U.S. Technological Innovation Systems for Service Robotics

MSc Thesis

Mark van den Brandt, 26th of May, 2010

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‘The robot is going to lose. Not by much. But when the final score is tallied, flesh and blood is going to beat the damn monster.’

- Adam Smith (Scottish philosopher and economist, 1723-1790)

Study	Industrial Engineering & Management
Track	Information Technology & Management
Faculty	School of Management & Governance
University	University of Twente
Student #	s0068810
Examination	Dr. Ir. Jeroen Kraaijenbrink (University of Twente)
Committee	Ir. Martin Wassink (University of Twente)
	Ir. Bart Sattler (TWA Network)

EXECUTIVE SUMMARY

BACKGROUND

The TWA Network functions as a bridge between research and business between the Netherlands and other countries. The TWA Network in Washington, DC has a focus on the innovation practices of companies, universities and governmental organizations in the robotics industry for the year 2009 and is the principal of this research.

OBJECTIVE

This research draws on technological innovation systems (TIS) theory to research innovation practices in the service robotics industry in the U.S. The goal is to identify relevant structural and dynamic factors of the TIS that lead to evolvement of the system and to formulate recommendations for the Dutch service robotics industry.

TECHNOLOGICAL INNOVATION SYSTEMS

TIS theory in combination with innovation literature lead to the formulation of the theoretical framework, that consists of structural factors and TIS functions. An industry-wide investigation of the three types of structural factors, actors, networks and institutions, reveals aspects of the TIS that are relatively stable over time. TIS functions represent the dynamic aspects of the system and occur in the form of individual events that can be categorized as one of the seven system functions:

F1. Entrepreneurial Activity
F2. Knowledge Development
F3. Knowledge Diffusion
F4. Guidance of the Search
F5. Market Creation
F6. Resource Mobilization
F7. Support from Advocacy Coalitions

The intensity and interactions between the functions indicate whether and which motors of innovations are present for a specific TIS. Four motors of innovation are identified with an increasing degree of industry maturity:

- Science & Technology Push Motor
- Entrepreneurial Motor
- System Building Motor
- Market motor

Interviews and historical data gave insight in function intensity and interactions for the two U.S. case studies Dexterous Manipulation and Autonomous Navigation.

Results

asef

Conclusions

asef

PREFACE

Several months of research has resulted in this thesis, the conclusion of my university career as a student of Industrial Engineering & Management. I owe an enormous debt of gratitude to a number of people for their support during the road towards the completion of my graduation assignment.

First of all, I would like to thank my university supervisors, Jeroen Kraaijenbrink and Martin Wassink, for their enthusiasm for this topic from the start onwards. Thank you for your sharp remarks and suggestions on the aspects of structure, relevant literature and for the general comments on the process. You were always available for questions, either directly, by e-mail, telephone, Skype or even in person in the U.S.

Of equal importance is the role for TWA in Washington, DC. Thank you very much for offering me the opportunity to live and work in Washington, DC for five months. You gave me all the freedom to design and guide the research in the desired direction. A special thanks for Bart Sattler, my direct supervisor in Washington, DC, for his very precise support and comments and of course for the great time that we had both within and outside the Embassy. The highlight of this time was definitely our trip with the Dutch robotics delegation to MIT, Harvard, Johns Hopkins and several companies in the greater Boston, Baltimore and Washington areas. Furthermore, I am particularly grateful to Paul op den Brouw, Barbara Staals, Gerda Camara and Karin Louzada as my colleagues at TWA and grateful for the great atmosphere with all my other fellow colleagues and interns at the Dutch Embassy.

Finally, my word of thanks goes out to my family and friends for their ongoing support and friendship, regardless of whether I was in Enschede, Washington, DC, Gouda or even Diemen-Noord.

Hopefully you will enjoy reading this report as much as I have had throughout my graduation assignment.

CONTENTS

1. INTRODUCTION

The first chapter introduces the research topic, determines the research focus (§ 1.1), formulates the research questions (§ 1.2) and concludes with the structure of the thesis (§ 1.3).

'Imagine being present at the birth of a new industry. Trends are now starting to converge and I can envision a future in which robotics devices become a nearly ubiquitous part of our day-to-day lives.'

- Bill Gates

The word 'Robot' was first coined in the play R.U.R. by the Czech writer Capek, where the author used the word Robot to describe a machine that functions as an artificial human being. A contemporary definition of the word robot describes a substantial larger range of machinery, being "an automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications" (International Federation of Robotics (IFR)). The IFR definition focuses solely on industrial applications, whereas applications of robots vary widely nowadays. Robots can amongst others be used in health care, domestic applications (domotica), for national defense purposes or as precise and swift operators in production settings. The interdisciplinary character of this field of knowledge causes research into a broad range of underlying phenomena including mechanical engineering, electrical engineering, artificial intelligence and human machine interaction.

Robotics technology already has a profound impact on society and all major robotics institutes expect a more intense role for robots in the future, a proposition that is backed up by the forecast that the number of robots in operation worldwide will increase from 6.5 million in 2007 to a whopping 18 million robots in 2011[1]. Research on robotics is carried out at institutes around the globe, including research at the corporate level, universities and other government related bodies. The broadness and complexity of the topic causes the emergence of specialists at specific institutes for different knowledge fields regarding robotics. This tendency combined with the rapid developments in the field leads to possibilities to deploy the specialist knowledge, especially when one is open to inter organizational and even international cooperation.

[1] European Robotics Technology Platform (Europ) Robotic Visions to 2020 and beyond, Strategic Research Agenda, July, 2009.

Research Principal

The TWA Network functions as a bridge between technological and business developments in the U.S. and the Netherlands and is the initiator and principal of this research. The TWA Network is a part of the Dutch Ministry for Economic Affairs and collects information on technological developments, innovation and technology policy abroad that can be used by Dutch companies, universities, knowledge institutes or the government (more information in Appendix B). As a part of the 2009 focus on robotics, the TWA Network has put forward the question how the United States robotics industry supports innovation. More specific, this relates to how companies, universities and research institutes innovate within the innovation system and what Dutch parties in the robotics industry can learn from U.S. innovation practices, either by adapting corporate strategies or government policies or by collaboration with U.S. parties.

In order to specify this broad research objective, sections 1.1 and 1.2 define the research focus and research questions. This formulation is based on an overview of the U.S. robotics industry in the international context with the goal to identify the most relevant segment of the U.S. robotics industry for this research.

1.1 RESEARCH FOCUS

In order to define the research focus, this paragraph analyzes the current segmentation (§ 1.1.1) and competitive landscape (§ 1.1.2) of the global robotics industry in order to identify the most relevant segment of the robotics industry for research.

1.1.1 Service robotics segment growth

In order to focus on the most relevant sections of the robotics industry, first a division of the industry into different segments is needed. Multiple classifications are used in both research and practice to distinguish different types of robotics applications. An intuitive segmentation of the robotics industry is provided by the European Robotics Technology Platform (Europ)(CARE, 2009) in the Strategic Research Agenda for robotics to 2020. It distinguishes between industrial robots used for manufacturing, professional service robots used in direct contact with humans in professional settings, personal service robots, security robots and space robots. The CCC/CRA/NSF U.S. Roadmap for Robotics (CCC, 2009) presents a different division of the robotics industry applications, dividing the industry in to manufacturing, logistics, medical, healthcare and service robotics sections.

This research deploys a division of robotics applications based on a combination of the Europ and CCC models and the IFR distinction between industrial and service robotics, as shown in Figure 1.1. The classification distinguishes between static industrial robots that are used in manufacturing facilities and service robots.

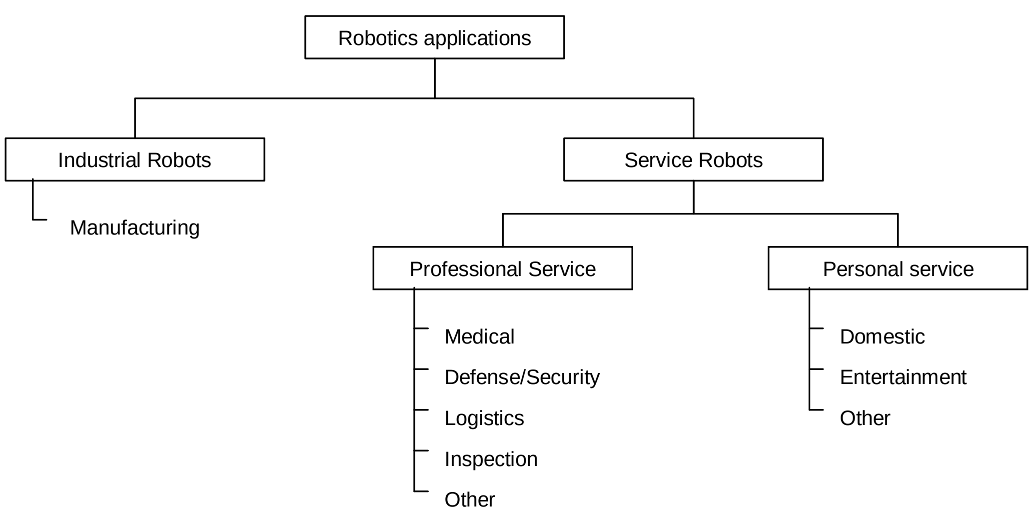

Figure 1.1 Robotics applications

The first commercial applications of robotics technology emerged in the manufacturing segment. This industrial robotics industry boomed in the late 1980s (World Robotics Stats, 2008) and experienced declining growth during the 1990s and into the 21st century. Several robotics institutes and consortia (IFR, CCC, JRA) regard the industrial robotics industry as a mature industry and forecast a steady, but relatively slow growth for the coming years.

The professional service and personal service segment currently grows at an increasingly rapid rate. A forecast by the Japanese Robotics Association[2] (JRA), as displayed in figure 1.2, shows the enormous market potential of both domestic and different types of professional service robotics, a forecast that is supported by other robotics research institutes such as the IFR and the CCC.

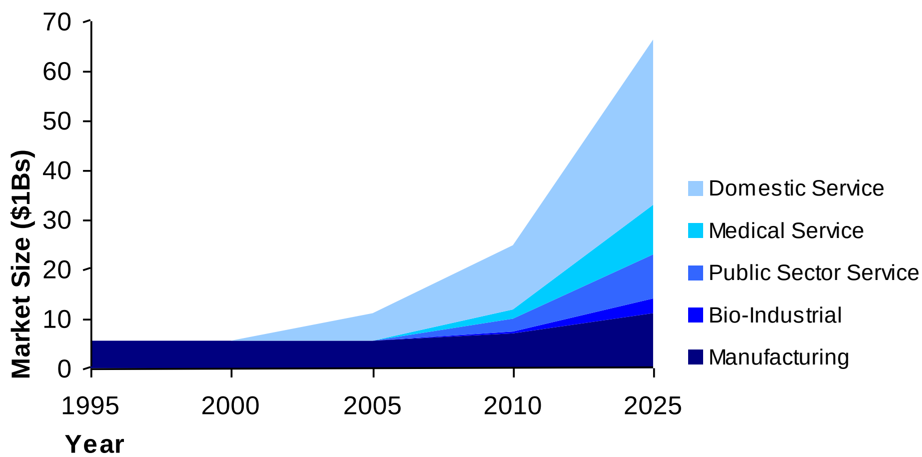

Figure 1.2 Worldwide Robotics Market Growth
(Source: Japanese Robotics Association)

The rapid expected growth of the service robotics industry implies large opportunities for the Dutch robotics industry and academia regarding both research initiatives and the commercialization of products. Research opportunities in this segment do not only concern direct applications in service robotics products, but more importantly a broad range of enabling technologies, such as actuation systems, energy and power systems, robot perception systems and human robot interfaces. Appendix B shows a comprehensive service robotics application collection based on the IFR segmentation.

[2] EUROP Sectoral report on Service Robotics, 2005, p. 10, derived from ftp://ftp.cordis.europa.eu/pub/ist/docs/europ/rob-plat-4.pdf on August 12, 2009.

The large market potential of the service robotics segment supports the choice of this research to focus on service robotics.

1.1.2 Competitive landscape robotics industry

The U.S. Robotics Roadmap 2009[3] and the WTEC 2006 Robotics Panel report[4] evaluate regional differences for the different robotics industry segments. Figure 1.2 summarizes the conclusions from both reports and highlights the current leadership position of the U.S. in professional service robotics (especially medical and defense applications), a position that is challenged by large investment programs in the EU (600 M Euro) and Korea ($1B).

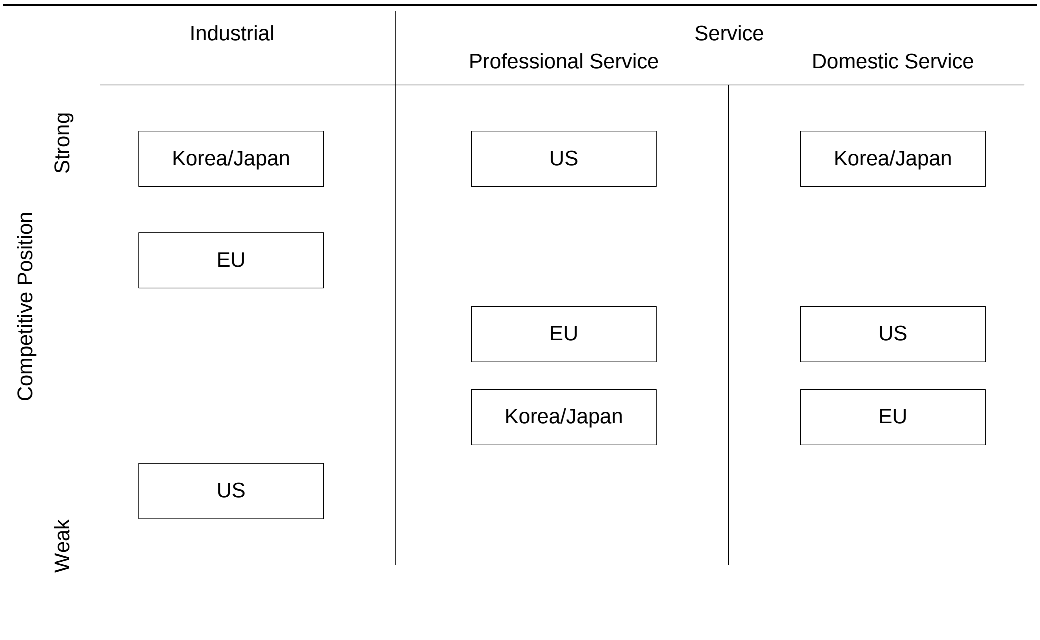

Figure 1.3 Competitive positions per region and industry segment

The leadership position of the U.S. in professional service robotics is manifested by several epoch making products such as the DaVinci surgical system[5]. The 2006 WTEC report also highlights the leadership role of the U.S. in basic, university-based robotics research into enabling technologies.

[3] CCC, A Roadmap for US robotics: From Internet to Robotics, p.4

[4] World Technology Evaluation Center Panel 2006 report on International Assessment of Research and Development in Robotics, p. xii

[5] www.intuitivesurgical.com

The Horizonscan 2006, a long term exploration study by the Dutch Ministry of Education, Culture and Science and more specifically the Consultative Committee of Sector Councils for research and development (COS), acknowledges the need for close collaboration between both governmental and corporate robotics developers in both the national and international context. The report identifies American and Asian initiatives that focus on integrating fields of knowledge such as Nanotechnology, Biotechnology, ICT and Cognitive Sciences in order to create a firm basis for both the academic and commercial development of robotics. American and Asian initiatives put in practice the approach of cooperation between parties in the different fields of knowledge related to robotics in order to stimulate the integration of knowledge from different fields. The Horizonscan 2006 subsequently concludes that the Netherlands currently lacks such an approach and suggests that more intense cooperation between research institutes, governments and companies can bridge the gap. The American experience in intense cooperation across fields of knowledge can serve as an example to bridge the gap defined in the Horizonscan.

1.1.3 Conclusion

The segment analysis (§ 1.1.1) justifies a research focus on service robotics as the most relevant segment for research. The investigation of the regional differences (§ 1.1.2) leads to the conclusion that the European robotics industry currently holds a mediocre competitive position in the fastest growing robotics industry segment, service robotics. The Horizonscan shows that the Dutch service robotics industry has to bridge the gap with the U.S. service robotics industry and that the U.S. situation can function as an example. Therefore this research chooses to focus on a comparison between the U.S. and Dutch service robotics industries.

1.2 RESEARCH QUESTION

Section 1.1.2 identified the leadership position of the U.S. in both basic research and applications of service robotics, providing this research with a focus on service robotics. Researching the service robotics industry asks for an approach that covers both the activities of individual organizations and at the same time puts focus on the relations between actors in the field. Relations between parties are especially important in the robotics industry, because of the highly integrative nature of robotics applications, combining several enabling technologies in a single application. A system approach covers both individual organizations and their interdependencies by regarding companies, research institutes and governments all as actors in the related innovation system. The innovation system approach has been adopted by researchers and policy makers as a suitable approach for researching the dynamics underlying innovation (Bergek et al., 2008). Within the innovation system literature, several research approaches exist. The results from the literature study (chapter 2) lead to the choice for Technological Innovation Systems (TIS) as the innovation system approached used in this research.

The research focus on technological innovation systems combined with the focus on service robotics specifies the broad research objective as stated in the introduction. This leads to the formulation of the main research question.

How does the technological innovation system for service robotics in the U.S. facilitate innovation and what can the Dutch service robotics industry learn from this?

Based on the literature study on TIS (as described in chapter 2), this research identifies three research levels within the TIS approach: structural factors, TIS functions and motors of innovation. The three levels allow for researching TIS with an increasing level of system dynamics.

1.3 Research Sub Questions

The research sub questions are based on the three analytical levels of TIS.

SQ1: What are structural factors for U.S. service robotics TIS ?

Structural factors describe the relatively stable aspects of an innovation system, based on the identification of actors, networks and institutions within the system.

SQ2: How do the different TIS functions operate for the U.S. service robotics industry?

TIS functions describe dynamics of the TIS based on events that can classified as one of the seven TIS functions: Entrepreneurial Activity, Knowledge Development, Knowledge Diffusion, Market Creation, Guidance of the Search, Resource Mobilization and Support from Advocacy Coalitions.

SQ3: How do the different TIS functions interact to form motors of innovation?

Analysis of interactions within and between TIS functions leads to the formulation of motors of innovation for specific TISs.

The three sub questions allow for a complete analysis of the U.S. TIS for service robotics. The results from this descriptive analysis are used to compare the U.S. innovation system with the Dutch innovation system and to formulate prescriptive recommendations.

1.4 Outline of the Thesis

Chapter 2 continues with the literature study into innovation systems. It starts with a general introduction into innovation, followed by an analysis of innovation system approaches that leads to the choice for TIS as the approach for this research. As Table 1.1 displays, subsequent paragraphs of the literature study discuss the three sub questions. The three sub questions have corresponding paragraphs in both the research method chapter (chapter 3) and the results chapters (chapter 4-6). As the table shows, SQ2 and SQ3 are answered by means of two case studies into two technologies. Chapter 7 includes the cross case comparison, formulates conclusions and recommendations and answers the main research question.

Table 1.1 Outline of the Thesis

SQ	Topic	Literature Study	Research Method	Results			Discussion
				Structural Factors	Case I	Case II	
	Innovation	2.1					
	System Approaches	2.2					
SQ1	TIS Structural Factors	2.3	3.2	4			
SQ2	TIS Functions	2.4	3.4		5.2	6.2	
SQ3	TIS Motors of Innovation	2.5	3.5		5.3	6.3	
	Cross Case Comparison		3.6				7

2. LITERATURE STUDY

This chapter reviews current scientific and other relevant literature to create a framework for answering the research question. Section 2.1 introduces the concept of innovation and the different chronological stages of technology development. Section 2.2 discusses several approaches to innovation systems to conclude with Technological Innovation Systems (TIS) as a valid approach for this research. Sections 2.3-2.5 operationalize TIS, describing how different functions of TIS can influence each other, causing motors of innovation that build up the innovation system. Section 2.6 concludes with the formulation of the theoretical framework.

'Innovation is not the product of logical thought, although the result is tied to logical structure.'
Albert Einstein

2.1 INNOVATION

Over the course of more than 70 years of innovation research, a range of definitions have been developed for the concept of innovation. Schumpeter (1934) was one of the first to define economic innovation and his interpretation of the concept still lives on in the work of scholars like Dosi (1988), who defines innovation as "the search for, and the discovery, experimentation, development, imitation and adoption of new products, new production processes and new organizational setups".

Dosi's definition of innovation describes a process of development starting at search and discovery, working towards adoption of the innovation. Narayanan (2001:29) specifies the process of technology development into a five step framework that distinguishes between the creation of new knowledge and the application of knowledge and further divides the application of knowledge into four subsequent stages of technology development: Applied research, development, engineering and commercialization. The framework applies to parties in the technological environment, being all parties that are concerned with technological advancements, ranging from the commercial development of new products to basic scientific research carried out at universities.

The technology development stages framework as shown in figure 2.1 can be used for every segment of the service robotics industry to map the scope of technology development processes at organizations and to categorize the participating organizations.

Besides clarification on the specific roles that organizations have in the technology development process, the framework also serves as an indication of the technological maturity of the industry segment based on the proposition that organizations start with commercialization of the technology after completion of the earlier stages of technology development (Sahal & Devendra, 1981).

Stage of Technology Development				
Creation of new knowledge	Application of knowledge			
Basic Research	Applied Research	Development	Engineering	Commercialization

Figure 2.1 Process of Technology Development (adopted from Narayanan, 2001)

Figure 2.1 points out the transfer of technology through different stages. It should be noted that organizations can be active and therefore categorized in any number of steps in the process depicted in figure 2.1, depending on the stages of technological development the organization covers.

Organizations can be interlinked to other parties both in the same stage of technology development, e.g. research alliances, and in earlier or subsequent stages of technology development, e.g. licensing or manufacturing. Therefore technologies develop in the context of a system which consists of actors, institutes, technologies and the interrelations between them (Carlsson et al., 2002). Several innovation system perspectives have been proposed in literature, as discussed in section 2.2.

2.2 Innovation System Perspectives

In order to research innovation in the service robotics industry, several theoretical innovation system concepts can be deployed. Literature on innovation systems discusses national innovation systems (NIS)(Lundvall, 1992), regional innovation systems (Cooke et al., 1997), sectoral innovation systems (Breschi & Malerba, 1997) and technological innovation systems (TIS)(Carlsson & Stanckiewicz, 1991). This section compares the different perspectives to conclude with a choice for the most appropriate perspective for researching the service robotics industry.

