ECHORD

Lab Tour to North America

Lab Tour to North America

ECHORD European Clearing House for Open Robotics Development

Lab Tour to North America

Lab Tour to North America

Final Report

ECHORD

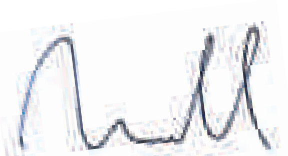
Technische Universität München

SEVENTH FRAMEWORK PROGRAMME

As part of ECHORD's structured dialogue, the aim of the North American lab tour was to look beyond the borders of Europe and consult global leaders in the robotics community in the U.S. and Canada about technology transfer between academia and industry. The first section of this report gives an overview of our findings on this complex subject. These findings are complemented by the insight gained on the tour and are followed by a short report of each of the labs we visited. Finally, we present an initial analysis of the main results.

The ECHORD team would like to sincerely thank the European experts for their commitment in joining us on the tour and for their contribution to this report. We could not have done it without them! We also wish to express our gratitude to the North American labs and their professors, managers, senior researchers and young professionals who were so kind to host our expert group and who taught us a great deal about academia-industry collaboration in the US. Our special thanks goes to the members of the ECHORD team at TUM who – working in the background – made a significant contribution to the literature research for this report: Anna Marcos-Nickol and Laura Voss.

Munich, March 12th, 2012
Alois Knoll, ECHORD Coordinator



Contents

1. Introduction

The European robotics industry is faced with multiple challenges. It is highly dominated by small and medium-sized companies, which lack the financial resources to invest large amounts of money into RTD and to push innovation. There are only a limited number of larger players operating on an international basis where innovation is driven by strong RTD departments.

At the same time, the industry is confronted with a powerful non-European competition mainly from Asia – traditionally from Japan, but currently increasingly from South Korea. The backbone of the robotics industry in Asia is comprised of larger companies with a different company structure. Nowadays, not only the robotics industry, but also the manufacturing industry of Japan is suffering tremendously. These problems are not due to the recent Tsunami, as some might guess. The GDP share of the area affected by the Tsunami is just 5% of the total national GDP. The manufacturing industry in Japan suffers from deflation and an ultra-high currency. This peak currency (30%-40% change within a few years) makes it hard to compete with Korea. The Asian lab tour (planned for June 2012) will investigate this situation in more detail.

Introduction

It is undisputed that Europe is strong both in terms of its robotics research as well as in industry. But the robotics community is fragmented and the stakeholders from industry and academia do not always work well together. Thus, academic labs are sometimes not aware of the availability of standard hardware that can be used for their scientific research.

An opinion held by many in Europe is that strengthening long-term collaborations between industrial stakeholders and academic labs will have a major impact on the economic prosperity and on the competitiveness of European robotics. And the strength of the European robotics industry – particularly in embedded systems – will have a decisive influence on the competitiveness of Europe as a whole. For that reason supporting industry-academia cooperation is a top priority in EC-funding.

ECHORD – the European Clearing House for Open Robotics Development – is the largest EU-funded project in robotics to date. The reinforcement of academia-industry cooperation is the primary concern of the project. Two initiatives promote this collaboration: first of all, 15 million Euro (of 19 million Euro total project funding) are invested in 51 experiments, in which target-oriented research focused on specific problems is done by small consortia in which academic partners and industrial users join their forces. Secondly, via the "structured dialogue" investigating academia-industry cooperation and using tools including targeted group interviews, Delphi studies, online questionnaires, conferences, workshops and extensive literature research. The purpose is to establish the best practice of academic-industrial cooperation in Europe and to identify the weak areas of cooperation between industry and academia.

And finally, ECHORD organizes two international lab tours – the first to North America and the second to Asia. For two weeks in October 2011, 6 European experts of European robotics (from the academic environment as well as from industry) and the ECHORD consortium leaders visited major academic and industrial labs in North America to find out more about the way industry and academia cooperate with each other in the U.S. and how funding influences their modes of cooperation. The personal interviews on site were facilitated by an online questionnaire which had been sent to the host labs beforehand.

The findings of the North American tour will be compared with those of the Asian lab tour, which will take place in June 2012.

2. Trip Overview

It was with great anticipation and enthusiasm that the ECHORD expert team began its tour in San Francisco, California with a kick-off meeting on Sunday, October 2, 2011. Many of the experts were already in San Francisco for IROS, so it was a smooth and logical starting point.

2.1. Sites on the tour

Site	Labs visited
Stanford	▪ Stanford University: Biomimetics and Dexterous Manipulation Lab ▪ Stanford University: Artificial Intelligence Lab ▪ Willow Garage ▪ Bosch Technology and Research Centre
San Francisco	▪ University of Southern California: Robotics Embedded Systems Laboratory ▪ University of Southern California: Computational Learning and Motor Control Lab ▪ University of Southern California: The Interaction Lab ▪ NASA Jet Propulsion Lab ▪ SynTouch LLC
Los Angeles	▪ University of Washington: Biorobotics Laboratory ▪ University of Washington: Robotics and State Estimation Lab ▪ University of Washington: Sensor Systems Research Group ▪ Microsoft Research
Philadelphia	▪ University of Pennsylvania: GRASP Lab – General Robotics, Automation, Sensing, Perception
Pittsburgh	▪ Carnegie Mellon University: CREATE Lab – Community Robotics, Education and Technology Empowerment
Boston	▪ Massachusetts Insitute for Technology (MIT): Computer Science and Artificial Intelligence Laboratory ▪ Massachusetts Insitute for Technology (MIT): Field and Space Robotics Laboratory and Space Systems Lab
Montreal	▪ McGill University: Mobile Robotics Laboratory ▪ McGill University: Centre for Intelligent Machines

The group consisted of experts from academia and from the European robotics. After being presented with a detailed brochure of the itinerary, the experts enjoyed a special dinner and discussed the various places they would visit en route.

