction costs play a role to prevent the realization of inter-firm collaboration. Also, it is shown that, within non-group collaboration, intra-industry collaboration is the most 'beneficial' type of collaboration, yet this type of collaboration is quite rare. Rivalry among firms seems to be an obstacle to the realization of this type of collaboration. From these facts, we can infer that "boundary of firms" is an important element to deter the innovative activities of RT which require the collaboration among firms.

The analysis on the RT related government sponsored R&D consortia in chapter 3 extends the analysis of Lechevalier, Ikeda, and Nishimura (2008) which showed that government sponsored R&D consortia have positive impact on the research productivity of participating firms and the impact is on average greater than market coordinated R&D collaboration.

The empirical results show that impact of the government sponsored research consortia on firms' research productivity significantly differ depending on the types of projects. Therefore, there is no evidence that public projects intrinsically have positive impact on research productivity or exert greater impact than market-coordinated R&D collaboration. Yet only the projects with more than ten participants and the ones whose participants belong to the same industry have positive impacts on the research productivity of participating firms. These kinds of R&D collaboration are in fact difficult to be realized by market coordination. Thus, government appear to have played the role of coordinator, helping to realize such R&D collaboration that cannot be undertaken by the coordination by markets but that have significant effects on research productivity.

The basis of the analysis in this paper is the viewpoint that the source of innovation failure and expected role of government are different among industrial sectors. There are a various sources of market failures in innovation, and appropriate policy instrument should differ depending on the types of market failures. Thus, the evaluation of government policy without the consideration for the characteristics of industry may not be appropriate. The detailed analysis of this paper exposes the problem of coordination in innovation in RT and shows the government role as a coordinator which promotes the collaboration and knowledge flow among firms. This paper analyzes only robot technology as a case study, but it carries the following general message with regard to the role of government in innovation: where inter-firm collaboration is required in innovation but the collaboration is hindered by rivalry among firms and transaction costs, the active involvement of the government as a coordinator to conduct large scale projects is necessary.

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Appendix : The Derivation of Spillover Pool

Firms are usually engaged in research activities in various fields. Jaffe [1986] expresses the technological position of a firm in the vector which are composed of the portion of its RandD effort in each technological field

$$F_i=(f_1 \cdot \cdot \cdot f_k)$$

where each element of technological position vector represents the ratio of RandD resources used by firm *i* in each technological field. One way to calculate the technological position of the firm using the distribution of RandD spending in each field, yet it is quite difficult to obtain the portion of RandD spending across technological fields. Thus, we follow Jaffe [1986] and use the distribution of patents that firm apllies in each technological field.To calculate the technological position of firms we classify RT patents into twenty micro technological fields based on the classification of JPO (2002).

Further, Jaffe [1986] defines the “techonological distance” between the firm i and j using the their vector of technological position, which takes the form of

$$T_{ij}=\frac{F_iF_j'}{[(F_iF_i')(F_jF_j')]^{1/2}}$$

Here, technological distance *Tij* is an index to measure the magnitude of similarity in the patent portfolio between the firms and it approaches to 1 as the similarity of technological position become more similar. Following Jaffe [1986], we assume that the technological position and technological proximity are fixed in the short run.

We can then calculate potential spillover pool of each firm using the index of technological distance. The idea behind this is that spillover effects for firm *i* will be bigger as its technological position become more similar to the firm *j*. The spillover pool for the firm *i* in time *t* is formularized as

$$K_{it}=\sum_{i\neq j}T_{ij}R_{jt}$$