2.2.1. National Innovation Systems (NIS)

Innovation systems research started with a focus on national innovation systems (NIS) (Lundvall, 1992). The NIS theory emphasizes the presence of multiple stakeholders in every innovation process. Companies, universities, knowledge institutes and the government all play a relevant role. Balzat (2006) perceives a national innovation system as "a historically grown subsystem of the national economy in which various organizations and institutes interact with and influence one another in the carrying out of innovative activity".

With the current level of globalization and international cooperation, one would expect a decline in the importance of national systems. Several empirical studies (Archibugi and Michie, 1995; Cantwell, 1995) however point out that spatial aspects remain important for certain innovation activities.

Lundvall proposes institutional dimensions that have a major impact on innovation and that could differ over countries: An example of such a dimension is the differing time horizons of agents. Within the robotics industry this is illustrated by the relatively short term orientation of Anglo-Saxon countries versus the long term orientation in Japan. The different time horizons at least partially explain the prominent humanoid research initiatives in Japan. The long term humanoid investments cause a longer payback period in comparison to the possible quick gains of for example industrial robots, an industry that is well established in Europe.

Lundvall identifies five Schumpetarian (Hirschman, 1958) strategies for companies in an innovation system: pioneers, adaptionists, imitators, complementors, and mixed strategies. Pioneers move on the cutting edge of technology, whereas adaptionists start their activity as soon as proof-of-concepts are present. Imitators try to improve specific aspects of existing products. Complementors are companies that apply or extend a certain technology in their specific niche market and mixed strategies consist of a combination of the other four strategies.

The strategy mix of an industry is determined by the different strategies that the industry players deploy and can therefore result in a balanced mix with relatively equal distribution of strategy types amongst companies, or an unstable mix, e.g. a surplus of imitators resulting in abated radical innovation. If either government policy or basic Schumpeterian game elements change (e.g. changes in intellectual property, international orientation) the strategy mix of the industry could shift towards a new state.

2.2.2. Regional Innovation Systems

Regional innovation systems (RIS) theory is similar to the NIS approach, however stresses the importance of regional clusters (Cooke et al., 1997). Malerba (1993) showed that the innovation system at the national, Italian level allocated resources to only a small number of relatively large companies, in general not the most innovative. True innovation however occurred at the sub national level, often by SMEs that were relatively untouched by the NIS.

The regional innovation system approach acknowledges the rise of regional and local business clusters as vehicles for economic competitiveness, both on the national and on the global level. This notion is supported by the renewed academic interest in clusters of innovation (Porter, 1998a). Porter proposes that a cluster of independent and informally linked companies and institutions is beneficial for its constituents. The organization in a cluster can lead to improved efficiency, effectiveness and flexibility. The main contribution of RIS research is the notion that distance does matter. The RIS approach allows for research on the micro level and therefore allows for a dynamical approach. According to Suurs (2009), the RIS approach normally does not include a detailed analysis of the process of technological innovation, an analysis that is important in the case of robotics.

2.2.3. Sectoral Innovation Systems

Sectoral innovation systems (SIS) propose sectors as the central unit of analysis (Breschi & Malerba, 1997; Malerba, 2002). A SIS is the combination of targeted products and a group of agents carrying out interactions for the development, manufacturing, marketing and sales of those products. Organizations in a specific sector develop through processes of interaction and cooperation and selection takes place in the form of competition, all interactions that are shaped by institutions (Malerba, 2002). Within the sector, organizations are subject to the sector's particular technological regime. The technological regime defines the nature of the problems organizations have to solve during innovation. This includes the level of technological opportunity for established firms, the ease of access to new technological opportunity by entrant firms, and the cumulativeness of learning (Marsili, 1999). Cumulativeness of learning relates to innovative successes that yielded a profit. The profit can be reinvested, increasing the probability of new innovations.

A major disadvantage of SIS theory is that the theory does not have a strong focus on technology and it largely neglects other organizations besides companies involved in the innovation system (Geels, 2004). A second disadvantage is the strong focus on the development of knowledge, and less attention for the diffusion of knowledge (Geels, 2004), a crucial aspect of the multidisciplinary service robotics industry.

2.2.4. Technological Innovation Systems

With increasing globalization and interrelatedness of markets, the innovative activities become more global as well. A technology, or the included knowledge, is hardly ever only embedded in the innovation system of a single country or geographical region, but more likely to be embedded in a similar form in different geographical areas around the world (Hekkert et al., 2007). According to Carlsson and Stankiewicz (1991) there are two sides to this development. On the one hand countries can no longer focus on only their internal research and development programs. On the other hand no country has to rely as heavily on domestic innovative activity as before.

Based on the globalization trend and the need for a more prominent role for technology in innovation systems, Carlsson and Stankiewicz (1991) propose an alternative theory of innovation systems, being technological innovation systems (TIS). TIS consist of network(s) of agents interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing and utilizing technology.

Carlsson and Stankiewicz (1991) propose that innovation system models other than Technological Innovation Systems treat technology as an exogenous variable, thereby neglecting the importance of technology as an independent variable of innovation. This is an important argument in favor of TIS as the main framework for the research, based on the central role of technology in the field of robotics. The argument is further supported by the strong roles for entrepreneurial activity and knowledge diffusion within the research into TIS (Suurs, 2009). These characteristics of TIS are especially relevant in the field of service robotics, since the robotics industry is a high tech industry with a central role for startups and a strong focus on knowledge diffusion. Knowledge diffusion is important based on the integrative nature of robotics technology, combining several enabling technologies and therefore knowledge into a single application.

Within the framework of technological innovation systems, Carlsson and Stankiewicz (1991) emphasize the need for economic competence, which they describes as the ability to identify, expand and exploit business opportunities. Besides this entrepreneurial aspect, infrastructural and networking components are the other two critical success factors within a technological system. Networks are an important element in the concept of technological systems, serving the purpose of exchanging information or knowledge.

2.2.5. Innovation System approach choice

Based on the prominent role of technology in the robotics industry and the important role of knowledge diffusion in this industry due to the multidisciplinary nature, Technological Innovation Systems (TIS) is the appropriate innovation systems approach for researching the service robotics industry. TISs inherently do not have geographical boundaries. This research' focus however lies on TIS in the U.S. situation, for two reasons. First, the researcher's placement in the U.S. puts practical limitations on a worldwide research. Secondly, insight into U.S. practices can lead to direct recommendations for actors in the Dutch TIS.

2.2.6. Conclusion

This section discussed several innovation systems approaches, TIS being the most relevant for this research based on the central role for technology in the robotics industry and the boarder-crossing nature of the industry. This research however takes into account the relevant findings from research into the other approaches. Examples are the multiple stakeholder approach from NIS and the importance of regional clusters, drawn from RIS theory.

Sections 2.3 and 2.4 continue with an operationalization of the theory of TIS. Bergek et al. (2008) describe an analytical scheme to research TISs that consists of an analysis of the structural factors of the TIS and dynamic, functional aspects. The focus lies on the TIS function approach that describes the dynamics of the innovation system, the structural components however provide a firm basis for the analysis of system dynamics (Bergek et al., 2008). Section 2.3 discusses structural factors, whereas section 2.4 discusses literature on TIS function dynamics.

2.3 STRUCTURAL FACTORS

Structural factors include elements of the TIS that are relatively stable over time (Suurs & Hekkert, 2009). The identification of the structural components that make up the innovation system defines actors, networks and institutions involved (Bergek et al, 2008). This research adds clusters to the relevant structural factors, based on the assumed importance of geographical location in the service robotics industry.

2.3.1 Actors

Etzkowitz and Leydesdorff (2000) define three categories of relevant actors in their spiral model of innovation, the 'triple helix': university, industry and government actors. According to Etzkowitz and Leydesdorff (2000), there has been a change from regarding the three actor categories, or institutional spheres, as independent towards a model that regards the different institutional spheres as intertwined and interdependent.
In the case of the service robotics industry, the collective of relevant actors in a TIS does not only include actors that contribute directly to the value chain, such as companies and universities, but also public bodies, venture capitalist, interest groups, organizations deciding on standards, etc. (Bergek et al., 2008).

2.3.2 Networks

Bergek et al. (2008) describe several types of networks of actors. Networks vary in their degree of formalization. On the formalized side of the spectrum networks have a specific task, clearly described in documentation, and are governed by a governing actor. An example of such a network is a government-initiated standardization network. On the other side of the spectrum are less orchestrated networks such as buyer-seller relationships or university-industry links (Bergek et al., 2008).

Literature states several other types of networks (Suurs, 2009; Bergek et al., 2008; Porter, 1998b):
- Technology platform consortia
- Industry associations
- Public-private partnerships
- Buyer-seller relationships
- University Alumni
- Company Alumni
- Venture Capital (VC) communities

2.3.3 Institutions

Institutions are the rules and boundaries in which a TIS develops. Examples are laws, regulations and norms, but also 'softer' aspects, such as culture. In order for a technology to diffuse, institutions should generally be aligned with technology developments. Institutions exist in two different forms: Formal institutions and informal institutions (Suurs, 2009). Formal institutions are laws and rules that are codified and often enforced by an authority. Informal institutions are more tacit and consist of the visions and expectations of actors. In the formative stage of a TIS, growth of the system is caused by the visions and expectations of individual researchers and entrepreneurs. While technology develops and a more clear direction is formulated, individual expectations shift into shared visions. The more developed informal institutions can in turn cause the emergence of formal institutions, in the form of government policies, laws, etc. Interventions into formal institutions are often targeted towards influencing informal institutions and thereby creating presence, skill and willingness of actors to further develop technology.

2.3.4 Clusters

If actors, networks and institutions are grouped and subject to geographic boundaries, the geographic concentration of interconnected companies and institutions in a specific field defines a cluster (Porter, 1998a; Porter, 1998b). According to Porter (1998a), clusters often fit within political boundaries, but can cross state or national borders. An example of such is the pharmaceutical cluster in New Jersey that expands into Pennsylvania. Clusters have an influence on competition in three different ways (Porter, 1998a). First of all, clusters increase the productivity of participating companies. Examples are improved productivity in logistics based on a solid transportation infrastructure and access to well-trained employees from universities with targeted educations. The second advantage is that clusters drive the direction and pace of innovation. Companies within a cluster can often implement innovations more quickly based on faster sourcing possibilities. Both sophisticated buyers and suppliers are likely to be present in the cluster, both driving direction and pace of innovation. The final advantage is the stimulation of new business formation, thereby expanding and strengthening the cluster itself (Porter, 1998a).

Porter (1998a) adds that solely the collocation of different actors in a specific field does create the potential for added economic value by clusterization, but is does not necessarily ensure its realization. A number of case studies have made clear that the actual realization of cluster benefits can take over more than a decade of cluster development.

2.3.5 Conclusion

Cluster research gives insight in the importance of geographical location of structural factors in the service robot industry.

Comparison of structural factors and TIS dynamics increases understanding of the interplay between the more static, structural characteristics and the more rapid changes in dynamic aspects, TIS functions. TIS functions require the backing of complementary structural factors to impact TIS performance. On the other hand, the presence of structural factors by itself does not positively influence the TIS, but can only do so by means of function instances. A misbalance or dysfunctional interplay between structural factors and TIS dynamics therefore leads to recommendations for one or both aspects. Section 2.4 continues with the discussion of TIS functions.

2.4 TIS FUNCTIONS

Several academic studies propose an operationalization of the dynamics of TIS by utilizing a set of seven functions of TISs (Hekkert et al., 2007; Suurs, 2009; Bergek et al., 2008). These functions map key activities in innovation systems and explain developments and changes in direction within specific TISs. The seven functions are:

F1. Entrepreneurial Activity
F2. Knowledge Development
F3. Knowledge Diffusion
F4. Guidance of the Search
F5. Market Creation
F6. Resource Mobilization
F7. Support from Advocacy Coalitions

Paragraphs 2.4.1-2.4.7 discuss the seven functions. TIS theory describes the seven functions on a broad, abstract level. Innovation theory outside TIS theory provides more precise insight into the knowledge related functions F2 and F3. The two knowledge related functions are especially relevant for the robotics technology, due to its integrative and interdisciplinary nature and therefore dependency on external sources of knowledge. Therefore these functions are described on a more detailed level using additional literature.

2.4.1. Entrepreneurial Activity (F1)

Recent research on TIS states that previous research on innovation system frameworks suffers from institutional determinism (Hekkert et al., 2007; Suurs & Hekkert, 2009). The researchers propose a more prominent role for the individual perspective, the perspective of the entrepreneur, since the entrepreneur plays a crucial role in practically all innovation literature and possesses the power to (once in a while) overthrow and change (elements of) the technological system, directing the process of technical change towards another course.

Entrepreneurs form the core of any innovation system and come up with new business opportunities and experiment with new technologies (Van de Ven, 1993). Entrepreneurial activity can be the start of a new company (or closure), a strategic change in direction, the launch of a new product, etc. Entrepreneurial activity does not only include new or small firms, but covers the more general Schumpeterian concept of an entrepreneurial function. This definition also includes the development of new product combinations by any type of actor, possibly including large companies.

Several authors highlight the importance of entrepreneurial experimentation (Hekkert et al, 2007; Holmen & Jacobsson, 2000). Entrepreneurial experimentation leads to selection and transfer of basic technologies to applications. Many of such experiments fail and some succeed, thereby contributing to a social learning process (Bergek et al., 2008). The progress of the TIS as a whole is at risk when no entrepreneurial experimentation takes place.

2.4.2 Knowledge development (F2)

According to Lundvall (1992) 'The most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning'. The function of knowledge development is therefore at the core of the innovation system. There are two general types of learning, being 'learning by searching' and 'learning by doing'. Generally, the first type of learning takes place at basic research facilities, e.g. university labs. The latter refers to learning from practical experience, e.g. adoption trials (Suurs, 2009). Both types of learning lead to the development of knowledge, of which different types can be distinguished. Examples of types of knowledge are scientific, technological, production, market, logistics and design knowledge (Bergek et al., 2008). This research focuses on the development of scientific and technological knowledge, since these knowledge types relate directly to technological innovations in robotics, whereas the other knowledge types function as prerequisites for successful commercialization of innovations.

Knowledge originates from different sources. The main method for knowledge development of scientific and technological knowledge however is R&D, performed by companies, universities, research labs, etc. Scientific and technological knowledge development can therefore be expressed in terms of publications, patents and R&D projects.

As already mentioned, Lundvall (1992) formulates knowledge as the most fundamental resource in the present economy. Learning, or knowledge development, is therefore a necessity for successful TIS development, especially in a high tech industry such as the service robotics industry. This notion, in combination with the important role of entrepreneurial activity (in the broad sense), raises the question how knowledge develops within companies and within networks of companies and other parties.

The theory of Open Innovation describes corporate activity in networks and how knowledge develops in networks (Chesbrough, 2003; Chesbrough, 2004). Chesbrough describes the factors that contributed to the erosion of the former Closed Innovation paradigm, a paradigm in which research projects progress solely within the boundaries of the firm. Factors that challenged the fundaments of Closed Innovation were the increased mobility of highly experienced and skilled people, the growing investment power of private venture capital (VC) firms, the necessity of a faster time-to-market for many products and services and increased global competition. The combination of these developments caused the emergence of outside options, the possibility to apply valuable knowledge beyond the traditional borders of the firm, by means of spin-offs, licensing agreements, joint ventures, etc. The trend also caused knowledge from outside the company to be more readily available by similar contractual or informal means. In the closed innovation paradigm, companies often were reinventing wheels (Chesbrough, 2003). The open innovation paradigm allows company researchers to reach out for external knowledge, shortening development times and keeping up to date with the latest findings by smart people outside the walls of the company. Chesbrough proposes that Open Innovation is not merely an option for companies, but often a necessity in the face of shorter time-to-market cycles and increased competition. Tushman (1997) and Benner and Tushman (2003) agree with the trend of increased importance of outside know-how by emphasizing the role of incorporating external information in their description of organizational innovation processes.

Table 2.1 states the contrasting principles of the Closed Innovation paradigm and the Open Innovation paradigm. Besides the focus on external knowledge and human resources, the comparison clarifies that Open Innovation includes a clear business orientation and an intellectual property (IP) policy.

Internal research remains an important pillar in the open innovation paradigm, since internal research allows a company to obtain a competitive advantage by combining external technologies into new architectures or combining internal and external research findings into new products. The ability of a firm to recognize the value of new, external information, assimilate it and apply it to commercial ends is embedded in the construct absorptive capacity (Cohen & Levinthal, 1990).

Table 2.1 Closed versus Open Innovation (adopted from Chesbrough (2003))

Closed	Open
The smart people in the field work for us.	Not all the smart people in the world work for us. We need to work with smart people inside and outside our company.
To profit from R&D, we must discover it, develop it and ship it ourselves.	External R&D can create significant value; internal R&D is needed to claim some portion of that value.
If we discover ourselves, we will get it to market first.	We don't have to originate the research to profit from it.
The company that gets innovation to market first will win.	Building a better business model is better than going to market first.
If we create the most and the best ideas in the industry, we will win.	If we make the best use of internal and external ideas, we will win.
We should control our IP, so that our competitors don't profit from our ideas.	We should profit from others' use of our IP, and we should buy others' IP whenever it advances our own business model.

The absorptive capacity of a firm depends on the absorptive capacities of the individuals that make up the firm, although it is not the direct sum of the individuals' absorptive capacity, but rather a mosaic of individual knowledge structures.

Besides the obvious need for technical knowledge, absorptive capacity also includes knowledge on where to find and how to use external information. Absorptive capacity should be developed in-house since it requires company-specific knowledge, which is for a large part tacit knowledge and therefore difficult to acquire externally by employing external specialists or hiring consultancy firms.

The Open Innovation and Absorptive Capacity paradigms highlight the importance of external knowledge integration. The function Knowledge Development should therefore not be regarded as solely internal functions of the firm or knowledge developer, but should be seen in strong interaction with functions performed by other actors, by means of the TIS function Knowledge Diffusion.

2.4.3 Knowledge diffusion (F3)

The characteristic structure of a technological innovation system is the network (Carlsson & Stankiewicz, 1991), with the primary function of networks being the facilitation of knowledge exchange between nodes, directly associated to the knowledge diffusion function of TIS. Knowledge diffusion therefore is the spreading of knowledge to different actors in a network.

The internal knowledge and capabilities necessary to perform multiple stages of technology development are not always sufficiently present in companies. External scientific and technological knowledge is therefore of major importance (Freeman, 1991). This leads to a need for collaboration and knowledge diffusion with other organizations in the same stage or subsequent stages of technology development. Collaboration with organizations in the same stage of technology development is regarded as horizontal collaboration, focusing on the acquisition of new or more in-depth knowledge on the subject. Collaboration with organizations that are active in the subsequent stage of technology development is regarded as vertical collaboration, e.g. cooperation on production techniques or the transfer of knowledge from basic research institutes to companies that have the intention to commercialize the technology. Knowledge diffusion can occur in different ways, ranging from information exchange at conferences to strategic alliances between parties in the innovation system.

The network aspect of knowledge diffusion is intensely research by academia. Academic literature includes several studies into networks of innovation (Chesbrough and Prencipe, 2008), inter firm collaboration networks (Ahuja, 2000; Powell et al., 1996; Stuart, 1998), collaborations between universities and companies (Liebeskind, 1996; Owen-Smith et al, 2002) and the role of the government in (international) R&D alliances (Narula & Dunning, 1997). The goal of this section is to conclude with a detailed framework of collaboration and knowledge diffusion methods that is suitable as a framework for research. This section deploys an increasing level of detail, discussing collaboration network general benefits, the structure of collaboration networks, and detailed collaboration network tie forms.

Collaboration network benefits

Academic research identified two forms of benefits from innovation networks, resource sharing and access to information spillovers (Afuah, 2000). Resource sharing allows a network of firms to connect knowledge, skills and physical assets. Access to information spillovers informs firms in the network about discoveries and failed approaches.

Collaborations between organizations are not only a means to compensate for inadequate internal capabilities, nor should collaborations be seen as separate from the organizational learning process (Powell et al., 1996). Collaboration supports the development of internal capabilities, thereby also increasing the organization's value as a collaborator, instigating a virtuous circle of increased collaboration value.

Collaboration network structure

Chesbrough and Prencipe (2008) propose that firms should mimic the technology dynamics of new product developments in the corresponding development of innovation networks. In practice, this means that companies should maintain close ties with universities and research labs in the early stage of development to explore alternative technological solutions since the technology is still in a state of flux. In the transition phase from exploration towards exploitation, contact with start-ups is essential to experiment with different configurations that exploit the enabling technology. At the time a 'standard' configuration has arrived, firms should switch their attention to more exploitative networks (e.g. customer or supplier networks) that are better equipped for exploitation of the technology configuration. The messy world of practice often blurs the neat distinctions of theory however (Powell, 1996). Exploitation and exploration are intertwined and organizational learning is both affected by access to knowledge and the capabilities for deploying such knowledge.

The structure of a network depends on the current stage of the collaboration network and on the set of specific characteristics of the industry technology and institutional factors (Kogut, 2000). An example is the defense robotics industry, in which a major portion of the development efforts are financed via DARPA grants, which makes DARPA the central player of the industry.

Networks in the pre-modular or transitional phase, or shortly in the exploration phase of technology research fit naturally with networking forms between firms and research centers or universities, while networks in the exploitation phase are better suited by networking between firms and the supplier base.

Scientific literature points out the importance of direct ties, indirect ties and structural holes as key characteristics of a network structure (Ahuja, 2000; Gulati & Garguilo, 1999). Direct ties are direct contacts between organizations in the network, by which active communication and information or knowledge exchange takes place. Indirect ties are ties with nodes in the network which an organization is not directly connected to, but does connect to via a mediating node in the network. Indirect ties thereby provide access to knowledge present at a partner's partners (Gulati & Garguilo, 1999). Structural holes are disconnections between a firm's partners, meaning that a subset of partners is not connected to each other. Structural holes in a network allow companies to access diversified new knowledge, because of the different forms of knowledge present at network partners and the lack of knowledge exchange between those partners.

Collaboration network relationships

The information and knowledge management requirements of partners in the innovation network determine the type and intensity of relationships between partners in the network. Depending on the stage of technology development and the type of organizations, partners can configure their networks using specific formal contractual terms such as joint ventures, or more informal alliances or shared development projects, tailored to the needs of every network relationship (Chesbrough & Prencipe, 2008).

Collaboration networks operating in an exploitation phase will primarily use equity ties (Koza & Lewin, 1998). Another indicator of strong ties is the initiation of joint ventures that create a new separate administrative entity. Weaker ties such as development agreements, licensing agreements and joint research collaborations are less formalized and usually more straightforward to withdraw from. Those weaker ties are associated with explorative stages of technology development.