Monday, the 3rd of October, began with a visit to Oussama Khatib's lab at Stanford, followed by spending the next day at the Willow Garage lab and the specialists at Bosch Research. Tuesday evening, the 4th of October took us down to Southern California to visit Gaurav Sukhatme at the University of California and then on to NASA Jet Propulsion lab, which included the highlight of robot systems for planetary exploration. We then flew to Seattle, where we were welcomed by Blake Hannaford and his team at University of Washington and by Stewart Tansley at Microsoft Research.

On Monday, the 10th of October, we flew to the East Coast to visit Vijay Kumar's group at the University of Pennsylvania, and then on to Carnegie Mellon (Howie Choset) and MIT (Daniela Rus and Steven Dubowsky). Our final academic stop was at McGill University in Montreal at the lab of Greg Dudek and Jorge Angeles.

The group broke up in Montreal, with all experts returning to Europe to their respective homes and institutions, full of new, innovative ideas and impressions of how robotics research is being done in North America. The trip was indeed a fantastic and enriching experience for all involved!

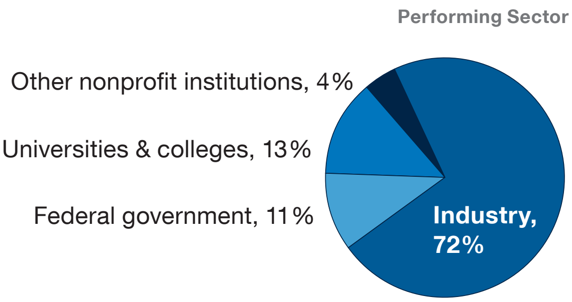
3. Analysis

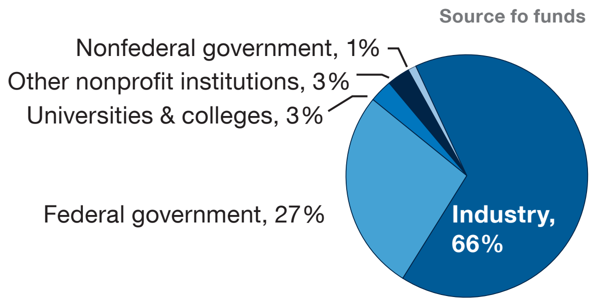
The statistical data published by the National Science Foundation (NSF) provide a good overview of the development of RTD expenditures in the US, clustered according to the type of work (basic research, applied research and development), the performing sector and the source of funds [1].

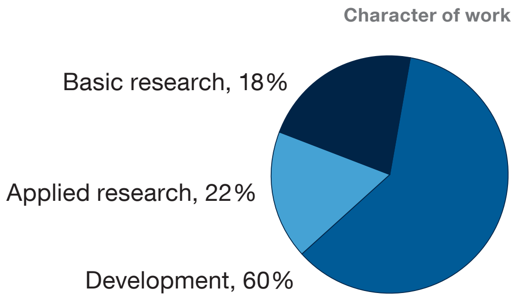
TABLE 2 U.S. R&D expenditures, by character of work, performing sector, and source of funds: 2007 (estimated); Source: [1]

	Source of funds ($ millions)					
Performing sector and character of work	**Total**	**Industry**	**Federal goverment**	**U&C**	**Other nonprofit organizations**	**Total expenditures (% distribution)**
R&D	**368,098**	**245,027**	**98,331**	**13,093**	**11,647**	**100.0**
Industry	265,193	240,743	24,450	*	*	72.0
Industry-administered FFRDCs	4,589	*	4,589	*	*	1.2
Federal government	24,744	0	24,744	0	0	6.7
U&C	48,913	2,799	29,468	13,093	3,553	13.3
U&C- administered FFRDCs	6,076	*	6,076	*	*	1.7
Other nonprofit organizations	15,346	1,485	5,767	*	8,094	4.2
Nonprofit-administered FFRDCs	3,236	*	3,236	*	*	0.9
Percent distribution by source	100.0	66.6	26,7	3.6	3.2	na
Basic research	**64,417**	**10,263**	**38,017**	**9,158**	**6,980**	**100.0**
Industry	8,933	7,480	1,453	*	*	13.9
Industry-administered FFRDCs	2,180	*	2,180	*	*	3.4
Federal government	4,869	0	4,869	0	0	7.6
U&C	36,801	1,958	23,199	9,158	2,485	57.1
U&C- administered FFRDCs	1,997	*	1,997	*	*	3.1
Other nonprofit organizations	8,260	824	2,941	*	4,494	12.8
Nonprofit-administered FFRDCs	1,379	*	1,379	*	*	2.1
Percent distribution by source	100.0	15.9	59.0	14.2	10.8	na
Applied research	**81,211**	**49,603**	**25,455**	**3,226**	**2,927**	**100.0**
Industry	54,713	48,537	6,177	*	*	67.4
Industry-administered FFRDCs	1,414	*	1,414	*	*	1.7
Federal government	7,839	0	7,839	0	0	9.7
U&C	10,102	690	5,310	3,226	875	12.4
U&C- administered FFRDCs	1,844	*	1,844		*	2.3
Other nonprofit organizations	4,844	376	2,417	*	2,051	6.0
Nonprofit-administered FFRDCs	454	*	454	*	*	0.6
Percent distribution by source	100.0	61.1	31.3	4.0	3.6	na
Development	**222,470**	**185,162**	**34,859**	**708**	**1,741**	**100.0**
Industry	201,547	184,726	16,820	*	*	90.6
Industry-administered FFRDCs	995	*	995	*	*	0.4
Federal government	12,037	0	12,037	0	0	5.4
U&C	2,010	151	958	708	192	0.9
U&C- administered FFRDCs	2,236	*	2,236	*	*	1.0
Other nonprofit organizations	2,242	284	409	*	1,549	1.0
Nonprofit-administered FFRDCs	1,403	*	1,403	*	*	0.6
Percent distribution by source	100.0	83.2	15.7	0.3	0.8	na