Powell et al. (1996) identified a set of different types of ties in innovation network relationships. This research started with the basic set of network tie types and adapted the list to the robotics industry, resulting in the set of relationship types as shown in Table 2.2. The list starts with relationships linked to explorative strategies such as research collaborations and continues towards more exploitative forms of relationships, such as licensing agreements and supply chain relationships. Table 2.2 shows the typical partners associated with specific relationship types and adds the complex tie to clarify that collaboration agreements can both include more than form, e.g. licensing and manufacturing contracts, and that collaboration agreements can evolve over time, transforming from a weak, explorative tie towards a more exploitation oriented relationship.

Table 2.2 Network relationship types

Type of Tie		Typical Partners
R&D alliance	Develops research program with another organization for a specific target	Other firms, research institutes, university labs
Outside investor	Partner invests funds	Venture capital firms
Investment	Firm invests funds (and usually human/scientific capital) in a partner	Other robotics firms
Joint Venture	Creation of a new company by multiple companies	Other robotics firms
Licensing In	Firm purchases rights to partner's idea	Universities
Licensing Out	Firm licenses idea to outside organization	Other robotics firms
Manufacturing	Firm contracts with partner to manufacture its product	Manufacturers
Supply/Distribution	Agreement to receive materials or to supply products to distributors	Suppliers, Distributors
Complex	Tie that contains more than one of the above listed activities	Any type of partner

2.4.4 Guidance of the search (F4)

The fourth TIS function, Guidance of the search, represents a selection process that facilitates convergence in development. Where the function knowledge development creates possibilities, guidance of the search defines foci that are chosen for further investments (Hekkert et al., 2007). The omnipresent scarcity of resources leads to a need for focus establishment. Guidance of the search grants a certain degree of legitimacy to the allocation of further resources to a specific technology (Hekkert & Negro, 2009).

The function includes activities that shape the needs, requirements and expectations of different actors in relation to the subject technology. The activities range from individual expert opinions to government policies in the form of institutions (Suurs, 2009).

Different actors can play a role in guiding the search. Governments by their policies and other institutes mainly by selection of research foci. Therefore selection occurs by policy priorities, research outcomes, etc. Both positive and negative instances of guidance occur in the form of success or failure of particular technological development trajectories.

2.4.5 Market formation (F5)

Usually the market for emerging technologies is initially very limited, due to a lack of insight into the ultimate applications of the technology in products (Hekkert et al., 2007). Therefore the function market formation regards the creation of new (niche) markets where new technologies have a possibility to grow. For TISs in the formative stage, there is often not yet a market mechanism in place. According to Bergek et al. (2008), the market then operates as a 'nursing market' in which learning space has to be opened up. Evolution of the market propels the TIS market into a 'bridging' phase, in which volumes increase and larger numbers of actors are associated with market mechanisms. A successful TIS can reach the final stage of market evolution, the mass market.

Due to the system spanning influence of market formation, the function is generally performed by government actors. Occasionally governments create niche markets, but a more frequent form of market creation is the approval of products before they can be made available to the public by regulatory institutes such as the U.S. Food and Drug Administration (FDA).

2.4.6 Resource Mobilization (F6)

Technology development requires the allocation of human, material and financial resources, the basic input for all activities within the TIS (Hekkert & Negro, 2009; Suurs, 2009). The allocation of resources is a direct prerequisite for knowledge development, showing the close link between the functions resource mobilization and knowledge development. Human resources mobilization relates to the ability of the TIS to attract people to develop both scientific and technological knowledge.

Financial resources mobilization generally starts out with government and subsequent university programs. Therefore in the early stages of a formative TIS, financial resources can be obtained by subsidies and investments. During the evolution of the system, more and more private actors will contribute to resource mobilization (Suurs, 2009).

In practice, resource mobilization can be operationalized by several constructs such as an increasing volume of capital, a growing volume of seed and venture capital or changes in the volume and quality of human resources (Bergek et al., 2008).

2.4.7 Support from advocacy coalitions (F7)

The rise of an emerging technology can cause resistance from organizations in competing markets or proponents of alternative technologies. Advocacy coalitions can counteract resistance and can create legitimacy for the specific technology (Hekkert & Negro, 2009). Advocacy coalitions function as political lobbies and advisors for interest groups (Suurs, 2009). Advocacy coalitions are usually private actors such as NGOs or industries organized in interest groups. Governmental organizations can function as advocacy coalitions as well, for example in the form of regional governments that lobby at the federal government. Research into the function can be done by analysis of interest groups and their lobby initiatives (Hekkert et al., 2007).

2.4.8 Conclusion

The previous sections have provided more detailed insight into the TIS functions, which forms the basis for the analysis of function interdependencies. Those interactions between TIS functions can lead to motors of innovation, as discussed in section 2.5.

2.5 MOTORS OF INNOVATION

Positive results in specific TIS functions can have a positive influence on other functions of the system. An example is the direct influence that 'Resource Mobilization' can have on 'Knowledge Development', by means of funding research. If these interactions between functions are recurring, the interactions can lead to virtuous cycles, defined as cumulative causation. These positive feedback loops in the technological system are defined as motors of innovation and can ultimately lead to accelerated build-up of the TIS (Suurs & Hekkert, 2009). The same logic however holds for the influence of negative events, causing a cumulative causation that results in vicious cycles and (partial) breakdown of the TIS (Suurs, 2009). Researchers can determine the motors of innovation for specific TISs and use this analysis to compare different technological systems.

Suurs (2009) proposes four motors of innovation:

1. Science and technology push motor
2. Entrepreneurial motor
3. System building motor
4. Market motor

The science and technology push motor relies heavily on diverse knowledge development (F2) and diffusion (F3), followed by guidance of the search (F4) to converge towards the most viable technologies. Subsequent funding (F6) leads to deeper insight into technologies. Appendix D shows visual representations of all four motors. According to Suurs (2009), the entrepreneurial motor occurs in a later stage of technology development. The entrepreneurial motor is centered around corporate activity (F1) in the form of experimentation, new businesses and changes in corporate strategy. Knowledge development (F2) and diffusion (F3) continue to play an important role and in this motor support from advocacy coalitions (F7) can lead to increases in activity for other functions, especially in resource mobilization (F6). The system building motor is based upon the entrepreneurial motor, however is extended by the incorporation of the market creation (F5) function. Networks of entrepreneurs grow and tighten, shifting from knowledge creation to mass market creation. The market motor represents the final motor in a formative TIS. The market motor includes all functions of TIS, except support from advocacy coalitions. In this stage, the TIS does no longer rely on funding and market creation from the government, and therefore no longer subject to the politics associated with advocacy coalitions.

This research uses the identification of motors of innovation to compare TISs in the U.S. and to compare the U.S. situation with the Dutch situation. Section 2.6 concludes the literature study with the overall theoretical framework.

2.6 THEORETICAL FRAMEWORK

The previous sections discussed the academic literature on innovation within the field of technological innovation systems. The literature study revealed that research into both structural factors and system dynamics is required for a thorough analysis of a TIS. Structural factors include actors, networks and institutions and define the context in which system dynamics take place. The findings from literature on system dynamics are summarized in the theoretical framework as displayed in figure 2.2.

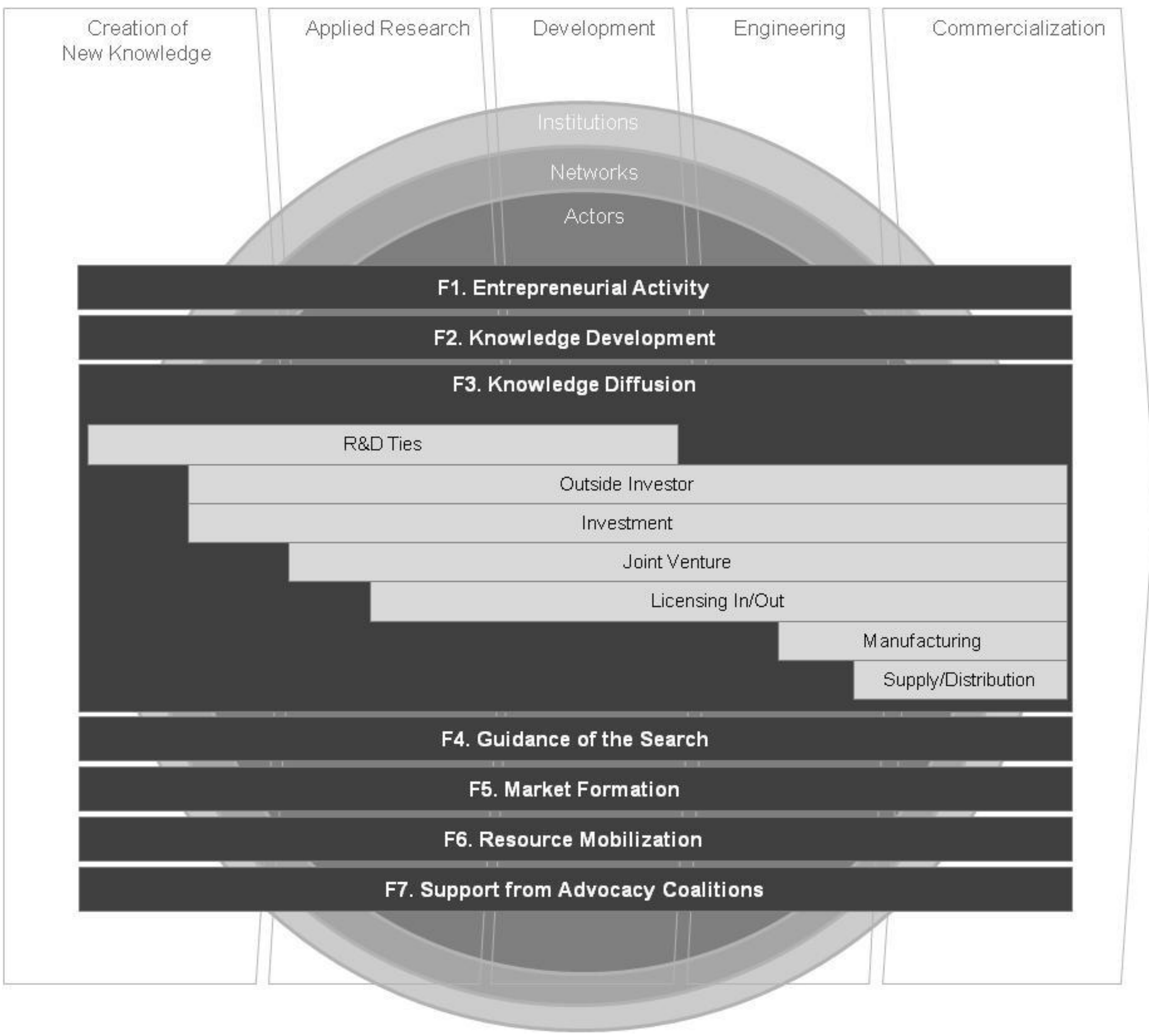

Figure 2.2 Theoretical framework

The framework proposes the transition of technology through different phases until market adoption. TIS Functions develop in the context of structural factors, of which the actors are directly connected to function events. Actors are organized in networks and the outer shell shows institutions as the structural factor that influences the complete TIS. The different TIS functions play a role in all stages of technology development. The discussed literature on network relationship types (table 2.2) allows for a more precise breakdown of the knowledge diffusion phase, based on the typical moment of occurrence of the different relationship types.

The TIS dynamics framework visualizes the different functions of TIS separately. In practice, the functions intensively interact and influence each other. An example of function interaction is the change in policy of the Dutch government towards subsidizing the development of sustainable energy technology. This policy mobilized resources and created a market for new sustainable technologies in the energy market, directly influencing two of the seven TIS functions.

The theoretical framework can be used for exploratory research into the innovation process of a specific industry, assessing the activities of individual firms, the type and intensity of collaborations between partners, the role of the government and the overall dynamics of the TIS. The overall goal of the theoretical model is to identify motors of innovation for a specific technology. Suurs (2009) tested the TIS framework and identified motors of innovation in the sustainable energy industry. This research reviews whether motors of innovation, or specific arrangements of TIS functions, are also a valid approach for researching the robotics industry.

3. Research Method

This chapter discusses the research methods for answering the research sub questions. Section 3.1 explains the overall Analytical Research Scheme. Section 3.2 - 3.6 further describe the different elements of the analytical research scheme.

'Panta rhei.'
All things are in flux.

3.1 Analytical Research Scheme

The research sub questions translate to the overall analytical research scheme as depicted in figure 3.1, including structural components (SQ1), TIS function analysis (SQ2), including event history analysis, the formulation of the historical narrative and trend pattern analysis, and motors of innovation (SQ3), based on interaction pattern analysis and motor identification.

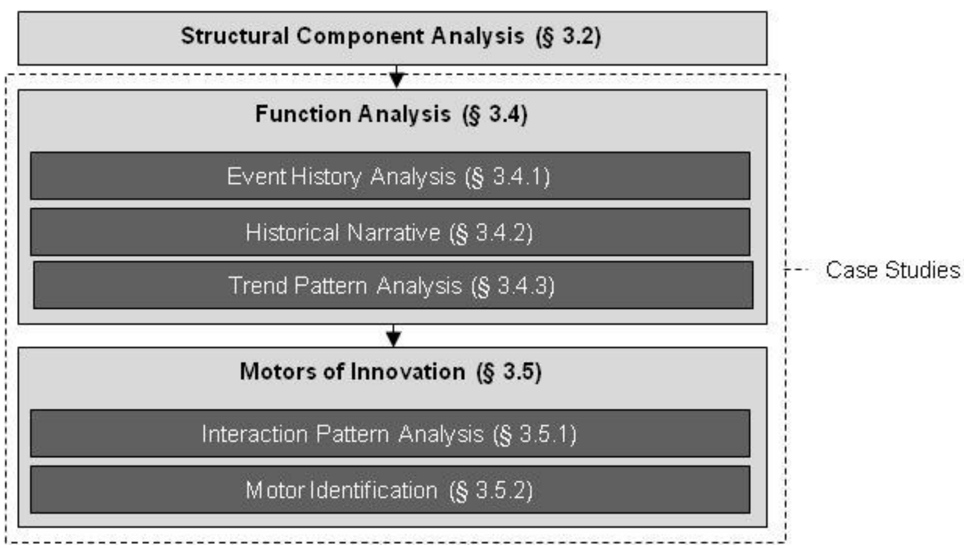

Figure 3.1. Research Scheme

Structural factors are discussed industry-wide. A complete TIS function analysis of the service robotics industry is impractical, due to its wide-spreading applications. To gain specific insights into the workings of the TIS functions, the function analysis, pattern analysis and identification of motors of innovation is done separately for both case studies. A cross case comparison serves as the synthesis of the results from both case studies.

3.2 Structural Factors

An analysis of the structural factors is made for the broad application field of service robotics. Previous research into TISs suggests that innovation researchers who are new to a certain technology or field of knowledge can start with a broad research approach and later on specify the area in focus (Johnson and Jacobsson, 2001). This allows for a thorough understanding of the field of application before a choice for a specific technological focus and related case studies is made.

Previous research into relevant companies and research institutes in the service robotics industry by the TWA Network (Rane, 2009) forms the basis for the company and research institutes overview. This overview is extended with information on networks and institutions based on interviews with TWA Network[6] representatives in Washington, DC, supported by information from secondary data sources, e.g. government documents and cluster overviews. The analysis of structural factors in the case of actors and networks ultimately leads to a database of relevant parties.

3.3 Case Study Selection

The main research question demands for deep insights in events that occurred in the process of technology development. For answering questions that require deep insight and that are directly related to ‘real life' situations, a case study approach best suits the needs of the research (Yin, 2003). The use of multiple cases strengthens the results of the research. The selection of case studies serves as a close representation of the field of service robotics and its dynamics. A cross-case comparison identifies differences and patterns in the system dynamics. Different enabling technologies function as the case studies for this research.

Case study selection for TIS regards the choice between a specific field of knowledge or technology as the first option or an application of technology as the second option. This research uses the enabling technology as it starting point. Enabling technologies for service robotics take many different forms; examples are robotic manipulators, autonomy, perception and navigation, etc. Appendix C shows a (partial) list of possible enabling technologies ranging from use in static service robots, mobile service robots and in robots that manipulate physical objects. The choice depends on the goals of the research and the technology discussed (Holmen and Jacobsson, 2000). The choice for an enabling technology also requires formulation of the boundaries regarding research into the possibly large number of subsequent applications of the chosen technology.

[6] Personal communication with P. op den Brouw and B. Sattler, TWA Network.

The selection of the case studies is made based on both the U.S. Robotics Roadmap 2009[7] and the Strategic Research Agenda for Robotics in Europe[8], in combination with discussions with the TWA Network. A

Case I: **Dexterous Manipulation**
Dexterous refers to manual dexterity, the human-like capability to precisely grasp, hold and relocate physical objects without damaging the object or any part of the direct surroundings.

Case II: **Autonomous Navigation**
A second important robot capability is the mobility to transfer to another location in order to extend the operational range, preferably autonomously.

The roadmaps list both enabling technologies as crucial capabilities for service robotics in the near future, making both case studies valid selections for further research. Moreover, both enabling technologies are integrated in robotics since the beginning of the field, making it possible to research development of the system over a long time period. A useful characteristic of both enabling technologies is their relatively unique application in the field of robotics. Other enabling technologies can have widespread applications outside robotics, making it more difficult to define the boundaries of the research.

Section 3.4 continues with the discussion of the research methods for TIS function analysis of both case studies.

[7] CCC, A Roadmap for US robotics: From Internet to Robotics

[8] Europ (European Robotics Technology Platform), Robotic Visions: to 2020 and beyond – The Strategic Research Agenda for Robotics in Europe, p. 30

3.4 TIS FUNCTION ANALYSIS

Research into TIS functions for the specific cases (enabling technologies) is carried out using the method of event history analysis.

3.4.1 Event History Analysis

Research into the dynamics of technological innovation systems requires a longitudinal view of the system. The system evolves over time as the technology development process progresses, which means that investigation of the system at a single point in time will not yield sufficient information on causes of either technological progress or stagnation. Prior research into TIS identified event history analysis as a suitable approach (Poole, 2000; Van de Ven, 1999). Event history analysis is a process approach that systematically analyses longitudinal data by identifying abrupt changes in the dynamics of a system and classifies them as events. The method is used to create a chronological overview of the events that shape technology development. The end goal is to formulate motors of innovation for the specific TIS. The remainder of this section discusses the data collection methods for events, the mapping of events to TIS functions and data validation .

Data collection

Research into secondary (historical) data is used to identify events (Zikmund, 1987).

The secondary data sources include journals, websites, databases and university archives. This wide range of sources is a prerequisite to cover the large set of events occurring at universities, companies and research institutes. Table 3.1 shows the different sources of data. Scientific journals are searched using Web of Knowledge, including backward en forward citation search to reveal other relevant publications. A minimum of 10 references to the scientific publication is set to ensure the inclusion of only publications that have had a significant impact on technology development.

Information from company websites and university news archives is only used to deepen information from other sources, in order to prevent sampling bias. The choice for MIT, CMU, Harvard and Stanford as researched universities is based on their leading role in robotics. An example of information derived from company and university websites is information about the different partners involved in a specific collaboration.

Previous research used newspaper articles as the main data source (Suurs, 2009). This research deepens the research methodology by including both scientific publications and patents.

Table 3.1 Data Sources

Type	Name	Information
Journal	Scientific Journals	Publications
	MIT Technology Review	Research/Product developments
	Science	Research/Product developments
	Robotics Business Review	Business/Product developments
Website	RoboticsTrends	Research/Product developments
	ScienceDaily – Robotics	Research/Product developments
	Company Websites	Background Information
Database	US Patent & Trademark Office	Patents
	Federal Business Opportunities	Grants & Contracts
	Hoovers	Company & Industry Information
University Archive	MIT News Archive	Background Information
	Harvard News Archive	Background Information
	Stanford News Archive	Background Information
	Carnegie Mellon News Archive	Background Information

Event mapping

Previous research mapped events to TIS functions based on interpretation by the researcher (Suurs, 2009). The use of more objective data sources such as scientific publications and patent databases allows for a more direct mapping of events to TIS functions.

Table 3.2 shows how events are mapped to the different TIS functions. The event types are derived from TIS theory (as described in § 2.4) and from the additional innovation literature discussed in chapter 2. For every event type, the source of this particular type is mentioned. Events can have a positive or negative influence on technology development. A negative influence on technology development can occur when research results criticize the usability of a specific enabling technology or when development is halted by the bankruptcy of companies or by law suits regarding patent infringements. The inclusion of negative events in the research is an important benefit of using event history analysis, possibly explaining slowed progress in technology development or even causing a total switch towards another enabling technology.

Table 3.2 Event mapping

Function	Event Type	Description	Sign
F1. Entrepreneurial Activity	Company Start/Spin-off (§ 2.4.1)		+
	Portfolio Expansion (Hekkert, 2007)	Exploring new applications	+
	Company Closure (§ 2.4.1)		-
F2. Knowledge Development	Research result (Suurs, 2009)	General new results	+/-
	Scientific Publication (§ 2.4.2)	Results from academic research	+/-
	Patent (§ 2.4.2)		+
F3. Knowledge Diffusion	R&D Alliance (§ 2.4.3)	Collaborative research	+
	Licensing (§ 2.4.3)	Licensing in or out	+
	Joint Venture (§ 2.4.3)		+
	Manufacturing (§ 2.4.3)	Manufacturing agreement	+
	Patent infringement (§2.4.3)	Lawsuit over patent infringement	+/-
F4. Guidance of the Search	Expression expectation (Suurs, 2009)		+/-
	Government guidance (Hekkert, 2007)		+/-
F5. Market Formation	Positive discrimination (Suurs, 2009)	Tax or other benefits for consumers	+
	Clearance (Suurs, 2009)	FDA or other approval of use	+
F6. Resource Mobilization	Government Investment (Suurs, 2009)	Grants, contracts	+
	Private Investment (Bergek, 2008)	Venture Capital, IPO	+
F7. Support Advocacy	Lobbying (Suurs, 2009)		+

The mapping of events to TIS functions ultimately results in a database of events, classified instances of the different TIS functions. The events are described using a number of variables, of which the TIS function classification is one. Table 3.3 describes the different variables as documented per event, referring to the relevant table or figure from the literature study where applicable.

Table 3.4 displays which variables are taken into account for the different TIS functions. The main difference lies in the variables that describe secondary actors, clusters and tie types, variables that are only applicable in the case of knowledge diffusion between two or more parties or an investment relation between two or more parties.

The end result is a database for each case study that describes events on all relevant variables.

Table 3.3 Event database variables

Variable	Description
Year, Quarter	Time Indication
Primary Actor, ClusterA	Identification primary actor and related cluster
Secondary Actor, ClusterB	Identification secondary actor (in case of a collaboration/tie) and related cluster (if applicable)
Function of TIS	Classification TIS function F1-F7
Tie Type	From Table 2.2: R&D alliance, Investment, Joint Venture, Licensing, Manufacturing, Supply/Distribution, Acquisition
Specification	Description of the event
Techn. Development Stage	From Figure 2.1: Basic Research, Applied Research, Development, Engineering, Commercialization
Application	From Figure 1.1: Medical, Defense, Security, Logistics, Inspection, Space, Personal service
Strength	Dollar value of the investments
Source	Source of the information

Table 3.4 Event variables mapping

	Year	Quarter	Primary Actor	ClusterA	Secondary Actor	ClusterB	Function of TIS	Tie Type	Specification	Technology Dev. Stage	Application	Strength	Source
F1. Entrepreneurial Activity	•	•	•	•	•	•	•		•	•	•		•
F2. Knowledge Development	•	•	•	•			•	•	•	•	•		•
F3. Knowledge Diffusion	•	•	•	•	•	•	•	•	•	•	•		•
F4. Guidance of the Search	•	•	•	•			•		•	•	•		•
F5. Market Creation	•	•	•	•			•		•	•	•		•
F6. Resource Mobilization	•	•	•	•	•	•	•	•	•	•	•	•	•
F7. Advocacy Coalitions	•	•	•	•			•		•	•	•		•

Data validation

In order to validate the findings in the database and to cross-check whether the sources cover all relevant events, semi-structured interviews are conducted. Sampling for the interviews is done using quota sampling, followed by judgment sampling and possibly snowball sampling if additional information is needed (Zikmund, 1987). Quota sampling identifies the different stratums as they are represented in the total population of actors in the service robotics industry. The major stratums are companies, universities and governmental organizations, based on the 'triple helix' model as described in section 2.3.1. The majority of actors are companies and therefore the majority of the interviews will be conducted with company representatives, in line with quota sampling. In order to determine which companies to interview, judgment sampling is used. The choice for actors to be interviewed is based on the number and type of appearances in the event database, together with the results from the structural factors analysis that identifies major actors. The choice is further supported by a qualitative judgment by the researcher and the TWA Network. If quota sampling together with judgment sampling are not sufficient, snowball sampling is used to identify possible interviewees based on previous interviews with other actors. Appendix G includes the interviewees, listed per case study.

The semi-structured interviews allow for more in-depth qualitative research into specific TIS functions, besides solely validating the event history database. Appendix E shows the complete list of questions as presented to company representatives. The set of questions deploys questions regarding structural factors and the different TIS functions, based on the literature study. In the case of university or government representatives, the relevant sub set of questions was asked. The questions are targeted specifically at the situation of the actor at hand, preventing general statements regarding the overall system based on assumptions from one actor regarding another actor.

3.4.2 Historical Narrative

The historical narrative describes the development of the TIS over time. The narrative identifies general enabling technology and application related trends based on differences in the variables 'stage of technology development', 'tie type' and 'application'. Changes in these three variables indicate progress or stagnation of the system as a whole. 'Stage of technology development' indicates the maturity of both the technology and the market, the 'tie type' variable gives insight in the degree of commercialization of collaboration forms between actors and 'applications' indicates until what extent the use of the enabling technology diversifies towards other applications. General trends are demonstrated by specific events from the event history analysis database. The event history analysis in combination with the historical narrative leads to the identification of episodes, periods of time that differ in their TIS function intensity and type. TIS episodes can later be mapped to different motors of innovation.

The historical narrative identifies general trends and serves as the context in which TIS functions develop.

3.4.3 Trend Pattern Analysis

TIS function analysis gives insight in the intensity of individual TIS functions at a specific point of time. This research however focuses on the development of the system over time. Previous research suggests time analysis by means of trend pattern analysis as the method for investigating differences within functions over time(Poole et al., 2000).

Trend pattern analysis is carried out within functions to review the intensity of function activity over time, based on the collected quantitative data and qualitative data from the interviews. Trend pattern graphs hereby give insight in the roles specific TIS functions have over time.

3.5 Motors of Innovation

Motors of innovation are identified using the results from TIS function analysis. The TIS function analysis describes activity over time within specific TIS functions. Motors of innovation are based on interactions between different TIS functions. These interactions are identified by using interaction pattern analysis and by mapping coexisting function intensities to the different motors.

3.5.1 Interaction Pattern Analysis

Interaction patterns describe the influence of specific TIS functions on other functions in a later stage of technology development. If the analysis reveals recurring interaction patterns, the system's motor(s) of innovation can be identified. The interaction pattern analysis is mainly based on qualitative analysis of the cause and effect relations between functions and supported by quantitative analysis of the data by means of cross correlation analysis of different TIS function time series. Cross correlation is a standard method for determination of the degree for which two series are related. For the TIS functions, the analysis can show correlations between the intensity of a specific TIS function and another TIS function at another point in time. Consider the two function intensity series x(i) and y(i) for the years i. The cross correlation r at delay d is

$$r = \frac{\sum_i [(x(i) - mx) * (y(i-d) - my)]}{\sqrt{\sum_i (x(i) - mx)^2} \sqrt{\sum_i (y(i-d) - my)^2}} \qquad (6.1)$$

A t-test is used to establish whether the correlation coefficient significantly differs from zero.

Previous researches have not used time series analysis, despite the large data sets used[9]. A significant correlation between function intensity at a specific moment in time and intensity of a different function at a later point in time strengthens the proposition of correlated functions.

[9] R.A.A. Suurs does agree that statistical analysis could strengthen the results from other means of pattern analysis (personal communication, September 29, 2009)

3.5.2 Motor Identification

If pattern analysis shows that a specific subset of TIS functions is overly present within a timeframe, a motor of innovation can be identified. Table 3.5 displays the mapping of TIS functions to the four motors of innovation as described in the literature study. Identification of motors is done using the aggregated trend pattern analyses for both case studies.

Table 3.5 Mapping Motors of Innnovation

	Function						
Motor	**F1. EntAct**	**F2. KDev**	**F3. KDiff**	**F4. MaCrea**	**F5. GuidSe**	**F6. ResMob**	**F7. SupAdv**
S&T Push		++	+		+	+	
Entrepreneurial	++	++	++		+	++	+
System Building	++	++	++	++	++	++	++
Market	++	++	++			++	

4. U.S. Service Robotics Structural Factors

This chapter contains the analysis of structural factors involved in the U.S. service robotics industry. Section 4.1 discusses the actors involved, Section 4.2 discusses networks and clusters and Section 4.3 institutions.

'We have enough robots in this business.'
Wally Dallenbach

4.1 Actors

The literature study identified three broad categories of actors that are relevant in the robotics field: governmental institutes, universities and companies.

4.1.1 Governmental Institutes

Important governmental actors in the field of service robotics are large federal agencies that guide and fund research. Table 4.1 displays a selection of the most relevant governmental institutes[10].

Table 4.1 Governmental Institutes

	Name	Main relevance for Robotics
DARPA	Defense Advanced Research Projects Agency	Invests in high-risk, high-reward projects for cutting edge technology in the defense sector
NSF	National Science Foundation	Investments in a wide area of basic and applied research
DoD	Department of Defense	Investments focused on technology applications for defense purposes
DHS	Department of Homeland Security	Investments in robotics for Explosive Ordnance Disposal (EOD)
NASA	National Aeronautics and Space Administration	Investments and research into robotic manipulators and autonomous navigation for space applications
NIH	National Institute of Health	Investments and research into minimally invasive surgery (MIS), robotics for rehabilitation and other healthcare applications
NIST	National Institute of Standards and Technology	Research into open architectures for robotics

[10] Personal communication with P. op den Brouw and B. Sattler, TWA Network.

The U.S. investment in robotics R & D are heavily focused on R&D for robotics in the defense sector. DARPA has a large amount, $ 3.3 billion[11], available per year for defense related research, of which a substantial amount goes to robotics. The NSF and related parties have invested an estimated $ 50 million[12] in robotics outside the defense sector up to this point.

DARPA targets its investments to three types of research:
~ 50% '6.1' research: basic research ~ 50% '6.2' research: applied research
Other '6.3' research: towards commercialization

4.1.2 Companies and Universities

Previous TWA research (Rane, 2009) identified 28 major research institutes and 13 companies. A subsequent scan of companies and universities involved in service robotics revealed a large number of small companies (n=47), of which the majority is active in close proximity to the major robotics research institutes, as shown in the geographical mapping in Figure 4.1. Appendix F lists the identified organizations, classified to their field of application and sorted by the state in which their headquarters is located. The list shows relatively large numbers of companies that are active in defense related robotics applications and robots for medical or rehabilitation purposes. This trend can be explained by the high amounts of funding that are available for both types of applications.

Figure 4.1 Geographical mapping of the company and university scan

[11] http://www.aaas.org/spp/rd/09pch5.htm, retrieved on September 16, 2009.

[12] http://www.zygbotics.com/2009/05/26/us-behind-the-curve-on-robotics-research/, retrieved on September 16, 2009.

4.2 NETWORKS

The analysis of actors in the U.S. service robotics industry and the subsequent geographic mapping show that networks of actors center around the main university research facilities. Those networks form around technological tasks or market formation (Bergek et al., 2008), other networks have political influence as their main goal. A breakdown of networks shows formal networks at the federal level, state level and informal networks within states or crossing borders.

On the federal level, the Congressional Caucus for Robotics informs the Members of Congress about key issues for the U.S. robotics industry based on emerging technologies. Besides the Caucus, there are several networks at the federal level that target a specific robotics application. An example is the AUVSI network, Autonomous Unmanned Vehicle Systems International. On the state level, organizations such as the Massachusetts Technology Leadership Council (MassTLC) and the Technology Collaborative (TTC), from the South Western Pennsylvania area, promote research and entrepreneurship for robotics in their corresponding areas. An example of a formal network that is not location based is the technology platform consortium formed around the Joint Architecture for Unmanned Systems (JAUS). Companies, universities and the principal of the consortium, DoD all strive to maximize compatibility of their different unmanned systems innovations, based on a joint software architecture.

On the informal level, a variety of networks exist, such as private-public, industry-university and buyer-seller links. The informal networks and bilateral ties are discussed more in-depth in the case studies, within the TIS function of knowledge diffusion.

4.2.1 Clusters

The robotics industry in the U.S. is divided into a number of geographic clusters. The main clusters have formed around Boston, Pittsburgh and the San Francisco / Los Angeles region. Companies in the clusters appear to interact in networks and align their activities to the focus of the cluster, co-led by the focus of the relevant university departments.

Mapping robotic applications to geographical regions[13] shows that the main differences in the clusters focus on the application of robotics. Figure 4.2 shows the proportion of firms in a cluster that focus on a specific type of application. The scan shows that the Boston

[13] Mapping to geographical areas performed in Google Maps: http://maps.google.com/maps/ms?ie=UTF8&msa=0&msid=106009881871279151266.0004705095f042204a371

cluster has a clear focus on logistics and military robotics applications, compared to the example cluster around San Francisco, with a clear focus is on medical applications.

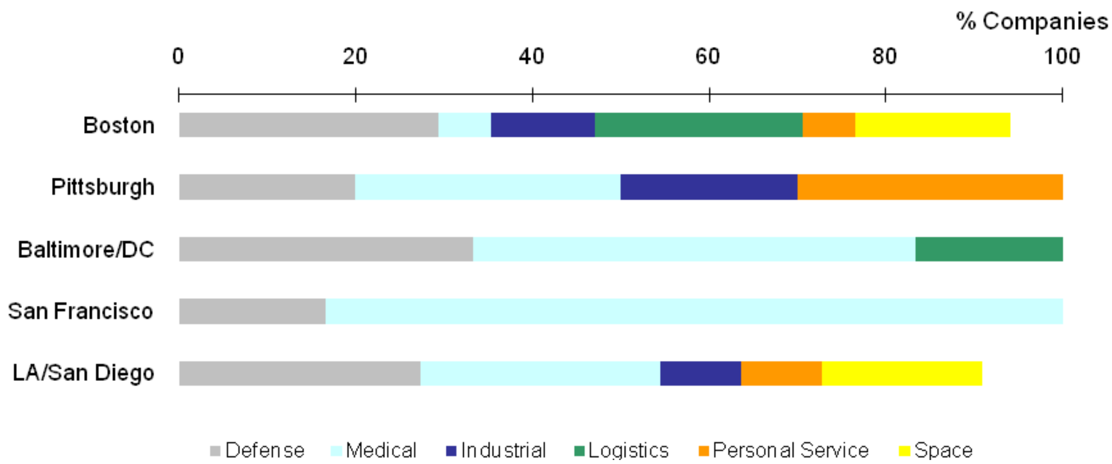

Figure 4.2. Robotics clusters

Major players in the Boston area are companies such as iRobot, Foster-Miller and Barrett Technology, closely located to Harvard University and the Massachusetts Institute of Technology (MIT). This region has a focus on research into robot vision, locomotion and autonomy for mobile robots, which is used in the military, logistical and personal service fields.

Pittsburgh's robotics cluster, also known as Roboburgh or RoboCorridor, includes companies such as General Dynamics, ReSquared and Bossa Nova, and Carnegie Mellon University. The cluster near San Francisco and Los Angeles is known for research in the universities of Berkeley and Stanford and enterprises such as Intuitive Surgical and Hansen Medical. The remaining cluster, Baltimore/Washington DC has a lower density of robotics companies than the previously mentioned regions.

4.3 INSTITUTIONS

Three main categories of formal institutions that are relevant for the service robotics industry exist: Funding & Grants (§ 4.3.1), IP legislation (§ 4.3.2) and FDA approval (§ 4.3.3).

4.3.1 Funding & Grants

Because of the heavy reliance on grants and investments by companies in the robotics industry, the different grant options, tender procedures and small business innovation programs are particularly relevant. An example are Small Business Innovation Research (SBIR) grants from different governmental institutes, that allow companies to conduct research into new technologies. SBIR Phase I investments have proof-of-concepts as the main deliverable. SBIR Phase II investments build upon this proof-of-concept to develop a technology towards commercialization. Small Business Technology Transfer (STTR) grants basically serve a similar goal, but these grants include a collaboration between a university or research facility with the subject company in order to promote technology transfer from research institutes. The different governmental institutes as listed in Table 4.1 all have separate SBIR and STTR budgets and select projects that are eligible for the grants.

4.3.2 IP legislation

Legislation on intellectual property for the protection of patents is strictly followed in the U.S. Therefore also in the service robotics industry, patent infringement lawsuits do occur. An example is the patent infringement case between Computer Motion and Intuitive Surgical regarding infringement of one of Intuitive Surgical's telesurgery patents in 2000.

Intellectual property legislation regarding the relation between universities and industry changed in 1980 with the Bayh-Dole Act. The crucial piece from the Bayh-Dole Act regards giving U.S. universities, small businesses and non-profits IP control over their innovations. No longer was government funded research automatically property of the government, but universities, small business and non-profits could elect to retain ownership under some restrictions. The main restriction was to grant the government a non-exclusive, non-transferable license to use the invention. The Bayh-Dole Act changed the way the government and universities commercialized patents and lead to more commercial licensing of intellectual property. On the other hand, companies are more eager to obtain government funding, because they have the choice to retain intellectual property rights.

4.3.3 FDA Approval

A relevant institution for healthcare robotics and a portion of personal service robotics is FDA (Food and Drug Administration) approval, e.g. robotic surgery equipment always need to be approved according to FDA regulations.

Informal institutions are complex to define industry-wide. One example of an informal institution that is clearly present is a culture of tender writing at companies, where the competency of writing a good tender is regarded as of equal importance to performing the actual research.

4.4 Conclusion

The discussion of structural factors draws the relatively static background on which the rapid changes within TIS functions occur, answering sub question 1. The overview of actors, networks and institutions allowed for the identification of five service robotics clusters, highlighting the importance of geographical location and reassuring the need to perform more in-depth research into the clusters by means of the interviews within the different case studies. The overview of structural factors identifies several possible candidate organizations for interviews based on their importance for the industry. Examples are DARPA, one of the main funders of the industry, a federal network organization such as AUVSI, a state level network organization like TTC and both companies that operate within clusters and outside clusters.

Chapter 5 continues with the results from the first case study.

5. DEXTEROUS ROBOTIC MANIPULATORS

'Any sufficiently advanced technology is indistinguishable from magic.'
- Arthur C. Clarke

5.1 INTRODUCTION

The first case study analyses the technological innovation system for the enabling technology of dexterous robotic manipulators. The ideal dexterous robotic manipulator masters two key aspects of manual dexterity: manipulative dexterity and grasp robustness. Manipulative dexterity refers to the ability of the robotic manipulator, most of the times a robotic hand or grasping device, to reach and relocate physical objects to any target location. A high level of grasp robustness requires the robotic manipulator to keep a firm hold of the object without applying disproportional force, while adapting to changes such as unexpected forces.

Examples of dexterous robotic manipulator applications are surgical robots, robots used for explosive ordnance disposal (EOD), space robotics and robotic arms and hands used for rehabilitation purposes. In the future, more and more robots will operate in human-centric environments, increasing the demand for dexterity. Human-centric environments are by nature unstructured, necessitating the need for a robot to have the capability of grasping and manipulating objects with unknown or irregular surfaces. Another aspect of human-centric environments is obviously direct physical contact with humans, requiring precision and control of robot movements and improved sensing capabilities to ensure safety.

Section 5.2 continues with the TIS function analysis that encompasses the event history analysis and the subsequent formulation of the historical narrative.

5.2 Function Analysis

5.2.1 Event History Analysis

The event history analysis lead to a total set of 237 events that mark the development of dexterous manipulation technology over time, starting in 1982. The events in the database are all mapped to the TIS functions (based on Table 3.2). Table 5.1 displays the number of events classified per TIS function.

Table 5.1 TIS Function instances

Function	Event Type	Number
F1. Entrepreneurial Activity	Company Start/Spin-off	20
	Portfolio Expansion	16
	Company Closure	0
	Total	**36**
F2. Knowledge Development	Research result	4
	Scientific Publication	28
	Patent	20
	Total	**52**
F3. Knowledge Diffusion	R&D Alliance	32
	Licensing	5
	Joint Venture	3
	Manufacturing	3
	Patent infringement	2
	Total	**45**
F4. Guidance of the Search	Expression expectation	2
	Government guidance	4
	Total	**6**
F5. Market Formation	Positive discrimination	0
	Clearance	2
	Total	**2**
F6. Resource Mobilization	Government Investment	89
	Private Investment	7
	Total	**96**
F7. Support Advocacy	Lobbying	0

The event database for dexterous manipulation is validated and extended with information from the interviews (Appendix G). The event database and the insights from the interviews form the basis for the formulation of the historical narrative, that identifies general trends in the development of dexterous manipulation, supported by specific events.

5.2.2 Historical Narrative

Research into dexterous robotic manipulators in the U.S. started in the early 1980s at NASA JPL [F2, F4, F6], but both academic and industry interest was limited those years. Salisbury (1985)[F2] was the first to acknowledge that in order to reach manual dexterity with a robotic hand with rigid, non-sliding and non-rolling contacts, at least nine degrees of freedom (DOF) are necessary.

In the same period, NSF awarded its first grant related to dexterous robotic hands to CMU [F6]. Collaborative research started in the space industry, e.g. the Utah/MIT Hand with NASA, and broadened from 1989 onwards to surgery applications, e.g. Computer Motion and military applications, e.g. US Army - Bonneville Scientific collaboration [F3, F6]. The 1991-1994 period shows a remarkable absence of activities. A notable development is the commercialization of MIT's Whole Arm Manipulator by Barrett Technologies.

1995 marks the start of a second active period with several SBIR grants [F6] awarded to startups and published research and patents from UMass and CalTech universities [F2].

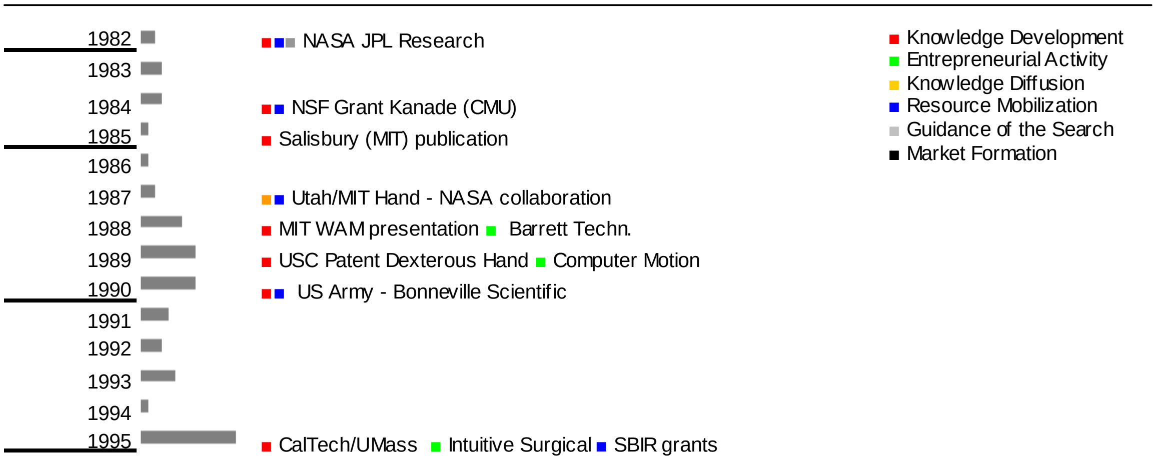

Figure 1. Timeline 1982 - 1995 Key Events

The Department of Defense (DoD)[F6] started investing in research into haptic teleoperation of robotic manipulators in 1996, by means of its SBIR and STTR programs. Research until then mainly focused on manipulation in controlled environments. This changed in 1997, when John Hopkins University started research into manipulation in uncontrolled environments under a NSF grant [F2, F3, F6].

The period 1999-2002 shows another dip in the quantity of events, although several companies spun off from universities in this period, such as re2, a spin-off from CMU [F1]. From 2003 onwards, investments into dexterous manipulators have increased, especially from large investments by the US Army, US Navy and the general NSF grants [F6].