FFRDC= federally funded research and development center; U&C= universities and colleges; na= not applicable; * = small to negligible amout, included as part of the funding provided by other sectors.
NOTES: Some figures for 2007 are estimates or based on incomplete source date and are subject to further revision. Funding for FFRDC performance is chiefly federal, but any nonfederal support is included in the federal figures. State and local government support to industry are included in industry support for industry performance. State and local government support to U&C included in U&C support for U&C performance.







Source: New Estimates of National Research and Development Expenditures Show 5.8% Growth in 2007 (http://www. nsf.gov/statistics/infbrief/nsf08317/)

3.1. Research programs relevant to robotics

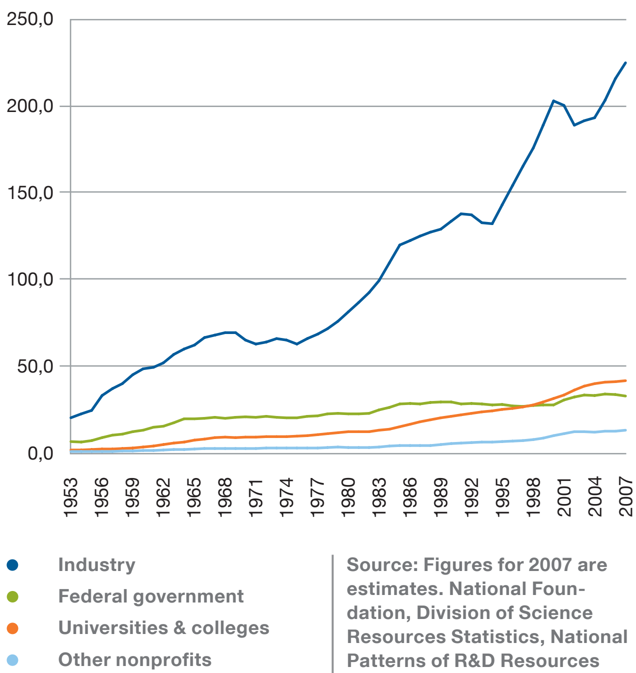
The U.S. R&D system shows a variety of performers and funding sources: the federal government, industry, universities and colleges, other government and nonprofit organizations. Organizations that perform R&D often receive outside funding, and some organizations fund R&D even though they do not perform the research they fund.

The statistics show that industry is the most important provider of research funds. Industry is mainly focused on encouraging development, followed by applied research. Their contribution to basic research is minimal. Both development and applied science are mainly performed by industry itself. Basic research funds mainly stem from the federal government and are allocated to universities and colleges. The funds provided by the federal government are more or less equally distributed among basic research, applied research and development. Universities invest little in development, but focus on basic research and applied research.

Federal R&D performers include federal agencies and federally funded research and development centers.

As the following diagram illustrates, the last few decades have seen a marked increase in the share of national R&D performed by universities and colleges. The analysis identifies the continuing, far larger, real-dollar expansion in R&D expenditures by industry as "the most striking long run trend".

FIGURE 2. U.S: R&D expenditures, by performer 1953- 2007; (200 constant $ billions)



Source: Figures for 2007 are estimates. National Foundation, Division of Science Resources Statistics, National Patterns of R&D Resources (annual series)

Taking a look at the total picture, the period between 1997 and 2007 was quite stable. The basic research fraction ranged from 15.6% to 19%, applied science from 18.5% to 23.4% and development from 57.8% to 63.9%. Universities and colleges were the predominant performer (57.1%) of basic research in 2007, with the federal government providing the largest share (59.0%) of the funding. Industry performed nearly two-thirds (67.4%) of applied research—and was also by far the largest funder (61.1%). Industry was even more predominant in development, where it performed the vast majority (90.6%) and also provided the largest fraction (83.2%) of the nation‘s development expenditures in 2007.

EU-funding in robotics has a clear focus on strengthening small and medium-sized companies as the backbone of the European economy. North America also wants to exploit the untapped innovation potential of SMEs and has developed specific funding schemes for this purpose (see on the left side).

3.2. Funding Schemes for SMEs

There are two funding schemes to do this: the "Small Business Research Grants (SBIR)" and the "Small Business Technology Transfer Program (STTR)". The ultimate goal is to use federal R&D in order to increase private sector commercialization of technology and to therefore support SMEs in creating a market for their innovative products and services.