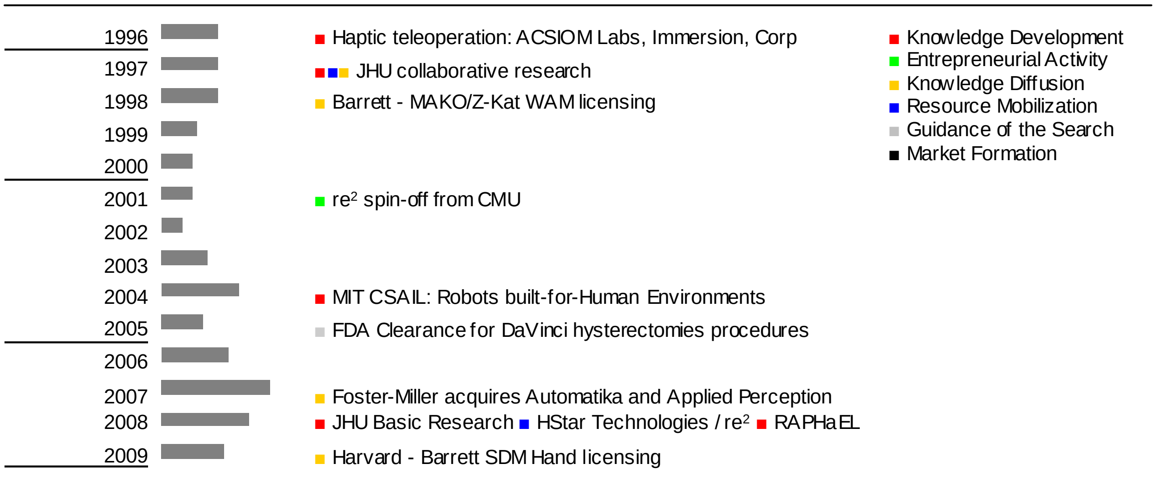

Figure 2. Timeline 1995 - 2009 Key Events

This decennium also shows an increase into the research on robotic manipulation in human-centric environments, e.g. an MIT CSAIL (Rodney Brooks et al., 2004) article on sensing and manipulation in built-for-human environments [F2].
The dynamic and unstructured nature of human-centric environments remains a challenge for robotic manipulators. Research in this area focuses mainly on medical applications, such as the Robotic Nursing Assistant from HStar Techn. and re2 [F1, F2].

Electric motors are the current dominant design to drive actuators for dexterous robotic hands. Research into alternatives is progressing, e.g. Virginia Tech's RAPHaEL[14], a hand based on pneumatic actuation [F2]. Research into even newer ways of actuation such polymeric gels or shape memory alloys (SMA) is still in the early stages.
In an effort to simplify the design of dexterous robot hands without sacrificing its use in unstructured environment, Harvard University developed the Shape Deposition Manufacturing (SDM) hand[15]. The SDM hand deploys 4 fingers, embedded sensors and only a single actuator for compliant grasps. Barrett Technology acknowledged the potential of the SDM hand by obtaining its license in 2009 [F3].
Multidisciplinary research into robot manipulation is expected to continue with a focus on compliant robot operation in unstructured and human-centric environment.

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[14] http://www.me.vt.edu/romela/RoMeLa/RoMeLa.html, retrieved on October 3, 2009.

[15] http://biorobotics.harvard.edu/research/SDM.html, retrieved on October 3, 2009.

Within the event history four periods, or episodes, of differing function intensity can be identified. '82-'87 with relatively little activity. '88–'94 starts with an increasing overall function intensity and broader applications of the dexterous manipulation technology, e.g. towards robotic surgery. '95–'02 shows increased activity, especially for resource mobilization. The final episode, from 2003 onwards includes the largest number of events, marking the overall development made. The historical narrative describes broad trends, trend pattern analysis reveals more precise trends per function.

5.2.3 Trend Pattern Analysis

This section discusses both the qualitative and the quantitative trend pattern analysis for the most occurring TIS functions [F1, F2, F3, F6] and a short discussion of the other functions. Quotes from the interviews illustrate specific function developments.

Entrepreneurial Activity [F1]

The event history analysis shows 36 major events within the function of Entrepreneurial Activity. These events often relate to the start of a company, either independently or in the form of a university spin-off (from MIT and Carnegie Mellon University). Interviews with company representatives showed that only a limited percentage of companies is funded with venture capital (VC), which is confirmed by a recent survey of the Massachusetts cluster, revealing only 20% of the respondents was funded by VC[16]. The remaining part uses mainly government grants to fund the initial projects. A trend that several companies acknowledge is their portfolio expansion from pure defense related projects towards development of dexterous robotic manipulators for healthcare purposes.

> "Our company first started in robotics with developing manipulators under DoD grants"… "After a couple of years, we figured that such manipulators could also be used for other applications, such as EOD in the short term or for elderly care in the future."

The department of Veterans Affairs (VA) has had a pivotal role in this transition, funding research into manipulators for battlefield recovery and prosthetics.

Knowledge Development [F2]

The event history analysis shows 52 events categorized as knowledge development. This allows for a trend pattern analysis as shown in figure 5.3. The trend plot shows distinct peaks in 1993, 1995 and 2004. The three peak years show an increase in patents, publications and articles on dexterous manipulators. 2004 marks an important year for

[16] Achieving Global Leadership: A roadmap for robotics in Massachusetts. Mass Technology Leadership Council, Inc., February 2009

robotic surgery, with patents on manipulators for robotic surgery accounting for a large part of the increase in intensity. This was followed by the important FDA clearance of the DaVinci for hysterectomies procedures in 2005, creating the market for this type of robotic surgeries [F5].

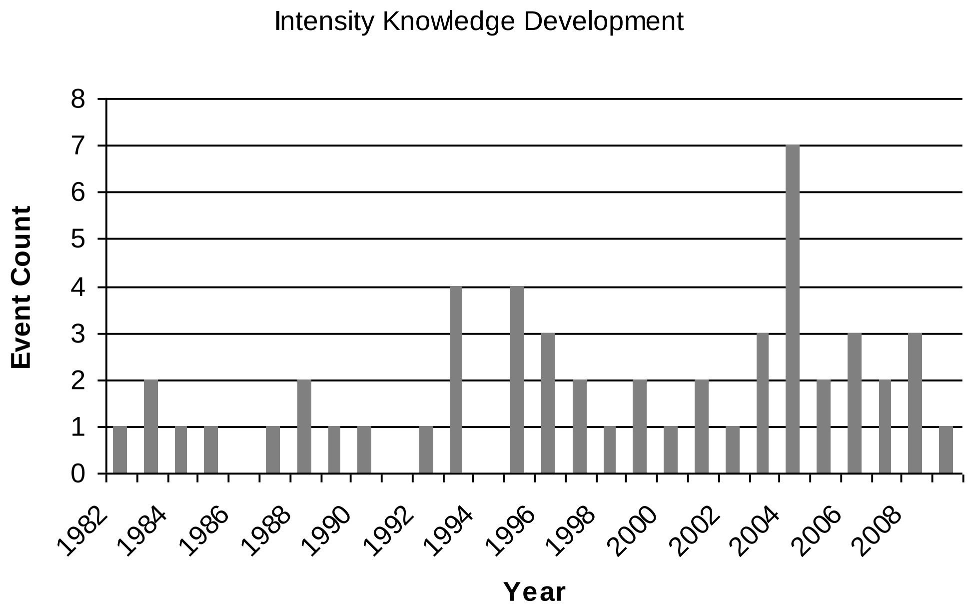

Figure 5.3. Trend pattern Knowledge Development

Service robotics companies do collaborate actively with partners in the ecosystem, but there is still a strong focus on internal R&D. Several reasons for this internal focus have come forward from the interviews. First of all, dexterous manipulation technology is not yet a mature technology, leading to specialized in-depth research by small groups of researchers in company labs and universities. The academic roots of most of the entrepreneurs causes a continued focus on specialized R&D. Secondly, there is a set of companies that work in the military field, operating within confidentiality bounds. This can lead to a protectionist culture, focusing on the protection of the company's intellectual property.

Knowledge Diffusion [F3]

Besides internal R&D, university labs are the main source for new knowledge. Companies use their academic roots to stay in contact with university labs. These relations serve multiple goals. Active scanning of research allows companies to stay on the cutting edge of technology development, access to knowledge spillovers and increases the visibility of the company. Increased visibility has a positive effect on passive scanning, where researchers contact companies directly if there are technology developments that can more effectively be pursued in a corporate setting. Companies mention improved access to graduate students as another benefit from university-industry relations. The improved access to the labor market is valued by companies as the main advantage of operating in a cluster. The second valued advantage from operating in a cluster is improved access to public goods. For the dexterous manipulation industry, improved access to public goods means possibilities for collaborative grant writing for SBIR and STTR grants, either with other SMEs or with universities.

Figure 5.4 displays knowledge diffusion intensity and the different instruments involved in knowledge diffusion. The graph shows that R&D alliances account for the largest part of knowledge diffusions. From 2003 onwards, a small increase in manufacturing, licensing and acquisition forms of knowledge diffusion shows that the technology is increasingly ripe for exploitation.

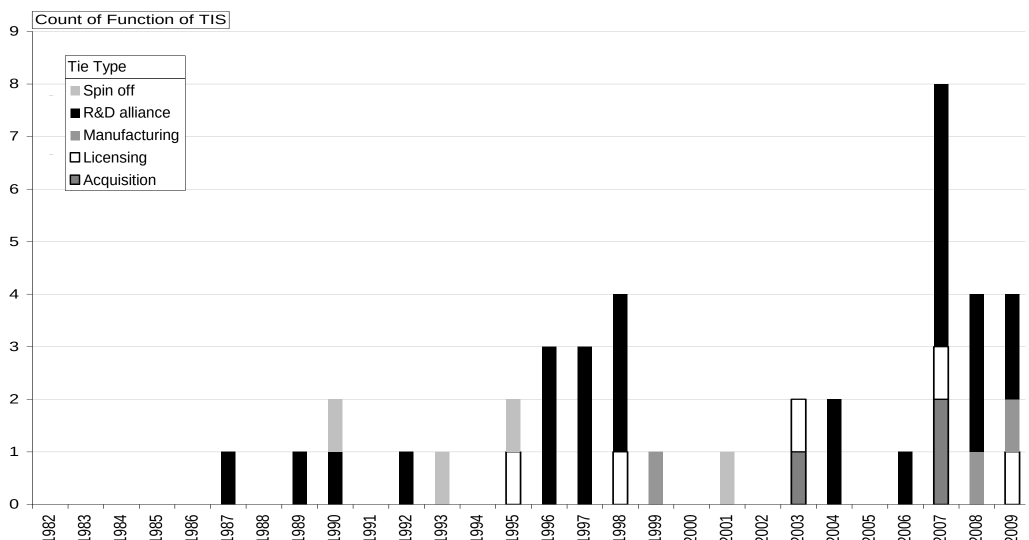

Figure 5.4. Trend pattern Knowledge Diffusion

There is a clear difference between companies and universities in the strategy the organizations deploy for knowledge diffusion. The interviewed companies use ad hoc strategies and agreements for the use of knowledge diffusion vehicles such as collaborative R&D and joint ventures (Table 2.2 for the complete list).

> "We use any of the mentioned vehicles for knowledge exchange.. We decide which vehicle to use depending on the characteristics of the possibility… There is no formalized strategy in place for this."

Several universities on the other hand deploy a formalized strategy including a range of partnership vehicles and related procedures. Examples range from memoranda of understanding (MOUs) with other universities to strict procedures for the licensing of intellectual property.
The event history analysis includes two instances of negative knowledge diffusion, both related to patent infringement in the robotic surgery application field. Especially the first case of patent infringement, Computer Motion versus Intuitive Surgical, was a major setback for the industry, slowing down research at both companies. The issue was resolved three years later by the merge of both companies, with the resulting company operating using the Intuitive Surgical brand name.

An analysis of the linkages between partners in knowledge diffusions exemplifies the importance of clusters in collaborations. Table 5.2 gives a breakdown of knowledge diffusion based on the geographical location of the parties involved. The five clusters as formulated in section 4.1 function as the cluster boundaries for this analysis.

Table 5.2 Cluster linkages

Geographical linkage of ties	Number
Within clusters	14
Between clusters	5
Cluster to other (within U.S.)	8
Cluster to other (international)	3
Subtotal cluster party involved	30
Other (both parties outside a cluster)	14
Total	44

A third of all activity takes place between partners that operate in the same cluster. Another third includes at least one party based in one of the clusters. This adds up to a total of two thirds of total activity involving a party based in one of the clusters.

Resource Mobilization [F6]

The data on resource mobilization shows a large number of government initiated investments. Half of the events shown in figure 5.5 stem from the different governmental SBIR and STTR programs for SME. The graph shows a stable growth in number of investments over the last few years (data in 2009 until October).

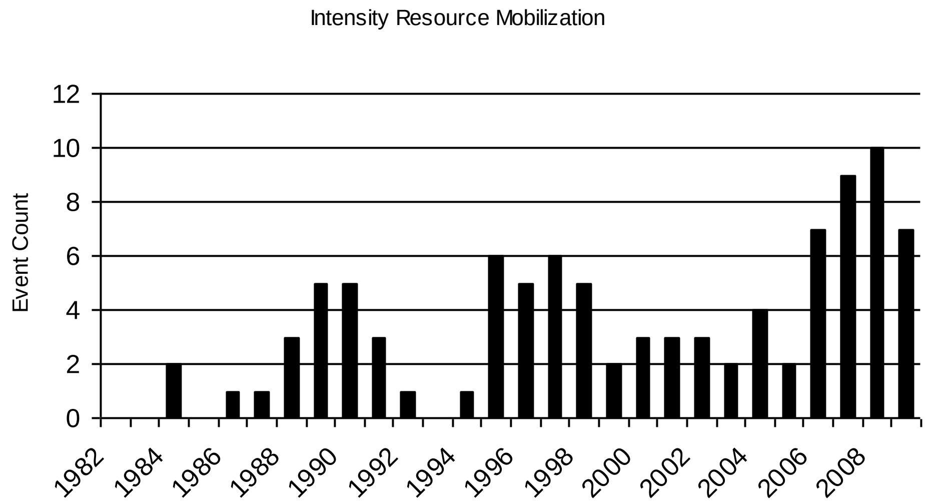

Figure 5.5. Trend pattern Resource Mobilization

Other TIS Functions [F4, F5, F7]

Guidance of the Search [F4] and Market Formation [F5] are underrepresented in the event history analysis because of the qualitative nature of the functions. Bergek et al. (2008) state that the functions can best be assessed in a qualitative form, discussing visions, beliefs in growth potential, the extent of government policy, etc. The case of dexterous manipulation shows that the events categorized as guidance of the search and market formation could also be fit with other functions, such as Support from advocacy coalitions (in the case of visionary roadmaps), Resource Mobilization (government policies and associated investments, tax policies).

The final function, support from advocacy coalitions, is not present in the event history analysis because the existing advocacy coalitions do not focus on specific enabling technologies, but represent different service robotic application fields or even (service) robotics as a whole. Examples are the different advocacy coalitions representing geographical areas such as the Massachusetts Technology Leadership Council (MassTLC) and the The Technology Collaborative (TTC, Pittsburgh). The interviewees emphasize on the increasingly important role of such organizations, linking cluster members by means of conferences, seminars and investment possibilities.

5.3 MOTORS OF INNOVATION

Causality between different TIS functions can be identified on a one-by-one anecdotal basis, e.g. linking a publication [F2] to subsequent licensing of the researched technology [F3]. This research strives to identify more generalizable patterns between TIS functions by means of interaction pattern analysis and motor identification.

5.3.1 Interaction Pattern Analysis

The interaction between the functions Knowledge Development and Resource Mobilization is particularly interesting, because this sheds light on how success in the form of knowledge development influences investments and how resource mobilization in turn leads to more knowledge development, an example of cumulative causation (Suurs, 2009).

Figure 5.6 shows the trend analysis for both knowledge development and resource mobilization. Based on the trend patterns, interaction occurs between peaks in knowledge development and resource mobilization several years later.

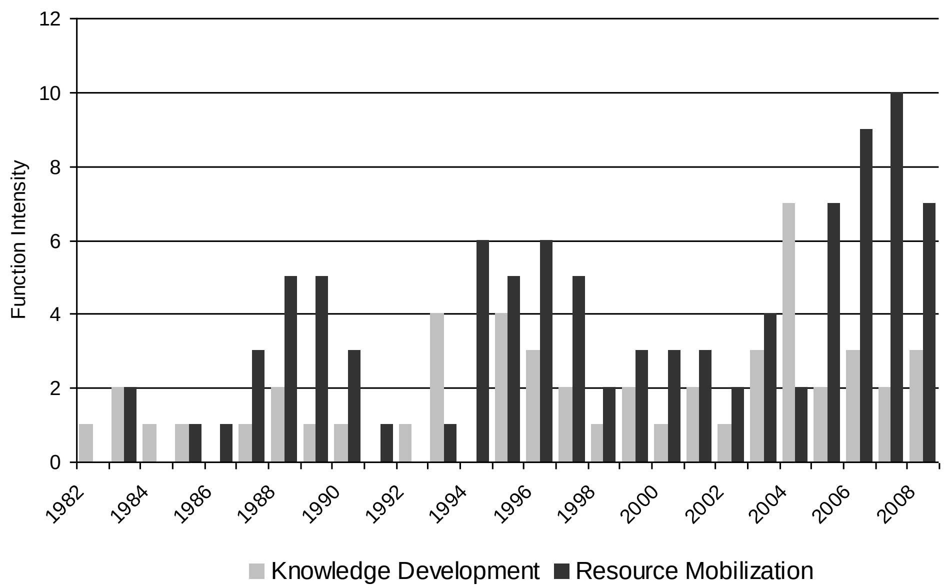

Figure 5.6. Interaction pattern analysis Knowledge Development & Resource Mobilization

An example can be basic research at universities that arouses the interest of investors (government or business). The interest is not instantly converted to investments, but this process takes some time. Figure 5.7 displays the cross correlation diagram for the comparison of both series, varying for different time lags (in years), showing a peak in correlation between knowledge development in year x and resource mobilization in year x+3.

On the basis of cross-correlation analysis of the data, there is a significant correlation (ϱ = .556, $p < 0.05$) between knowledge development and resource mobilization 3 years later[17]. Interviews with university representatives confirmed the analysis that there might be a significant time lag between knowledge development publications and new investments. Several interviewees however point out that the obvious causal link between resource mobilization for research and subsequent knowledge development is of equal importance. The data however does not show a specific time lag for this functional interaction. A possible explanation for this effect might be the differing research periods across research projects.

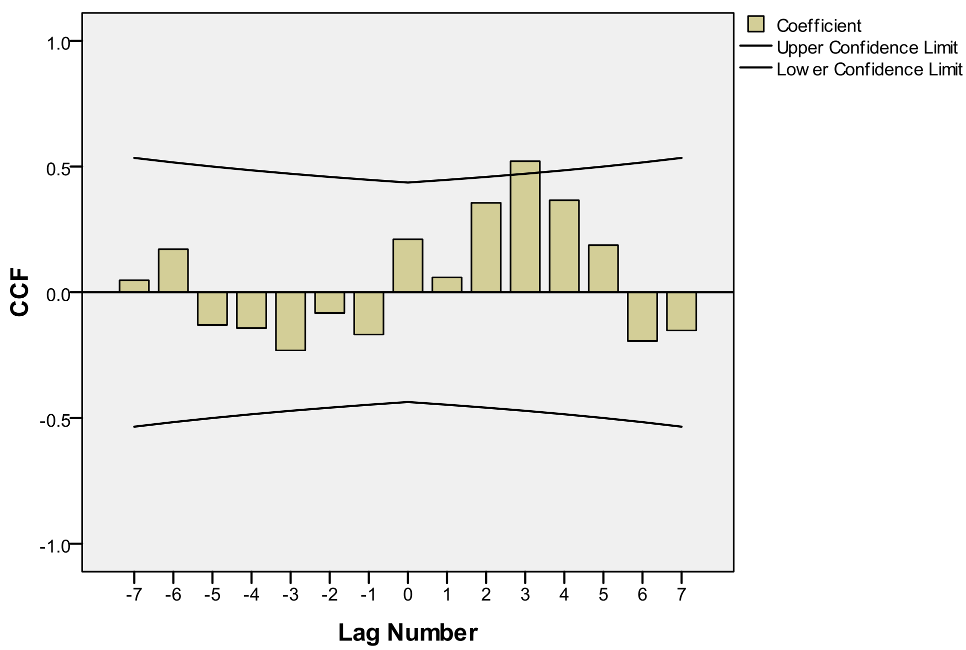

Figure 5.7. Cross Correlation analysis Knowledge Development & delayed Resource Mobilization (SPSS diagram)

[17] Correlation analysis does not prove causality, but provides more insight into the intensity and delay of the correlation that occurs, supporting the results from the qualitative study.

5.3.2 Motor Identification

The historical narrative identified four episodes of differing function intensity. Figure 5.8[18] shows the overall function intensity for the different episodes, marked as episodes A-D.

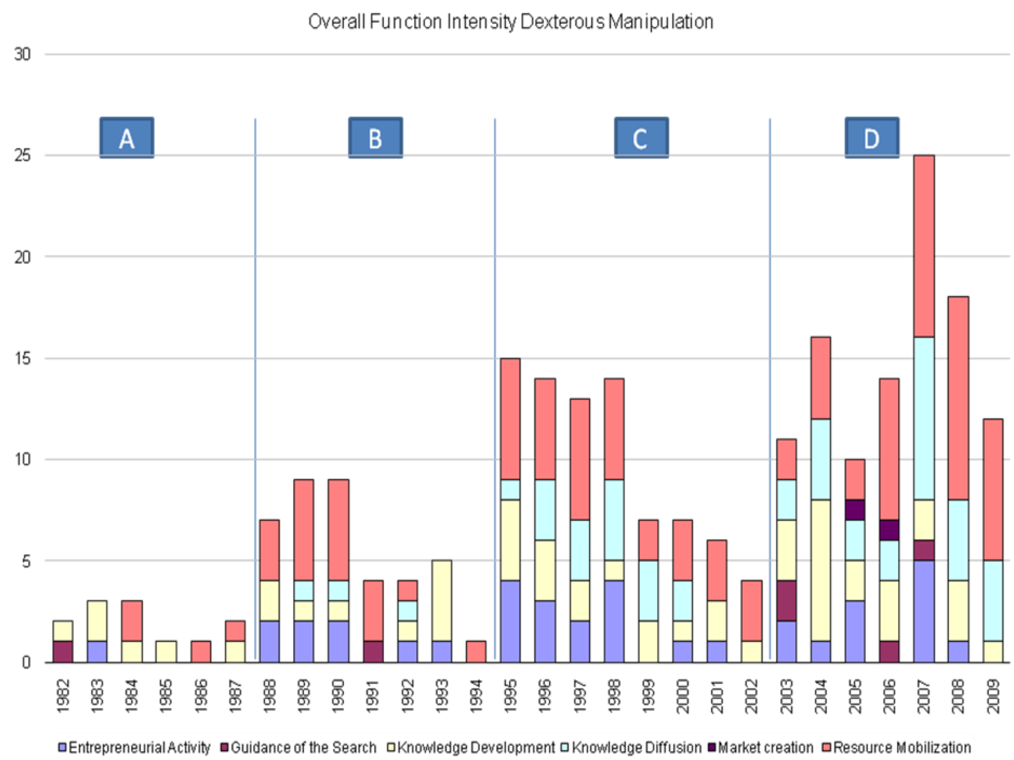

Figure 5.8 Motors of Innovation

Mapping of the event intensities to the different motors of innovation from literature results in the following identified motors of innovation.