There are two major differences between SBIR and STTR [2]:

- SBIR Program: the principal investigator must be primarily employed at the small business at the time of the award and for the duration of the project period, while under the STTR Program, primary employment is not stipulated.
- STTR Program: requires research partners at universities and other non-profit research institutions to have a formal collaborative relationship with the small business in question. The small business has to perform at least 40% of the STTR research project, while at least 30% of the work is to be conducted by the single, "partnering" research institution.

The requirement applicable to STTR Programs have not been made a "sine qua non" in the ECHORD project, but mixed consortia made up of academic research labs and potential industrial users resulting in a stable collaboration which could last even beyond ECHORD's funding period are at least one objective of the ECHORD project.

SBIR-type funding schemes have not yet been implemented by EC-funding for industrial R&D in robotics, but it is on the "Horizon 2020" (FP8), which will promote pre-commercial procurement (PCP) in order to strengthen the industrial base of robotics in Europe.

3.2.1. Small Business Research Grants (SBIR)

The creation of the Small Business Innovation Research program by the U.S. Congress in 1982 was a reaction to America's loss of competitiveness in global markets. Congress committed each federal agency to allocate approximately 4% of its annual budget to fund these R&D activities [3].

Based on this regulation, federal agencies with extramural research and development budgets exceeding $100 million are obliged to run SBIR programs by investing an annual set-aside of 2.6% (FY2012) for small companies to conduct innovative research or research and development (R/R&D) that has potential for commercialization and public benefit. Currently, eleven Federal agencies participate in the SBIR program: the Departments of Health and Human Services (DHHS), Agriculture (USDA), Commerce (DOC), Defense (DOD), Education (DoED), Energy (DOE), Homeland Security (DHS), and Transportation (DOT); the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF).

To date, over $16 billion have been awarded by the SBIR program to various small businesses. The objectives of the SBIR Program include:

- Using small businesses to stimulate technological innovation
- Strengthening the role of small business in meeting Federal R/R&D needs
- Increasing private sector commercialization of innovations developed through Federal SBIR R&D
- Increasing small business participation in Federal R/R&D
- Encouraging participation by socially and economically disadvantaged small business concerns and women-owned business concerns in the SBIR program

As mentioned above, Horizon 2020 will initiate a similar initiative for Europe, the so-called PCP (pre-commercial procurement), to facilitate the commercialization of innovative robotics products and services from SMEs which are of interest to the public sector. As for connections with the PCP initiative, new business opportunities for robotics and a fairly huge market potential can be seen in the following areas:

- Health & medicine
- Agriculture
- Cleaning
- Nuclear dismantling and maybe nuclear upgrade
- Construction of buildings and infrastructure

3.2.2. Small Business Technology Transfer Program (STTR)

STTR is the second largest program geared to small business [4]. The goal is to expand the public/private sector partnership by opening the door for joint venture opportunities for small business and the nation's premier nonprofit research institutions, which are instrumental in developing high-tech innovations, but frequently confine innovation to the theoretical. STTR strives to combine entrepreneurial skills and high-tech research efforts. The technologies and products are transferred from the laboratory to the marketplace. The small business profits from the commercialization, which, in turn, stimulates the U.S. economy.

STTR consist of two phases: The first phase is the "proof of concept", the second phase is the application development. Again, Europe is likely to take a similar step for robotics in Horizon 2020. However, the structure of the robotics manufacturers in Europe – dominated by small companies which lack the financial resources for heavy investments – is a challenge. Trying to strengthen the role of SMEs – anywhere – is based on the perception that SMEs are where innovation and innovators thrive. But the risk and expense of conducting serious R&D efforts can be beyond the means of many small businesses.

3.3. Major funding agencies in the US

The majority of the labs visited during ECHORD's North American lab tour cited cooperation with the funding agencies briefly described below.

3.3.1. National Science Foundation (NSF)

The National Science Foundation (NSF) is an independent organization of the US government, financially supporting science in all fields apart from medicine [5]. On an annual basis, the foundation received about 40.000 proposals, of which about 10.000 are selected for funding. With an annual budget of about $6.8 billion (FY 2011), the NSF accounts for approximately 20 percent of all federally supported basic research conducted by America's colleges and universities. In many fields, such as mathematics, computer science and the social sciences, NSF is the major source of federal backing.

In 2011, the NSF spent $635.10 million for the subprogram Computer & Information Science & Engineering (non-defense programs) [6]. This amount was split up as follows:

- Computing & Communication Foundations $175.77
- Information and Intelligent Systems $168.74
- Computer & Network Systems $209.84
- Information Technology Research $80.74

3.3.2. Defense Advanced Research Projects Agency (DARPA)

The Defense Advanced Research Projects Agency, short DARPA, (established in 1958 as ARPA) is the funding agency of the US Ministry of defense. DARPA supports multi-disciplinary approaches in both basic research and applied research. DARPA's scientific investigations embrace the full span from laboratory efforts to the creation of full-scale technology demonstrations in the following fields: biology, medicine, computer science, chemistry, physics, engineering, mathematics, material sciences, social sciences, neurosciences and more. The most successful and well-known project of the agency is certainly the Arpanet, which was the origin of the internet.