[18] Intensities of different functions in figure 5.8 can not be directly compared with each other within years, since TIS function intensities are based on different mapped events. Function intensities can be compared within functions between years.

A. 1982 – 1987 *No motor present*

The earliest episode shows very limited function intensity

B. 1988 – 1994 *Science & Technology (S&T) Push motor*

This episode shows an increase of resource mobilization. Precise analysis of the types of resource mobilization reveals that the majority are NSF grants, aimed towards the stimulation of basic research at universities, indicating a move towards a S&T Push motor. The increased resources are not directly transformed in measurable knowledge development events however. Knowledge diffusion is still very limited in this period.

C. 1995 – 2002 *Entrepreneurial motor*

The start of the third episode shows an increase in entrepreneurial activity, with several start-ups, spin offs and technology transfer deals from universities to companies. In this period, the TIS shifts from university-centered innovation towards more and more innovative activity stemming from companies. Resource mobilization in this period also increases and further supports the trend towards industry innovation by showing large numbers of SBIR grants involving small companies and increasing numbers of VC fundings.

D. 2003 – 2009 *Market motor*

The final episode up to now shows the largest intensity of events. The first instances of the market creation function suggest a further development towards commercialization and a more mature TIS. This notion is supported by a change in the tie types for the function knowledge diffusion. From 2003 onwards, knowledge shifts from mainly R&D alliances towards more and more collaborations focused on commercialization, such as licensing and manufacturing agreements and the acquisition of other companies.

6. AUTONOMOUS NAVIGATION

"If every tool, when ordered, or even of its own accord, could do the work that befits it … then there would be no need either of apprentices for the master workers or of slaves for the lords."

- Aristotle, 322 BC

6.1 INTRODUCTION

The first case study described dexterous technology to manipulate objects within reach of the robotic manipulator. A second important robot capability is the mobility to transfer to another location in order to extend the operational range. Mobile robots up to this moment are often teleoperated, e.g. the military Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles (UAVs). There is however a vast amount of research and development being done in the field of autonomous navigation.

Autonomous navigation is an enabling technology or capability that can be broken down in to a combination of sensing, perception, localization, mapping and planning technologies, as shown in figure 6.1. Actuators for locomotion are outside the scope of this case study, since locomotion can be regarded as rather independent from the other aspects, using the direct task related output from the other technologies.

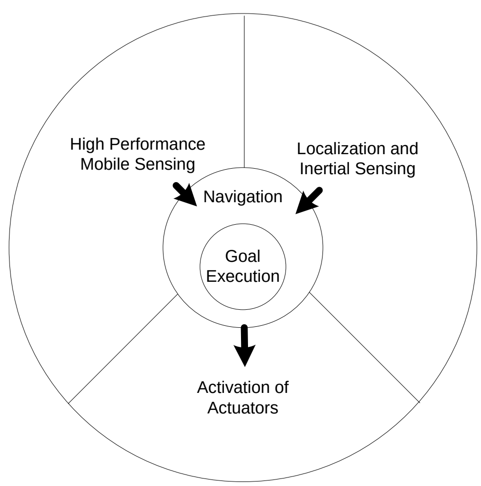

Figure 6.1 Diagram Autonomous Navigation

Section 6.2 continues with the TIS function analysis that encompasses the event history analysis and the subsequent formulation of the historical narrative.

6.2 Function Analysis

6.2.1 Event History Analysis

The event history analysis lead to a total set of 209 events that mark the development of autonomous navigation technology over time, starting in 1986. The events in the database are all mapped to the TIS functions (based on table 3.2). Table 5.1 displays the number of events classified per TIS function.

Table 5.1 TIS Function instances

Function	Event Type	Number
F1. Entrepreneurial Activity	Company Start/Spin-off	6
	Portfolio Expansion	7
	Company Closure	0
	Total	**13**
F2. Knowledge Development	Research result	13
	Scientific Publication	19
	Patent	22
	Total	**54**
F3. Knowledge Diffusion	R&D Alliance	28
	Licensing	1
	Joint Venture	1
	Manufacturing	3
	Patent infringement	0
	Total	**33**
F4. Guidance of the Search	Expression expectation	10
	Government guidance	14
	Total	**24**
F5. Market Formation	Positive discrimination	0
	Clearance	0
	Total	**0**
F6. Resource Mobilization	Government Investment	68
	Private Investment	5
	Total	**73**
F7. Support Advocacy	Lobbying	4

The event database for dexterous manipulation is validated and extended with information from the interviews (Appendix G). The event database and the insights from the interviews form the basis for the formulation of the historical narrative, that identifies general trends in the development of autonomous navigation, supported by specific events.

6.2.2 Historical Narrative

Research into the different aspects of autonomous navigation started halfway during the 20th century. The first integrated efforts however did not emerge before the mid-80s, with research at CMU [F2] and at DARPA [F2, F6]. DARPA's Autonomous Land Vehicle (ALV) was equipped with several sensors and traveled between two designated waypoints in the hills around Denver in 1986. The grey bars in figure 6.2 show the overall system activity (number of events) for the period 1986-2000. It shows limited activity during the late 80s, where most of the events are related to basic research into sensors for autonomous navigation [F2]. 1990 marks the start of iRobot [F1], a spin off from MIT's Artifical Intelligence Lab (AIL). The company's first projects were all related to defense applications, as was the case for most projects until 1993. In 1993, CMU developed a working prototype for autonomous harvesting, Demeter [F2], which was one of the first integrated prototypes developed for application outside the defense scope.

In 1994, sensor technology progressed with advances in LIDAR (Light Detection and Ranging) that uses characteristics of scattered light to determine the range of objects [F2].

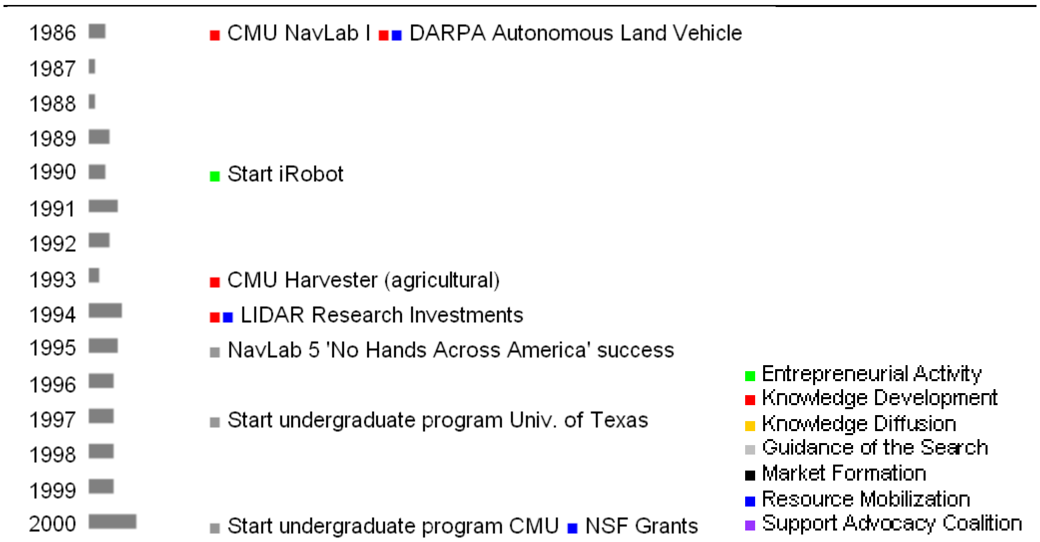

Figure 6.2 Timeline 1986 – 2000 Key Events

A notable application of this technology was in CMU's NavLab 5 [F2], which traveled almost autonomously (>98% of the time) for 3000 miles during the "No Hands across

America" project in 1995. The project received widespread media coverage, increasing the general interest for autonomous navigation capabilities [F4].

The 1997-1999 period shows a low intensity of events, with notable exceptions in basic research funded by NSF grants [F2, F6] and the start of two different undergraduate programs at CMU and the University of Texas, the former focusing on robot perception, the latter on mobile robots.

As figure 6.2 and 6.3 display, overall TIS function intensity gradually increased from 2000 onwards. In 2001, the US Army initiated the Robotics Collaborative Technology Alliance (CTA) [F2, F3], a consortium of robotic companies that conduct collaborative research into unmanned systems, of which a large portion is target on autonomous ground vehicles. The consortium serves a second goal besides research by serving as an advocacy coalition for military robotic systems [F7]. A year later, iRobot launched its first personal service robot, the robotic Roomba vacuum cleaner [F1]. The Roomba turned out to be a very successful product, cleaning millions of rooms. The simple control algorithms allowed for spiral cleaning, wall following and random angle changing after bumping into an object. Despite its very limited autonomous capabilities, the Roomba is a large commercial success [F1, F6]. In the same year, Applied Perception, Inc. received a grant for the development of an autonomous vehicle for battlefield extraction of wounded soldiers [F6].

2003 lists events that show progress in LIDAR development, or LADAR (Laser Detection and Ranging), the acronym used in military contexts.

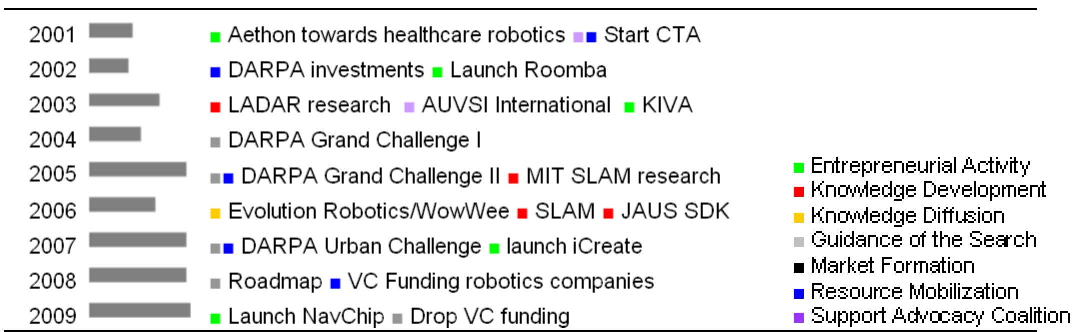

Figure 6.3 Timeline 2001 – 2009 Key Events

DARPA's vision [F5] of creating autonomous land vehicles in the near future lead to the creation of three subsequent competitions for autonomous vehicles, the two DARPA Grand Challenges in 2004-2005 and the DARPA Urban Challenge in 2007 [F5, F6]. None of the participants of the first Grand Challenge completed the route in the Mojave Desert, leading to criticism and skepticism about the possibilities of near-term applications of autonomous navigation technology [negative F5]. The two later competitions prove to be successes however, with victories by Stanford University in 2005 and CMU in the 2007 Urban Challenge. The Urban Challenge changed the scenery from a desert environment to an urban setting, where the vehicles were subject to more intense interaction with other vehicles and had to obey traffic regulations.

Navigation in unknown environments such as the urban setting in the DARPA Urban Challenge requires a simultaneous localization and mapping (SLAM) algorithm for sensor data fusion. The SLAM problem is known as a chicken-and-egg problem. The robot relies on a map for localization and to update a map, it requires the new position of the robot. Research into SLAM at MIT was funded by NSF in 2005 [F6] and tested by the University of Southern California (LA) in an automotive setting in 2006 [F2]. 2006 also shows the expected applicability of autonomous navigation technology for entertainment robots, in the form of an international R&D alliance between Evolution Robotics (based in LA, USA) and WowWee Robotics (Hong Kong, China), producer of entertainment humanoids.

After years of independent defense related projects on autonomous navigation, DoD and DHS initiate projects to ensure compatibility between different autonomous navigation platforms and technologies from 2006 onwards[F4]. Examples of these projects are the development of a Joint Architecture for Unmanned Systems (JAUS), its complementary Software Development Kit (JAUS SDK) and the development of a Roadmap for Autonomous Vehicle Testing by GeorgiaTech.

Commercialization of autonomous navigation technology continues in 2007 with the launch of iRobot's new platform iCreate. iCreate allows the user to develop its own code and algorithms for navigation of a Roomba [F1].

The historical narrative shows slowly increasing TIS function intensity. Based on the event history analysis and the historical narrative, 2 main episodes can be identified. The first episode until 1999 shows little innovative activity. The activity that does take place is limited instances of basic research at universities and large research labs. From 2000 onwards, the second episode brings more activity, with increases in several TIS functions. The historical narrative describes global trends, trend pattern analysis reveals more precise trends per function.

6.2.3 Trend Pattern Analysis

This section discusses both the qualitative and the quantitative analysis for the most occurring TIS functions [F1, F2, F3, F6] and a short discussion of the other functions. Quotes from the interviews illustrate specific function developments.

Entrepreneurial Activity [F1]

All events related to entrepreneurial activity from 1986-2000 focus on military robotic applications of autonomous navigation technology. From 2000 onwards, companies find new applications of their technology. First in EOD purposes for DHS, still closely related to the previous DoD application. The strategic change by Aethon in 2001 towards the use of autonomous robotics in healthcare technology marks a shift away from traditional DoD and DHS applications. Aethon, formerly developing robots for research purposes, started developing healthcare robotics and more specifically autonomous robotic distribution of patient charts, medication, etc. throughout hospitals. The shift to different applications is supported by the launch of iRobot's Roomba in 2002 and the start of Kiva Systems in 2003, providing autonomous solutions for the semi-structured environment of warehouses.

The identified number of events mapped as entrepreneurial activity is insufficient to perform trend pattern analysis on. This is to large extend caused by the limited information companies that develop for military organizations publish about research projects, caused by confidentiality issues. According to the interviewees, the large portion of classified research also leads to limited possibilities for international projects.

Knowledge Development [F2]

The knowledge development functions behaves relatively stable over time, as figure 6.4 shows. The event history database shows that CMU plays an important role in autonomous navigation research, especially in the period until 2006. This resulted in being the best performing team in DARPA's first Grand Challenge in 2004 and lead to several start-ups in the Pittsburgh area, e.g. ReSquared.

The event history analysis shows an equal distribution of types of knowledge development. Patents, publications and research results all have similar intensities over time and therefore do not shed light on a possible trend towards commercialization. The event database however does show that research increasingly strives to integrate the different aspects of autonomous navigation.

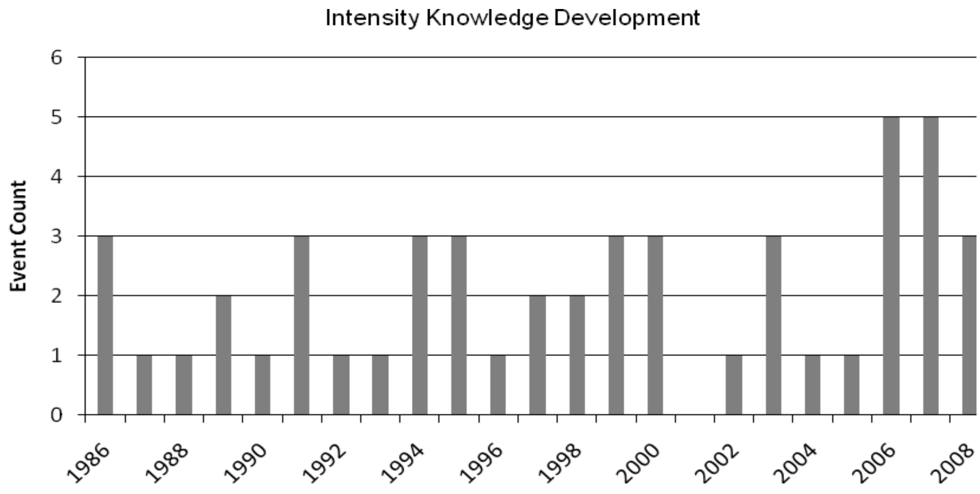

Figure 6.4. Trend pattern Knowledge Development

Knowledge Diffusion [F3]

Knowledge Diffusion is practically absent in the first ten years of TIS development for autonomous navigation, as shown in figure 6.5. The main reason for this lack of collaboration is confidentiality, due to military projects. Although often several companies participate in DoD projects, communication and knowledge transfer usually occurs through the central hub, the military department. The interviews however reveal that several occurrences of knowledge diffusion slip under the radar of this research, because the collaborations are informal and ill documented.

> "The industry for autonomous navigation is very small. Our company makes use of a lot of informal contact. Everybody knows everybody, and a lot of times collaboration takes place in very informal ways.'

Interviewees point out that Open Innovation practices have occurred throughout the history of this case study, based on the informal and strong contacts between parties in the service robotics industry.

The last few years show an increase of activity, mainly in R&D alliances, but also in some manufacturing agreements. International opportunities for collaborations are sparse, again caused by confidentiality aspects. The interviews however make clear that it is possible for international parties to participate in DHS/DoD projects as sub contractors to the main U.S. based contractor.

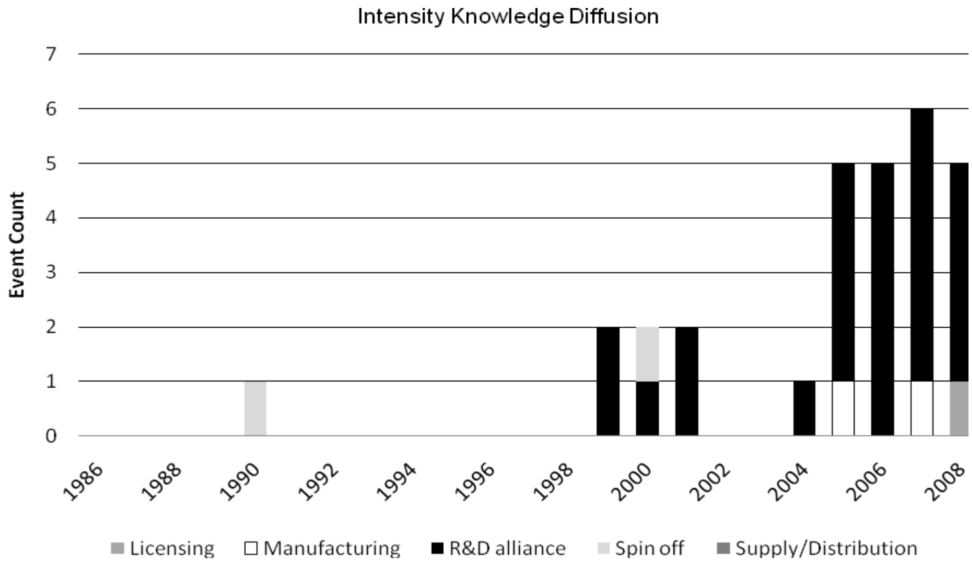

Figure 6.5. Trend pattern Knowledge Diffusion

An analysis of the linkages between partners in knowledge diffusions exemplifies the importance of clusters in collaborations. Table 6.2 gives a breakdown of knowledge diffusion based on the geographical location of the parties involved.

Table 6.2 Cluster linkages

Geographical linkage of ties	Number
Within clusters	5
Between clusters	5
Cluster to other (within U.S.)	11
Cluster to other (international)	4
Subtotal cluster party involved	25
Other (both parties outside a cluster)	8
Total	33

One third of all knowledge diffusions include parties that are both members of one of the identified clusters. 75% of all knowledge diffusions include at least one organization that is part of a cluster, pointing out the importance of clusters in knowledge diffusion.

Resource Mobilization [F6]

The trend pattern of the function resource mobilization shows a sharp upward starting in 2002. Both before the increase in intensity and afterwards, SBIR grants make up the majority of events. Based on the interviews, the increase could be caused by the wars in Iraq and Afghanistan, leading to more R&D funding, especially in the field of EOD of Improvised Electronic Devices (IED), a task that is performed by teleoperated robotic platforms and manipulators.

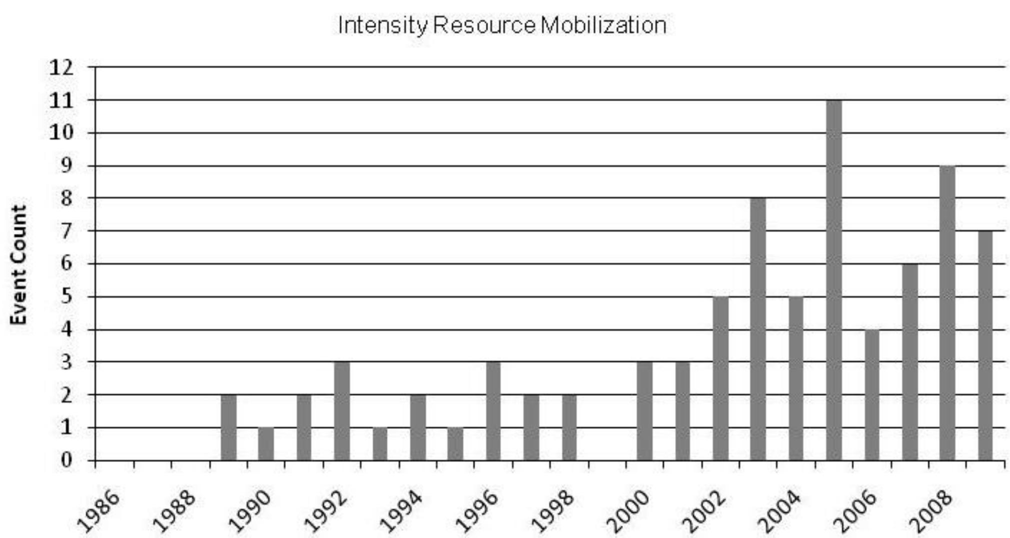

Figure 6.6. Trend pattern Resource Mobilization

Another reason for the increased availability of resources are the DARPA challenges that started in 2004. The challenges mobilized resources in both a direct and indirect way. Direct increases in resources came from sponsoring and prize money for participants of the challenges. The indirect increase in resources was caused by the significant publicity that the challenges created.