DARPA funding has changed in recent years. Instead of concentrating purely on military application, the agency is now turning to more long-term research. DARPA has its own research labs and major projects, such as the 5 year program RCTA (Robotics Collaborative Technology Alliance) [7]. The purpose of this program is to enable the creation of future highly autonomous unmanned systems and permit those systems to effectively conduct military operations in mixed environments.

3.3.3. Air Force Office of Scientific research (AFORS)

Air Force research Lab (AFRL) is responsible for all the research activities in the US Air Force [8]. The Air Force Office of Scientific Research (AFOSR) manages the entire basic research program of the Air Force. The European Office of Aerospace Research and Development (EOARD), London, UK, is a detachment of AFOSR.

The mission of AFOSR is to support basic science that profoundly impacts the future Air Force. Their programs are intended to:

- Support graduate education,
- Encourage development of research excellence in critical technological areas where research facilities and qualified researchers are lacking,
- Train personnel to conduct high-quality research,
- Stimulate mutual research interests between the Air Force and institutions of higher education.

The AFORS is an example for the fact that education can be a powerful enabler of knowledge transfer from theory into practice [9]. Another example of this is Willow Garage, which was one of the hosting companies of ECHORD's North American lab tour.

3.3.4. University Research Initiative (URI) Programs

This is a funding program explicitly geared to supporting research initiatives of American universities undertaken to solve problems critical to national defense. The purpose of URI is to enhance universities' capabilities to perform basic science and engineering research and related education in science and engineering areas critical to national defense.

3.3.5. Other funding sources and initiatives relevant to US robotics

These funding initiatives were discussed extensively during ECHORD's tour:

The National Robotics Initiative [45] is to accelerate the development and use of robots in the United States that work beside, or cooperatively with, people. This program will address the entire life cycle from fundamental research and development to industry manufacturing and deployment. The NRI was established in conjunction with the Advanced Manufacturing Partnership [51].

Similar to the Strategic Research Agenda developed by EURON, the Computing Community Consortium [46] has developed a roadmap for robotics for the United States. USA has a strong record of research in defense related robotics with leadership for unmanned aerial and ground vehicles. In comparison the standing of R&D on non-military applications is less impressive. Both for industrial/manufacturing and service applications the fields are dominated by efforts in Europe, Asia and Australia. Consequently, there is a need to carefully consider how the USA can ensure availability of non-military technologies in a 5 to 15 year perspective. Through a grant from NSF, the Computing Community Consortium has approved a study to formulate a targeted R&D roadmap for robotics.

3.3.6. Differences between US, EU and Asia

While in Europe and Asia, especially Japan and Korea, significant amounts of funding have been and are being invested in all areas of robotics technology, the US investment outside of military applications remains very small. Accordingly, the U.S. currently leads in such areas as robot navigation in outdoor environments, robot architectures, and in applications to space, defense and underwater systems. However, very few programs have been established in the commercial, healthcare, and industrial sectors. In contrast to the US, Korea and Japan have national strategic initiatives in robotics. The European community massively invests through Europe-wide programs (e.g. FP7). Europe also has significant programs in eldercare and home service robotics. Japan and Korea have programs for robot mobility, humanoid robots, and some aspects of service and personal robots (including entertainment).

The differences in the funding policy between North America and Europe is confirmed by the feedback to the online questionnaire stating that none of the visited experts was aware of any project similar to ECHORD in the US. Interviews with experts during the tour confirmed that the funding schemes of the EC are perceived as very beneficial and effective, potentially leading to successful entrepreneurship. Horizon 2020 will probably see a reinforcement of those funding instruments which have a long tradition in the US, namely the STTR and SBIR-like programs.

Irrespective of the differences in the funding schemes between the US and Europe to promote progress in robotics research, both – industrial as well as academic labs in North America – tackle the research foci and scenarios which very similar to those addressed by ECHORD. Remarkably, the only exception may be the "cognitive factory" which will be in the centre of EU-funding for the remaining runtime of FP7.

Via the ECHORD project, the EU Commission is promoting the use of standardized hardware. During the exchange of views, many academic experts visited in North America revealed a strong interest to use standard hardware in their university's labs as well. Academic labs, though, have special requirements the hardware has to meet. These requirements include accessibility of interfaces and the possibility to modify the controller. In addition, the openness of companies to react to these "customization" requirements (and to reveal confidential information to a certain extent) is a must in the cooperation between industry and academia in the US.

The "CCC Roadmap for U.S. robotics" identifies several markets where early commercial solutions are appearing and where service robotics is likely to have the greatest impact ("low-hanging fruits") [12]. Among the areas identified are healthcare, national infrastructure and resource management, energy and the environment, security, transportation and logistics, and education and entertainment. The state-of-the art in these fields as well as their opportunities for the future are described in further detail in the next section of this report.

There is a clear link between the new opportunities for robotics and the aging population, which is one of the key drivers of robotics development. The demographic development (which is even more severe in Japan than in the US) is beneficial to the robotics development in two ways: (i) the need to address a shrinking work force (here professional service robotics can serve as a workforce multiplier for increased economic growth), (ii) the opportunity to develop solutions that will meet healthcare needs (addressed by domestic service robotics), which is expected to enable sustained personal autonomy. Increasing productivity and reducing costs are identified as the common denominator of service robotics by the CCC roadmap.

The impact of funding schemes on research foci is illustrated by Rodney Brooks [13], who has been accredited a leading role to the US in deploying service robotics. He receives fierce competition from Japan and Korea in these fields. The strengthening of these two countries – along with Taiwan – can be attributed to the fact that the domination of the service robotics industry has been established as key national goals.

Service robotics is also regarded as a very promising field by the European Commission. There is no comparable national program to FP7 in the US. Robotics research has largely been funded by the Department of Defense and NASA. Brooks states that the former is now more focused on military applications, while the latter has little room for extramural research. This trend goes at the expense of service robotics (domestic as well as industrial), which plays a key role in strengthening the competitiveness of the US in manufacturing areas where it has been lost to Asian players. While US floor cleaning robots are relatively well known, there are significant new markets for robotics emerging in healthcare (prostheses, surgery, and hospital operations), fulfillment centers, and agriculture.

There was a strong impression among the EU-experts during the tour that Europe is better at fostering industry-academia collaboration and they consider EU-funding a big enabler to make this happen.

Sources: [10, 11]

3.4. State-of-the-art

Robots were traditionally used in constructed environments requiring little sensoring. When taking a look at the state of the art in US robotics, it is important to note that this development still has an impact today, as manufacturing robots are still only used in industries (see [13]) where the overhead of building the necessary special environments can be absorbed, i.e. factories that produce very expensive objects (automobiles or silicon wafers), or to high-volume manufacturers with low product diversification (such as disposable medical devices).

Since the 1970's, the target of extending robot capabilities to unstructured environments (for instance navigation or – later on – ground robots in the US military for forward scouting and IED remediation) has been in the focus of research. The DARPA Urban Challenges 2005 and 2007 have produced a huge progress in autonomous navigation. Concurrently, the first service robots have become common, with several million autonomous cleaning robots deployed in ordinary US households. Also in Europe, sales are increasing [14].

The findings of literature research as well as the statements of experts visited and interviewed during the lab tour suggest that certain areas of research and application are highly attractive for robotics nowadays. The opportunities for growth in robotics described below are a cross-section of the topics tackled in the professional literature. The reflections on the current situation and outlook of robotics in the US are entirely market-driven. Therefore the approach – and the clustering – is different from the Strategic Research Agenda for European robotics which combines a market-pull strategy (resulting in the identification of 5 sectors and 6 application scenarios) with a technology-push strategy (analyzing technologies to define the opportunities they offer) [15].

3.4.1. Manufacturing

The US has the strongest manufacturing sector in the world with stable productivity increases higher than those of the IT industry. At the same time labor-intensive manufacturing has gone offshore. Thus, labor-intensive manufacturing would have been a high-impact target for expanding the use of robots, but has not been tackled, as robots are restricted to structured environments. Robotics in high-volume areas (for instance automotive) has a long tradition, but the US no longer has a significant market share in these areas. This development – together with the fact that robotics "has not fully embraced the IT revolution and has very little in the way of flexible computation and perception" prevents innovation. As the affluence of low-cost labor is not indefinite, the US will need more intelligent robots for manufacturing.

Interviews during the lab tour confirmed the statement that – as manufacturing went out of North America and Canada – only automation can change this and must be a strong research focus for the future.

3.4.2. Military, Defense and Homeland Security

Thanks to large funding investments by the DoD and NASA, the US currently leads the world in military robotic applications. Especially research on increasingly autonomous unmanned ground and air vehicles is very active in the US. This is one reason why the US investment in robotics outside of the defense area is very small.

Sources: [12, 13]

3.4.3. Robotic Vehicles

The US is generally acknowledged as the world leader in military applications of robot vehicles. Search and rescue robots and underwater robot vehicles are also very active research areas. Again, US investments strongly emphasize the development of vehicles with military applications, and the US leadership in robotic vehicles is dependent upon DOD and NASA spending. The translation of vehicle capabilities to innovation and commercial applications proves to be difficult under these circumstances. The main trend in this area is the increase of autonomy for robotic vehicles. Remote operation by human users is gradually being replaced by supervisory control of autonomous operations. Future challenge areas with need for further research are, amongst others, power, propulsion, computation, control, sensors, and navigation.

Sources: [10, 16, 17]

3.4.4. Medicine and Healthcare

Robotics in medicine and healthcare is another increasingly active field. Especially robot-assisted surgery and assistive robotics aimed at the elderly and other special-needs populations are fields in which the US is currently leading. However, activity is rapidly increasing in other countries.

In addition to surgery and assistance, other application areas are expected to have significant impact in the future, for example the replacement of limbs though robot prosthetics. Also behavioral therapy, for example for autistic patients, seems to have a lot of potential.

In order to tap the potential, a number of technological and research challenges will have to be met, e.g. intuitive human-robot interaction and interfaces, automated understanding of human behavior, automated understanding emotional and physiological state, long term adaptation to user's changing needs, quantitative diagnosis and assessment, context-appropriate guidance, image-guided intervention, high dexterity manipulation at any scale, sensor based automated health data acquisition, safe robot behavior

Sources: [12, 16, 17]

3.4.5. Humanoid Robots

Humanoid robots, especially for service and assistance, are a continuing field of research. Currently Japan is the most active country in this field, but the US lead in certain research sub-areas, such as algorithm development for limb control, upper-body applications, dexterous manipulation, grasping, and eye-hand-coordination skills. However, humanoid robotics research also faces a number of challenges: design, packaging and power, bipedal walking, wheeled lower bodies, dexterous limbs, mobile manipulation, human–robot Interaction

Sources: [10, 16, 17]

3.4.6. Service Robots

A field that is closely connected, even overlapping with medicine, healthcare, and humanoid robotics, is the area of service robots.