Up to 2008, government related institutes were largely responsible for funding. In 2008 however, venture capitalists provided VC funding to the companies Aethon, Evolution Robotics and KIVA Systems. The intensity of VC investments drastically decreased in 2009, according to the CEO of MobileRobotics caused to a large extent by the financial crisis. The decrease in funding especially hit the segment of professional and personal service robotics, whereas funding for defense related projects remained at a relatively constant level.

Other TIS Functions [F4, F5, F7]

Events of the function Guidance of the Search [F4] occur multiple times throughout the event history. Crucial events were the three DARPA challenges, both stimulating additional research and determining the current state of progress. The first DARPA Grand challenge can be regarded as negative guidance of the search since none of the teams completed the track. The first Grand challenge did however show the potential of the technology. Another example of negative guidance of the search is the reluctance of VC funds to continue investing in autonomous navigation in 2009. This reluctance however is caused more by the economic downturn than by negative prospects of autonomous navigation applications.

The function Market Creation [F5] is absent in the Event database. In fact, all the DoD and DHS investments can be seen as the creation of a market for defense robots, blurring the distinction between the functions Market Creation and Resource Mobilization, as was the case with the first case study.

Support from Advocacy Coalitions [F7] for the industry comes from industry associations such as the AUVSI, the National Defense Industrial Association (NDIA) and the Robotics Technology Consortium (RTC). The degree of organization is high, because of the importance to lobby for funding at the U.S. Congress.

6.3 MOTORS OF INNOVATION

As is the case with the first case study more generalizable patterns between TIS functions are analyzed by means of interaction pattern analysis and motor identification.

6.3.1 Interaction Pattern Analysis

Interaction pattern analysis has been carried out on the two most occurring TIS functions; Knowledge Development and Resource Mobilization. In the autonomous navigation case however, the interaction pattern analysis does not reveal a significant cross correlation over time between the two variables.

6.3.2 Motor Identification

The historical narrative identified two episodes of differing function intensity. However, based mapping the TIS function intensities to Motors of Innovation, an additional period has been created, resulting in a total of three episodes. Figure 6.7 shows the overall function intensity for the different episodes, marked as episodes A-C.

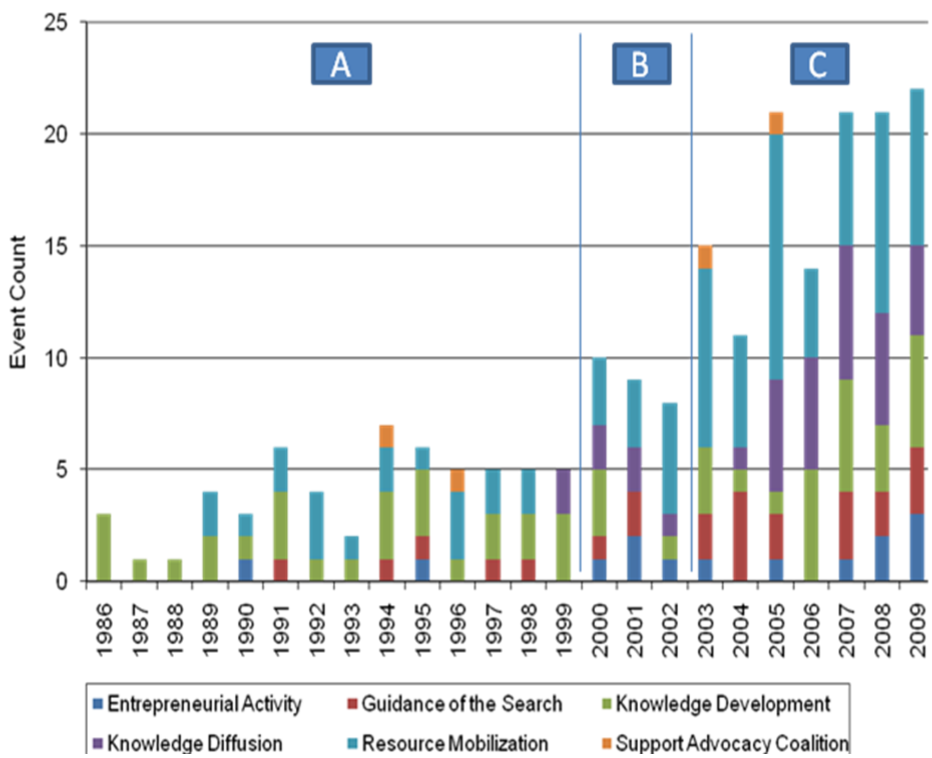

Figure 6.7 Overall TIS Function Intensity Autonomous Navigation

Mapping of the event intensities to the different motors of innovation from literature results in the following identified motors of innovation.

A. 1986 – 1999 *Science & Technology (S&T) Push motor*

The first episode can be classified as a low intensity Science & Technology Push motor. The low intensity refers to the lack of interaction between the functions knowledge development and resource mobilization. Overall very little growth is achieved during this period.

B. 2000 – 2002 *Science & Technology (S&T) Push motor*

Episode B shows an increase in activity, especially in the functions knowledge diffusion and resource mobilization. The investments come from NSF programs targeted towards funding basic research. The low intensity of the knowledge development functions suggests that results from the funding of basic research in this period are not (yet) visible in this episode.

C. 2003 – 2009 *System Building motor*

The final episode starts with a sharp increase in US Army funded R&D. The military interest continues with the DARPA Grand Challenge I in 2004. This is one of the examples of Guidance of the Search, a function that is clearly present in this episode. Another typical TIS function for the System Building motor, Support from Advocacy Coalitions also shows several instances during this episode.

Market Creation, a third central TIS function to the System Building Motor, is absent during this episode. Market creation however takes place in a more direct form, by means of direct investments in R&D projects, instead of typical Market Creation activities such as tax exemptions.

7. Discussion

This chapter concludes with a comparison of both case studies (§7.1.1), the recommendations that can be formulated for the Dutch service robotics industry (§7.2), the contributions for both research (§7.3) and practice (§7.4) and the limitations and suggestions for further research (§7.5).

'When simple things work together, they can create what appears to be complex behaviors to a naïve observer'
- Bryan Adams, iRobot

7.1 Conclusion

7.1.1 Cross Case Comparison

General trends and structural factors

Similarities in the way both case studies originated with mainly defense applications and broadened their application range over the years. Both case studies show gradually increasing TIS function intensity, suggesting build-up of the system.

The functions Entrepreneurial Activity, Knowledge Development, Knowledge Diffusion and Resource Mobilization show cross case importance and form the core of TIS development. The other three functions serve as supporting functions, with an important role for Guidance of the Search in the Autonomous Navigation case. The interviews however do point out that Support from Advocacy Coalitions is perceived by actors as becoming more and more important to the system. Advocacy Coalitions do not only lobby for scarce resources, but can also serve as industry associations that allows for more direct access to collaboration partners.

Both case studies highlight the importance of clusters for knowledge diffusion. An overwhelming majority of knowledge diffusion activities includes at least one actor that is part of one of the identified clusters.

TIS Functions

Both case studies stress the importance of universities as a fertile ground for entrepreneurial activity, by means of university spin-offs and university-industry collaborations. Spin off companies maintain their strong bond with the mother university, leading to readily access to research results, often in the form of a part time job position at a university research group. The availability of cutting edge technological knowledge, human resources present at universities and obtainable benefits from knowledge spillovers are the main reasons that several of the most successful companies in both case studies are spin offs from university research labs. Examples in the case of dexterous manipulation are ReSquared, as spin off from CMU and Barrett, a spin off from MIT. iRobot, the company that spun off MIT, is an example in the case of autonomous navigation.

In both case studies, knowledge development starts out with internal basic research carried out at universities. As the TIS progresses, basic research remains an important pillar, but more applied forms or knowledge development emerge in parallel. This gradual trend towards more applied forms of knowledge development is particularly present in the case of dexterous manipulation. In the case of autonomous navigation, research swiftly started to have an applied focus, based on the defense related investments that require the development and often production of an physical product. This in comparison to the years of basic research funded by NSF grants without tangible applications in the dexterous manipulation case.

Knowledge Diffusion increases over time for both case studies. This can be caused by development of the TIS, transforming from internal, basic research towards more applied, integrative forms of development that require the integration of external information. Another possibility is the relatively recent change in culture regarding protection of intellectual property and the paradigm shift from the Closed Innovation paradigm towards the adoption of Open Innovation practices. Increases in knowledge diffusions are inherent to open innovation practices. The interviews suggest that development of the TIS is the main reason for increases in knowledge diffusion, since Open Innovation practices have occurred throughout the history of this case study, based on the informal and strong contacts between parties in the service robotics industry.

Resource Mobilization for both case studies shows a long period of government sponsored research and recent growth of funding possibilities. In the case of autonomous navigation, technology development towards commercialization is marked by several instances of VC funding.

Interaction patterns

Interaction pattern analysis in the dexterous manipulation case identified a significant cross correlation between knowledge development and resource mobilization and No significant findings for the interaction between knowledge development and resource mobilization in the case of Autonomous Navigation. The limited number of events could explain this lack of cross case similarity.

Motors of Innovation

The two cases show different patterns of motors of innovation. The dexterous manipulation case follows the theoretical proposition of transition from a Science & Technology Push motor towards an Entrepreneurial motor. The System Building motor however is skipped and the system transforms towards a Market motor. In the case of autonomous navigation, the S&T push motor is followed by a System Building motor, skipping the entrepreneurial motor.

The absence of the System Building motor in the case of dexterous manipulation has a clear reason. Companies that were already active in defense related applications experimented with a broader range of applications, funding this experimentation with profits from their DoD/DHS grants. If experimentation was successful, products were launched and broad directly to the market, without the need of niche market creation by the government, as would be the case in a System Building motor.

The absence of the Entrepreneurial motor in the case of autonomous navigation is caused by the control that DoD exerts over the direction of research. Companies active in the field are dependent on the strategic direction that DoD and its departments formulate for autonomous navigation. An entrepreneurial motor could still emerge for this case if concrete applications beyond the military become more widely available.

7.2 RECOMMENDATIONS

This section formulates recommendations for the Dutch service robotics industry, thereby answering the second part of the main research question. In order to formulate practical recommendations that are applicable in the Dutch situation, interviews are carried out with Dutch representatives from companies, governments, research institutes and universities (as listed in Appendix G). The interviews deploy the same list of questions as used for the U.S. actors, but participants are asked to evaluate the TIS as a whole, instead of only their individual role.

The analysis of the U.S. TIS for service robotics in combination with the qualitative information regarding the Dutch situation leads to recommendations on both the overall system level (§7.2.1) and for specific actor groups (§7.2.2).

7.2.1 System Level

The analysis of the U.S. TIS highlights the importance of cluster thinking, a notion that should be more prominently embedded in the Dutch service robotics industry. At the moment, the four major research clusters are formed around the three technical universities and the University of Amsterdam. The clusters operate relatively independently while the geographical spanning of the U.S. clusters shows that the Netherlands as a whole could operate as a more integrated cluster.

One of the ways to establish both a broader and deeper cluster view is the initiation of a national advocacy coalition. In the current situation, regional development agencies function as advocacy coalitions. A nation-wide advocacy coalition can initiate an integrated lobby for the service robotics industry and can create a breeding ground for more collaboration and knowledge diffusion. Such an advocacy coalition is currently in the making, based on initiatives from the University of Twente. The strong bonding of this advocacy coalition to the Twente cluster brings up the important challenge to involve organizations from elsewhere in order to create an integrated effort.

An important task for the advocacy coalition in cooperation with the other actors is the formulation of a roadmap for service robotics in the Netherlands that formulates a long term vision and provides guidance to individual actors.

7.2.2 Actor groups

Recommendations for actor groups are targeted to the three organizational types of the 'triple helix' model, governments, industry and universities.

Governments

Governmental institutes that provide funding for research should take into consideration the time lag between different functions and between the different motors of innovation. Build up of the formative TIS for dexterous manipulation took 21 years before a market motor was reached. Besides this, governmental institutes should take into account the long time spans from investing in cutting edge technology development until actual applications.

Companies

From a technology perspective, developments in both Autonomous Navigation and Dexterous Manipulation show the trend of robotic applications that operate in unstructured environments, instead of the traditional application of robots in structured industrial environments. Development of technology that allows robots to effectively, efficiently and safely operate in unstructured, human-centric environments therefore should be the R&D focus.

Compatibility with standards becomes more and more important, as shown by the development of the Joint Architecture for Unmanned Sytems (JAUS). As technology development progresses towards commercialization, applications integrate technologies from different sources that have to be compatible in order to function properly. Companies have to be aware of the standards for their technology, but should furthermore anticipate integration with other technologies by developing industry-wide standards.

Companies in the U.S. robotics industry are very well aware of the different funding possibilities offered by governments. This is supported by an informal institution, a culture of tender writing. The interviews with Dutch actors make clear that Dutch companies are often not aware of funding possibilities within national innovation programs and are seldom aware of the recently available large funds for robotics from the European Union.

U.S. Companies identify access to high quality human resources as the main advantage from cooperation within clusters and/or with universities. Dutch companies can benefit from the available pool of human resources at universities by more actively pursuing collaboration possibilities with research institutes.

The interviews with U.S. actors make clear that it is possible for international parties to participate in DHS/DoD projects as sub contractors to the main U.S. based contractor. This requires an active role for international parties that are interested. International parties have to build an informal network of companies and react swiftly to new grant openings in order to become a sub contractor.

Universities

Both case studies show the large change of success that spin off companies from universities have in the service robotics industry, especially when both parties maintain close bonds, for example by a part time job position at the university. Universities should therefore actively promote entrepreneurship within their faculties and should adapt technology transfer policies to support spin offs.

7.3 CONTRIBUTIONS FOR RESEARCH

Contributions for research are made on three different levels: contributions to general innovation theory (§7.3.1), specific TIS function theory (§7.3.2) and research methodology (§7.3.3).

7.3.1 General Theory

This research into service robotics validates the TIS function approach and Motors of Innovation theory in a field of technology that has not been researched before using these theories.

The results show that the model of Technology Development should not be considered as a one dimensional, chronological model with strict boundaries between the different stages. Basic research at universities remains important throughout the process of technology development, providing input to more applied forms of research that are initiated over time.

7.3.2 TIS function theory

This research deepens insight in the functions entrepreneurial activity, knowledge development and knowledge diffusion by enhancements based on the theory of Open Innovation, collaboration theory and cluster theory.

Collaboration theory and the use of specific collaboration types gives insight in the state of technology development of the system and supports the identification of motors of innovation.

The results from this study show the ambiguity of the Market Creation function. The theoretical 'raison d'être' of the market creation function seems to be the governmental market creation for the sustainable energy market, the subject of the majority of TIS analyses up to this moment. The creation of niche markets in other technology fields might not occur in the form of general tax exemptions, but could be realized by means of direct investments into specific projects, as is the case for the service robotics industry.

7.3.2 Research Methodology

The research methodology for TIS function analysis objectifies the research method by including patent analysis, scientific publications, use of funding and grant databases for equal comparison. Besides this, the research methodology introduces cross correlation as a valid approach for researching interaction patterns.

7.4 Contributions for Practice

From a practical point of view, this research formulates recommendations for the Dutch service robotics industry, as listed in section 7.2.

Practical results for the TWA Network include specific insights into the U.S. service robotics situation. The TWA Network can use this information to improve its bridge function between U.S. and Dutch organizations. Furthermore, the TWA Network can use the developed TIS framework to research other TISs, as its role extends the boundaries of the service robotics TIS.

For the Dutch industry, the two case studies suggest new enabling technologies and applications for Dutch organizations active in the technology fields of dexterous manipulation and autonomous navigation. The structural factors analysis, supported by the event history analysis points out possible U.S. partner organizations for Dutch organizations in search of collaboration possibilities with U.S. parties or market entrance possibilities. The overview of institutions and funding possibilities provide insight in the specific U.S. situation for Dutch companies that want to become active in the U.S.

7.5 SUGGESTIONS FOR FURTHER RESEARCH

The TIS framework from this study can be used to research the TIS build-up of other enabling technologies that are relevant for the service robotics industry. Research into other enabling technologies could identify show whether specific motors of innovation are applicable to the service robotics industry or that motors of innovation differ between enabling technologies, as the results from this study suggest. Investigation of other enabling technologies can also increase insight into the ambiguous Market creation function and whether this function should be altered or even removed from the set of TIS Functions.

Further research can lead to more precise identification methods for motors of innovation. The mapping of TIS function intensities to motors of innovation as used in this study does identify characteristics that can be used for classification, but the method is rudimentary.

REFERENCE LIST

Afuah, A. (2000). How much do your co-opetitors' capabilities matter in the face of technological change? *Special Issue, Strategic Management Journal, 21,* 387–404.

Ahuja, G. (2000). Collaboration Networks, Structural Holes, and Innovation: A ongitudinal Study. *Administrative Science Quarterly, 45,* 425-455.

Archibugi, D., Michie, J. (1995). The globalization of technology: a new taxonomy. *Cambridge J. Econ. 19,1.*

Balzat, M. (2006). *An Economic Analysis of Innovation. Extending the concept of National Innovation Systems.* New Horizons in Institutional and Evolutionary Economics.

Benner, M.J., Tushman, M.L. (2003). Exploitation, Exploration and Process Management. *Academy of Management Review, 28, 2,* 238-256.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S. and Rickne, A. (2008). Analyzing the functional dynamics of Technological Innovation Systems: A scheme of analysis. *Research Policy, 37,* 407-429.

Cantwell, J.A. (1995). The globalization of technology: what remains of the product cycle model? *Cambridge J. Econ. 19, 1.*

Carlsson, B., Stankiewicz, R. (1991). On the nature, function and composition of technological systems. *Journal of Evolutionary Economics, 9*, 93-118

Carlsson, B., Jacobsson, S., Holmén, M., Rickne, A. (2002). Innovation Systems: Analytical and Methodological Issues. *Research Policy 31, 2,* 233-245.

CCC, CRA and NSF (2009). *A Roadmap for US Robotics. From Internet to Robotics.*

Chesbrough, H. (2003). *Open Innovation. The new Imperative for Creating and Profiting from Technology.* Harvard Business School Press, Boston, MA.

Chesbrough, H. (2004). Managing Open Innovation. *Research Technology Management, Jan-Feb 2004,* 23-26.

Chesbrough, H., Prencipe, A. (2008). Networks of innovation and modularity: a dynamic perspective, *Int. J. Technology Management, 42, 4,* 414–425.

Cohen, W.M., Levinthal, D.A. (1990). Absorptive Capacity: A New Perspective on Learning and Innovation. *Administrative Science Quarterly, 35*, 128-152.

Coordination Action for Robotics in Europe (2009). *Robotics Visions to 2020 and beyond. The strategic research agenda for robotics in Europe.*

COS (2007). *Rapport Horizonscan 2007. Naar een toekomstgerichte beleids- en kennisagenda.* Den Haag.

Contractor, F., Lorange, P. (1988). *Cooperative Strategies in International Business*, Lexington, MA: Lexington Books.

Dosi, G. (1988). Sources, Procedures and Microeconomic Effects of Innovation, *Journal of Economic Literature, 26,* 1120 – 1171.

Etzkowitz, H., Leydesdorff, L. (2000). The dynamics of innovation: from National Systems and "Mode 2" to a Triple Helix of university–industry–government relations. *Research Policy, 29, 2,* 109-123.

Freeman, C. (1991). Networks of Innovators: a synthesis of research issues. *Research Policy, 20, 5,* 499-514.

Geels, F.W. (2004). From sectoral systems of innovation to socio-technical systems. Insights about dynamics and change from sociology and institutional theory. *Research Policy, 33,* 897–920.

Gulati, R., Garguilo, M. (1999). Where do interorganizational networks come from? *The American Journal of Sociology, 104, 5*, 1439–1493.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting & Social Change, 74,* 413-432.

Hekkert, M.P., Negro, S.O. (2009). Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technological Forecasting & Social Change, 76,* 584-594.

Hirschman, A.O. (1958). *The Strategy of Economic Development.* Yale University Press, Clinton, MA.

Kogut, B. (2000). The network as knowledge: generative rules and the emergence of structure, *Strategic Management Journal, 21, 3,* 405–425.

Koza, M.P., Lewin, A.Y. (1998). The co-evolution of strategic alliances. *Organization Science, 9, 3,* 255–264.

Liebeskind, J.L., Oliver, A.L., Zucker, L., Brewer, M. (1996). Social Networks, Learning, and Flexibility: Sourcing scientific Knowledge in New Biotechnology Firms. *Organization Science, 7, 4,* 428-443.

Linstone, H.A., Turoff, M. (1975). *The Delphi Method: Techniques and Applications.*

Lundvall, B.A., (1992). National Systems of Innovation—Toward a Theory of Innovation and Interactive Learning. Pinter Publishers, London.

Malerba, F. 1993. The national system of innovation: Italy. In: Nelson, R. (Ed.), National Innovation systems. Oxford Univ. Press, Oxford.

Malerba, F. (2002). Sectoral systems of innovation and production. *Research Policy, 31,* 247-264.

Marsili, O. (1999). Technological Regimes: Theory and Evidence. *Eindhoven University, November 1999.*

Narayanan, V.K. (2001). *Managing Technology and Innovation for Competitive Advantage.* Prentice-Hall, Inc.

Narula, R., Dunning, J. (1997). Explaining international R&D alliances and the role of governments. *MERIT Research Memoranda, 11.*

Owen-Smith, J., Riccaboni, M., Pammolli, F., Powell, W.W. (2002). A Comparison of U.S. and European University-Industry Relations in the Life Sciences. *Management Science, 48, 1,* 24-43.

Poole, M.S., van de Ven, A.H., Dooley, K., Holmes, M.E, (2000). *Organizational Change and Innovation Processes, Theories and Methods for Research.*

Powell, W.W., Koput, K.W., Smith-Doer, L. (1996). Interorganizational Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology. *Administrative Science Quarterly, 41,* 116-145.

Porter, M.E. (1998a). Clusters and the new Economics of Competition. *Harvard Business Review, November-December 1998.*

Porter, M.E. (1998b). *On Competition.* The Harvard Business Review Book Series.

Sahal, Devendra. (1981). *Patterns of Technological Innovation.* Reading, MA: Addison Wesley, 1981.

Schumpeter, J. (1934). *The Theory of Economic Development.* Harvard University Press, Boston

Scott, J., Tallia, A., Crosson, J.C., Orzano, A.J. (2005). Social Network Analysis as an Analytical Tool for Interaction Patterns in Primary Care Practices. *Annals of Family Medicine, 3, 5,* 443-449.

Owen-Smith, J., Riccaboni M., Pammolli, F., Powell, W.W. (2002). A Comparison of U. S. and European University-Industry Relations in the Life Sciences. *Management Science, 48, 1,* 24-43.

Rane, S. (2009). Service Robotics – USA. *Available at TWA Network, Washington DC.*

Stuart, T.E. (1998). Network Positions and Propensities to Collaborate; An Investigation of Strategic Alliance Formation in a High-technology Industry. *Administrative Science Quarterly, 43*, 668-698.

Suurs, R.A.A.. (2009). *Motors of sustainable innovation. Towards a theory on the dynamics of technological innovation systems (Thesis).* Innovation Studies Group. Utrecht University, the Netherlands.

Suurs, R.A.A., Hekkert, M.P. (2009). Motors of sustainable innovation (Draft version). *Proceedings of the DIME Workshop on Environmental Innovation, Industrial Dynamics and Entrepreneurship, Utrecht.*

Tushman, M.L. (1997). Special Boundary Roles in the Innovation Process. *Administrative Science Quarterly*, *22, 4*, 587-605.

Van de Ven, A.H. (1993). The development of an infrastructure for entrepreneurship. *Journal of Business Venturing, 8,* 212–230.

Van de Ven, A.H., Polley, D.E., Garud, R., Venkataraman, S. (1999). *The Innovation Journey*. Oxford University Press.

Yin, R. (2003*). Case Study Research*. Sage, London.

Zikmund, W.G. (1987). *Business research methods*. Dryden Press.

Terminology and Abbreviations

AGV	Automatic Guided Vehicle
CCC	Computing Community Consortium
CMU	Carnegie Mellon University
CRA	Computing Research Association
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DoD	Department of Defense
EOD	Explosives Ordnance Disposal
FDA	U.S. Food and Drug Administration
IFR	International Federation for Robotics
JAUS	Joint Architecture for Unmanned Systems
JRA	Japanese Robotics Association
LADAR	Laser Detection and Ranging
LIDAR	Light Detection and Ranging
MassTLC	Massachusetts Technology Leadership Council
MEMS	Micro Electro Mechanical Systems
MIT	Massachusetts Institute of Technology
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NIH	National Institute of Health
NIS	National Innovation System
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
SBIR	Small Business Innovation Research
SLAM	Simultaneous Localization and Mapping
SME	Small or Medium Sized Enterprise
STTR	Small Business Technology Transfer
TIS	Technological Innovation System
TTC	The Technology Collaborative
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
VC	Venture Capital

LIST OF FIGURES AND TABLES

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APPENDIX A: TWA NETWORK

The TWA Network consists of a home base in The Hague, the Neterlands and utilizes 15 branches around the world to collect and share knowledge on technological developments, policy and innovation. The organization strives to fulfill four objectives.

- Increasing the knowledge on innovation policy and technological developments abroad that can be used by the Ministry of Economic Affairs with a focus on nine technological themes and the application of technology by companies.
- Increasing the knowledge on technological and scientific developments en related trends regarding innovative entrepreneurship that can be used by firms and knowledge institutes by regular reports.
- Exploration of the focus technologies. This implies timely offering of R&D and technology information to Dutch companies, knowledge institutes and universities, thereby allowing those organizations to anticipate technological and market developments.
- Building a network of contacts to facilitate cooperation between Dutch and foreign organizations.

The TWA Network's branch in Washington DC uses robotics as a special topic of interest for 2009 and as a part of this focus initiated more in-depth research into the U.S. robotics technological innovation system.

APPENDIX B: SERVICE ROBOTICS APPLICATIONS

Personal / Domestic Robots

- Robots for domestic tasks
  - Robot butler/companion/assistants/humanoids
  - Vacuuming, floor cleaning
  - Lawn mowing
  - Pool cleaning
  - Window cleaning
- Entertainment robots
  - Toy/hobby robots
  - Robot rides
  - Education and training
- Handicap assistance
  - Robotized wheelchairs
  - Personal rehabilitation
  - Other assistance functions
- Personal transportation (AGV for persons)
- Home security & surveillance

Professional Service Robots

- Field robotics
  - Agriculture
  - Milking robots
  - Forestry
  - Mining systems
  - Space robots
- Professional cleaning
  - Floor cleaning
  - Window and wall cleaning (including wall climbing robots)
  - Tank, tube and pipe cleaning
  - Hull cleaning (aircraft, vehicles, etc.)
- Inspection and maintenance systems
  - Facilities, Plants
  - Tank, tubes and pipes and sewer
  - Other inspection and maintenance systems
- Construction and demolition
  - Nuclear demolition & dismantling
  - Other demolition systems

  - Construction support and maintenance
  - Construction

- Logistic systems
  - Courier/Mail systems
  - Factory logistics (incl. Automated Guided Vehicles for factories)
  - Cargo handling, outdoor logistics
  - Other logistics
- Medical robotics
  - Diagnostic systems
  - Robot assisted surgery or therapy
  - Rehabilitation systems
  - Other medical robots
- Defense, rescue & security applications
  - Demining robots
  - Fire and bomb fighting robots
  - Surveillance/security robots
  - Unmanned aerial vehicles
  - Unmanned ground based vehicles
- Underwater systems
- Mobile Platforms in general use
- Robot arms in general use
- Public relation robots
  - Hotel and restaurant robots
  - Mobile guidance, information robots
  - Robots in marketing
  - Others (i.e. library robots)
- Special Purpose
  - Refueling robots
  - Others
- Customized robots
- Humanoids

Appendix C: Enabling Technologies

- Sensing
  - LADAR: laser radar
  - Stereovision
  - Tactile feedback
- Perception
  - Sensor data fusion
  - Object detection
  - Object localization
- Communication
  - Wireless
- Artificial Intelligence
  - Learning algorithms
- System integration
  - Standards
  - Metrics
- Man-machine interfaces
  - HRI: human robot interaction
  - Ergonomics
  - Interfaces
- Cooperative behavior
  - Robot cooperation
  - Robot Human cooperation
  - Robot Component cooperation
- Machine health
  - Monitor, Diagnose and Mitigate system failures
- Miniaturization
  - Nanotechnology
- Energy transformation
- Biotechnology

Robot Mobility Enabling Technologies

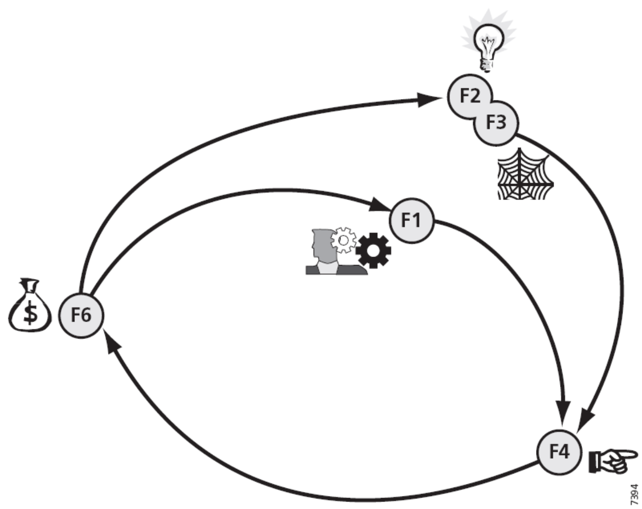
- Navigation
  - Localization
  - Mapping
- Mobility
  - Locomotion: land, air, water, underwater
- Energy supply
  - Autonomous energy supply
  - Energy storage
- Control
  - Motion planning

Robot Task Enabling Technologies

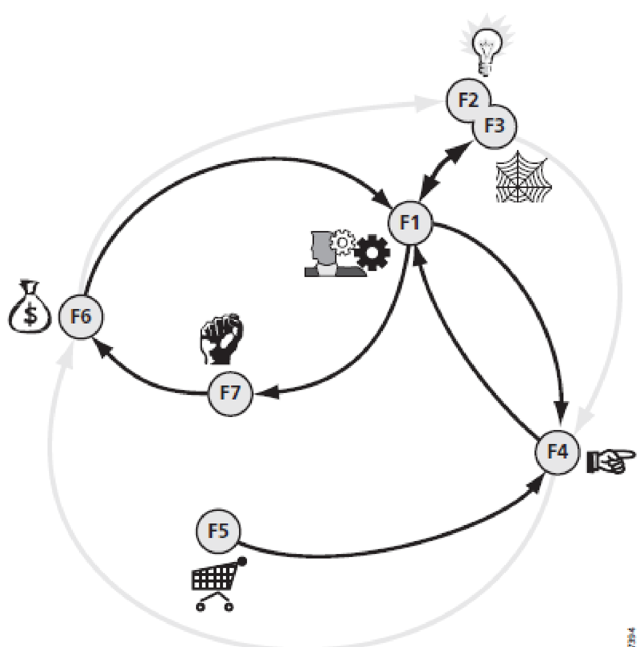
- Manipulators
  - Dexterity
  - Haptics
  - Movement planning
- Actuators

Appendix D: Motors of Innovation

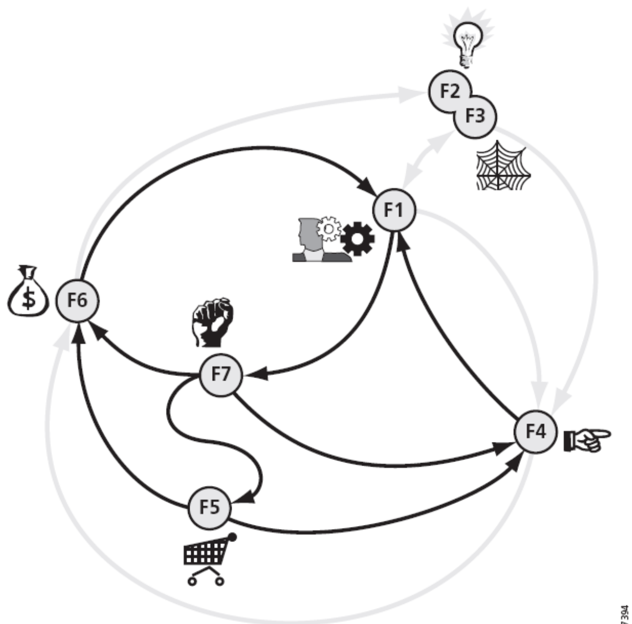
Science and technology push motor (adopted from Suurs (2009))



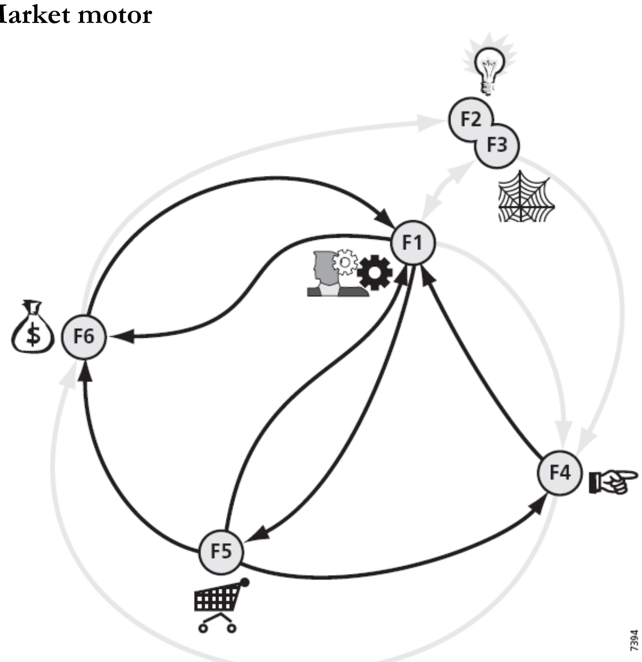
Entrepreneurial motor



System building motor



Market motor



APPENDIX E: INTERVIEW QUESTIONS

Structural Factors

- What are the relevant actors in your segment?
- What are relevant networks for your organization ?
- How do these different networks influence your organization?
  - Technology platform consortia
  - Industry associations
  - Public-private partnerships
  - Buyer-seller relationships
  - University Alumni
  - Company Alumni
  - VC communities
- What are relevant institutions for your organization?

F1. Entrepreneurial Activity

- How did your company start [F1]?
  - Spin off, .., etc.
- How has your company's portfolio changed over de years [F1]?
- How is your business model defined? [F1]
  - What is your target market?
  - What are your key value propositions?
  - Who are the key third parties?
- Does your company operate internationally?

F2. Knowledge Development

- Where have the important ideas in your company/industry come from? How do they fit with your business model? [F2]
  - Visit Conferences
  - Organize conference
  - Employ university professors
  - Employ graduate students
  - Fund external research at a university
  - Active scanning: select research yourself
  - Passive scanning: let researchers contact you with proposals
  - Scout start-up companies
  - Partnerships with start-up companies
  - Acquire promising start-ups
  - Create start-up companies

- What role have start-up organizations played? Have they been able to penetrate the market and gain share? Where have their ideas come from? What is their business model? [F2, F3]
- What role do universities play in contributing knowledge and understanding to your company and industry? In what areas of importance to your company are the key departments in those universities working? Who are the top professors in that areas? [F2, F3]]
- How do you manage you intellectual property (IP)?

F3. Knowledge Diffusion

- What kind of vehicles does your company use for knowledge diffusion and how? How would you rate the vehicles in importance? [F3]
    - R&D alliance
    - Investment
    - Licensing
    - Manufacturing
- What are/would be the main advantages to act in a robotics cluster? How would you rate the advantages in importance? [F3]
    - Better access to employees and suppliers
    - Access to specialized information (market, technical, competitive)
    - Complementarities (boost from good performance of others)
    - Access to Public Goods (investments to the cluster)
    - Better motivation/inspiration/measurement
- Do you mainly collaborate with partners inside your own cluster? How do you collaborate with partners outside the cluster? Do you collaborate on the international level?
- How can companies actively help building a robotics cluster? Do you feel government interventions can help build a robotics cluster? How?

Other functions F4-7

- What role do venture capitalists and other private equity investors play in your industry? Are they active investors? What explains the bets that they are making? How do these bets compare to the bets your own company is making? [F6]
- What is the role of advocacy coalitions in the build up of the innovation system/cluster? [F7]
- What is the role of governmental institutes and universities in guiding the search for this technology? [F4]
- Do markets evolve completely naturally for this technology or are they formed by the government? [F5]

APPENDIX F: U.S. SERVICE ROBOTICS ACTORS

OrgType	Name	Location	State	Technologies	Applications
Company	Kinetic Muscles	Tempe	AZ		Rehabilitation
Company	AeroVironment	Monrovia	CA	UAV	Defense, Engery
Research Lab	Angelus Research	Anaheim	CA	Autonomy	Defense, Manufacturin, Educational
University	California Institue of Technology Robotics	Pasadena	CA	underwater, locomotion, network	medical, prof. service
Company	Hansen Medical	Mountain View	CA		Medical
Company	HeadThere, Inc.	San Fransisco	CA	video conferencing	prof. service, personal service
Company	Hitec RCD	Poway	CA	Humanoid	Personal Service, Toy
Company	Integrated Surgical Systems - Robodoc	Fremont	CA		Medical
Company	Intuitive Surgical	Sunnyvale	CA		Healthcare, Medical
Company	Liquid Robotics	Palo Alto	CA	Autonomy, water, propulsion, platform	Professional service
Government	NASA JPL	Pasadena	CA		Space
Company	Robomedica	Irvine	CA		Rehabilitation
Company	SeaBotix	San Diego	CA	underwater	Inspection
Government	Space and Naval Warfare Systems Center Pacific	San Diego	CA	Automony, Underwater	Defense, Space
University	Stanford AI	Palo Alto	CA		
University	UC Berkeley Robotics & Human Engineering Lab	Berkeley	CA	exoskeleton, biomemetic locomotion,	Defense, Medical
University	University of South California (USC)	Los Angeles	CA		
University	Florida State University, Machine	Gainesville	FL	Underwater, Autonomy	

	Intelligence Lab				
Company	Gecko Systems	Conyers	GA	Platform, Sensing, Autonomy	Personal Service (Care), Healthcare, Security
University	Georgia Tech Robotics & Intelligent Machines (RIM@GT)	Atlanta	GA		
Hospital	Rehabilitation Institute of Chicago	Chicago	IL		Rehabilitation
University	Purdue University - Robot Vision Lab	West Lafayette	IN	Vision, Navigation	
Company	BarrettTechnology	Cambridge	MA	Dexterity	Healthcare, Space, Manufacturing, Medical
Company	Boston Dynamics	Waltham	MA	Autonomy, Locomotion	Defense
Company	Corindus	Natick	MA		Medical
Research Lab	Draper	Cambridge	MA	Autonomy, Biomedical, Sensing	Defense, Space, Energy
Company	Foster Miller	Waltham	MA	Autonomy, Locomotion, Platform	Defense, Security, Inspection
Company	Harvest Automation	Groton	MA	Platform	Agricultural
Company	Heartland Robotics	Cambridge	MA		manufacturing
Company	Intuitive Automata	Boston	MA	HMI	Personal Service
Company	iRobot	Bedford	MA	Autonomy, Sensing	Defense, Domestic
Company	KIVA systems	Woburn	MA		Logistics
University	MIT Agile Robotics Team (CSAIL)	Cambridge	MA	Autonomy	Logistics
Research Lab	MIT Lincoln Lab	Cambridge	MA		Defense, Space, Security
Company	Segway	Bedford	MA	Locomotion, Platform	Personal Service, Logistics
University	University of Massachusetts, Lab for Perceptual Robots & Robotics and Biology Lab	Amherst	MA	Autonomy, Dexterity	
Research	Woods Hole Oceanographic Institution	Woods Hole	MA	underwater	

Lab					
University	Worcester Polytechnic Institute	Worcester	MA		
Company	AAI	Hunt Valley	MD	UAV	Defense
Company	Advanced Technology & Research	Columbia	MD	Naval, Underwater	Logistics
Company	AnthroTronix	Silver Spring	MD		Rehabilitation
Government	Baltimore Veterans Affairs Medical Centrum	Baltimore	MD	exoskeleton	Rehabilitation
Company	Encore Path	Baltimore	MD		Rehabilitation
Company	Intelligent Automation Inc.	Rockville	MD	network, plaform	Defense, Logistics, Rehabilitation
University	John Hopkins University (JHU)	Baltimore	MD		Medical
Government	National Institute of S&T (NIST) Manufacturing Engineering Lab	Gaithersburg	MD		
University	NSF Computer-Integrated Surgical Systems and Technology Engineering Research Center	Baltimore	MD		Medical
University	UMD RAMS Robotics Automation, Manipulation & Sensing Lab	College Park	MD	sensing	Medical
Company	Vecna Robotics	Greenbelt	MD		Military Healthcare, Defense, HS
Company	International Robot Support	Clinton Township	MI	production	manufacturing
Company	KUKA	Clinton Township	MI		Manufacturing
Company	Mobile Intelligence	Livonia	MI	autonomy	
University	University of Michigan, Mobile Robotics Lab	Ann Arbor	MI	Navigation	
Company	Toro	Bloomington	MN		Prof. Service
University	North Carolina State University (NCSU)	Raleigh	NC	evolutionary, sensing,	medical
Company	DEKA	Manchester	NH		Rehabilitation
Research Lab	Intelligent Systems Robotics Center (ISRC)	Albuquerque	NM	locomotion, networks, industrial	Defense, manufacturing
University	Cornell University	Ithaca	NY		
University	Case Western Reserve University -	Cleveland	OH	biomimetic	Defense, Space

	Biorobotics Lab			locomotion	
Company	Yobotics	Cincinatti	OH	Locomotion, Humanoid	Personal Service, Rehabilitation
Company	Aethon	Pittsburgh	PA	Autonomy	Medical
Company	Alien Robotics	Pittsburgh	PA	Software	Personal Service, Medical
Company	Astrobotic Technology	Pittsburgh	PA		Space
Company	Automatika	Pittsburgh	PA	Locomotion	Industrial, Defense
Company	Bossa Nova	Pittsburgh	PA		Personal Service, Toy
Company	Butterfly Haptics	Pittsburgh	PA	haptic interface	medical, prof. service
Company	Cardiorobotics	Pittsburgh	PA		Medical
University	Carnegie Mellon University (CMU) National Robotics Engineering Center (NREC)	Pittsburgh	PA		
Company	General Dynamics	Pittsburgh, PA, Westminster, MD	PA		Defense, manufacturing
Company	Interbots	Pittsburgh	PA		Toys
Company	Johnson & Johnson, Independence Techn.	Langhorne	PA		Rehabilitation
Other	Pittsburgh Technology Collaborative (TTC)	Pittsburgh	PA		Defense, Toys
Company	Redzone Robotics	Pittsburgh	PA	platform, autonomy	Inspection
University	Vanderbilt University	Nashville	TN	working memory, vision	
Government	DARPA	Arlington	VA		
Government	Office of Naval Research (ONR)	Arlington	VA	underwater, exoskeleton	
University	Virginia Tech RoMeLa	Blacksburg	VA		
Research Lab	D&ME Pacific Northwest National Lab	Richland	WA	Autonomy, Platform	
Company	Qcomp	Greenville	WI		Manufacturing, Logistics

APPENDIX G: INFORMATION SOURCES

Dexterous Manipulation

Name	Organization	Date	Additional Info[19]
Bill Thomasmeyer	Pittsburgh TTC	September 9, 2009	
Beth Hollis	Butterfly Haptics	October 12, 2009	IROS 2009
Jesse Hayes	Schunk	October 13, 2009	IROS 2009
S.K. Gupta, Jeff Coriale	University of Maryland	October 19, 2009	
Reeg Allen	Re squared	October 20, 2009	
Morgan Taylor	VPI Engineering	October 21, 2009	
Russell Taylor	Johns Hopkins University	October 21, 2009	

Autonomous Navigation

Name	Organization	Date	Additional Info
Morgan Taylor	VPI Engineering	October 21, 2009	
Reeg Allen	Re squared	October 20, 2009	
Robert Bolles	SRI International	October 14, 2009	IROS 2009
Robert Mandelbaum	DARPA	October 14, 2009	IROS 2009
Patrick Goode	Northrop Grumman	August 12, 2009	AUVSI Unmanned
Chris Jones	iRobot	August 12, 2009	AUVSI Unmanned
Eric A. Levine	MITRE	August 11, 2009	AUVSI Unmanned
Rob IJsselstein	TNO Defense & Security US	October 7, 2009	

Netherlands

Name	Organization	Date	Additional Info
Nico Arfman	OostNV		
Jan Leideman	Demcon		
Sebastiaan Berendse	TWA Netwerk		
Rob IJsselstein	TNO Defense & Security US	October 7, 2009	
Stefano Stramigioli	Utwente/RoboNED		

[19] Additional info includes the conference at which the meeting took place.