Service robotics can be subdivided in two aspects: professional and domestic service robotics – as outlined by the SRA (Strategic Research Agenda). Professional service robotics includes agriculture, emergency response, pipelines and the national infrastructure, forestry, transportation, professional cleaning, and various other disciplines. Principal markets and drivers in professional service robotics are energy environment, manufacturing logistics, homeland security, and infrastructure protection. Personal service robots on the other hand, assist people in their daily lives in their homes or help them compensate for mental and physical limitations. Here, principal markets and drivers are healthcare, quality of life, entertainment education, automotive, and transportation.

Scientific and technical challenges the field of service robotics will have to face in the future include:

- Mobility (e.g. outdoor, 3D-navigation)
- Manipulation (perception, tactile sensing, grasping) and physical interaction with the real world
- Planning (e.g. dynamic path planning)
- Perception and sensing (also for unstructured environments)
- HRI (e.g. intuitive user interfaces), and safety for operation near humans
- Networks of robots, sensors, and users

Sources: [10, 12, 16, 17]

3.4.7. Networked Robots

Networked robots have a variety of application possibilities. In the US, numerous research facilities focus on military applications, e.g. networked unmanned vehicles or the coordination of a space shuttle, human operators on earth, the astronaut, and the shuttle arm. Japan has a bigger monetary investment in networked robots than the US, and Japan and EU seem to be slightly ahead in terms of research on sensors and perception.

Sources: [10, 16, 17]

3.4.8. Space Robotics

A vast and active application field, especially in the US, is space robotics. There has been a drop in investment in space robotics, but in the US, more funds are still being invested than in Europe or Asia. Major research issues in space robotics include: control in the presence of large time delays, mobility, navigation and vision on remote planets (extreme environments), manipulation and autonomous operation. Future work is expected to lead to planetary robots that operate autonomously for days on end, and robots that can construct and assemble other space hardware and equipment while in space.

Sources: [12, 16, 17]

3.5. Upcoming trends

In Europe as well as in the US, experts are committed to working out roadmaps to address current and future needs in order to streamline the RTD efforts in robotics. For Europe one key document – the Strategic Research Agenda (SRA) [15] – has been elaborated by the "European Robotics Technology Platform" (EUROP). Prominent examples for roadmaps in the US are the "Roadmap for US Robotics from Internet to Robotics" [12] and the "FY2009–2034 Unmanned Systems Integrated Roadmap in manufacturing" [18]. The EU-experts see the following areas gaining importance in the near future ("low-hanging fruits"):

- Distribution (e.g. automated fulfillment centers)
- Agriculture
- Sensor networks in the environment (distributed robotic systems interaction as collective system)
- Micro- and nano robotics (robots for micro and nano manipulation, nanoscopically and microscopically small robots).

The participants of the "CCC Workshop" [12] identified several markets where these early commercial solutions are appearing and where service robotics is likely to have the greatest impact. The areas identified are:

- Healthcare: robotics technology has enormous potential to help minimize costs, aid and assist healthcare workers, and enable aging citizens to remain longer in their homes, living as independent adults
- Energy and environment: is ripe for the emergence of robotics technology applications, especially in energy and monitoring the environment.
- Manufacturing & Logistics: robotics technology promises to transform small scale, or "micro", manufacturing operations and in the process promote the transition of manufacturing back to America.
- Automotive and transportation: advanced driver assistance, collision avoidance systems, and public transportation areas that are expected to become increasingly automated. Unmanned transportation systems and solutions developed for limited scale environments, such as airports, will be adapted for implementation in urban centers and other general purpose environments (see DARPA Urban Challenge 2005 & 2007 [19]).
- Mining: we can see impact on both the underground and surface mining industries.
- Homeland and infrastructure protection: applications in border protection, search and rescue, port inspection and security, and other related areas as well as in the automation of the inspection, maintenance, and safeguarding of our nation's bridges, highways, water and sewer systems, energy pipelines and facilities, and other critical areas of infrastructure.
- Entertainment & education: especially as product "enabler". In particular, robotics has the potential to significantly address the science, technology, engineering, and math ("STEM") crisis facing the US.

The capability to tap the potential of robotics technology and to expand the fields of application will depend on the ability to meet the key challenges and to develop the key capabilities robots need in order to address the motivating scenarios for the future. "While certain critical capabilities and underlying technologies were domain-specific, the synthesis effort identified certain critical capabilities that were common across the board, including robust 3D perception, planning and navigation, human like dexterous manipulation, intuitive human-robot interaction, and safe robot behavior " [12, p. 2]. It was agreed that the technology has sufficiently progressed to enable an increasing number of limited scale and/or semi-autonomous solutions that are pragmatic, affordable, and provide real value.

While the challenge of achieving fully autonomous solutions in the long run remains primarily technological, the challenge in the short term is how to best "cross the chasm"; it is one of identifying the right value propositions, driving down costs, developing efficient, effective systems engineering processes, determining how to best integrate such solutions into current or adapted processes, and otherwise addressing the know-how gap of transitioning technology into products.

Additional sources: [13, 16, 17]

3.6. Differences between the US, Canada and Europe

All respondents to the tour questionnaire – irrespective of whether they are located at industrial or academic labs - stated differences between the US / Canada and Europe. The industrial respondents underlined that European research was more focused on Cognitive Systems and that competitions were more prevalent in Europe than in the U.S. The interviewees from academic institutions stated that US research is more dominated by defense / military applications (due to the funding which flows into research) while service robotics is more of an afterthought. This might be changing now. Apart from the fact that the US has developed a roadmap specifically for service robotics, there is also an upcoming ISO standard for service robotics [20, 21].

The goals of fundamental research are similar for Europe and North America. The respondents confirm that there is a more coordinated, top-down structure for Europe and Asia than for the U.S.

All parties involved see a strong interdependence between funding and application development. In Europe, there is more funding for HRI and Cognitive Systems at present, but the situation might change with the National Robotics Initiative in the U.S. While the EC supports large projects, with long-term, speculative, open objectives under FP7, Canada and the US focus more on short-term projects.

Taking a look at the information about funding schemes for SMEs in the US – SBIT and STTR – and combining those with the statement above, the result suggests that HORIZON 2020 has been significantly influenced by what the Americans have done in the past – while the US researchers envy Europe for the funding they get. According to the American experts the robotics industry in Europe (with the financial support provided by the existing FP programs) is perceived as innovative and growing. More and more startup companies in Europe are doing innovative work. The market is set to expand, particularly if a low cost upper body or humanoid platform can be developed.

When asked about the developments that enhance the competitiveness in the US market, the industry mentioned proliferation of good software (e.g. Willow

Garage's "ROS") for building robot applications as a boon, while academia underlined the importance of computing platforms, sensors and actuators. Both industry and academia however, agree that making robots useful to people in their everyday lives is the major contribution robotics can make to solve major societal challenges. Robotics must deliver results to keep funding coming in. Academia stresses the importance of industry standards for robots and software.

3.7. Robotics and Education in North America

Clearly, "[the] awareness of the potential synergies between technology transfer and education is not new" [22]. There are several synergies between educators, industry and researchers:

- Educators aspire to educate with relevance to industry and provide students with competitive advantages through valued skills and knowledge.
- Industry relies on an adequate supply of eager graduates who are well prepared to meet the challenges of software development in a globally competitive marketplace.
- Researchers use the educational environment as a micro-laboratory, observing software development behaviors, developing new technologies, using students as study subjects, and validating technologies on student projects before their deployment in industry.

Several case studies since the late 80's illustrate the development and the efforts universities made to increase their technology transfer with respect to education in engineering faculties in order to enhance their own competence and strength in the end. Although these case studies show that everyone benefits from education-industry collaborations, in most cases it is industry that gains the most [23]. Examples are:

University of Maine [24]: In the late 80's the Department of Electrical Engineering at the University of Maine started a student-project with the MITRE Corporation in Bedford, MA with a course for over 15 years. Junior as well as senior students got the opportunity to work in the company, to develop their own prototypes and to write reports about it.

CMU [25]: Carnegie Mellon University in Pittsburgh started an experiment in 1990 where undergraduate students were used to transfer academic know-how on software technology to the semiconductor industry in a two-week internship. The basic idea behind the project was the observation that very little university-developed software gets used in industry because engineers are just too busy to try it out. Although the students were actually able to establish strong ties to some of the participating companies, there was no follow-up by the university.

University of Texas [26]: two programs over a period of six years were started at the University of Texas which also received funding by the Semiconductor Research Corporation, SEMATECH, the Texas Advanced Technology Program and grants from industry.

Kettering University [27]: there was strong industry-university collaboration started at GMI Engineering & Management Institute. Students were supposed to write a thesis on a project relevant to an industrial sponsor. The students alternated between school and their respective workplace. The faculty provided collateral seminars and allowed inexperienced faculty members to spend time in industry. While the faculty prepared scientific papers and seminars, integrating the hand-on-knowledge in the classroom, the industrial partners were able to incorporate the latest technological developments and testing methods.

Dakota State University [28]: Start-up Program for Undergraduate at Dakota State University in collaboration with the Lake Area Improvement Corporation. This program helps promising students to set up and run a technology venture by funding them and providing a supportive infrastructure. The cost per venture is very low, and the program aids in discovering promising students.

The positive impact of interlacing education and industry in the technology sector has long been recognized but yet it seems that attempts to close the still existing gap between industry and universities by enhancing undergraduate students to transfer state-of-the-art know-how to industry remains inadequate. An effort with a broader impact must still be made.

As the individual lab reports illustrate, Willow Garage demonstrates in a very impressive way that students as interns are the main medium for innovation and knowledge transfer in both directions.

Nevertheless, the emerging trend is to encourage and to support senior students to get to know industrial environments and even to begin their own start-up (see more under point 3.8 of this report). Engineering and entrepreneurship converge more and more into entrepreneurial engineering, "defined as the development and transfer of technology into commercially viable products and services with sustainable competitive advantage in the global marketplace" [29]. Successful knowledge and technology transfer require proactive and persistent interaction by both the university and the company. Both have to understand each other's needs, capabilities and limitations, and develop a bond of mutual confidence.

3.8. Technology Transfer, IP handling and Start-Ups

When it comes to harvesting the financial benefits of any innovative idea, there are mainly six different approaches to bring it to the market:

- To sell the idea or concept outright
- To sign a licensing agreement and to participate in the success of a product,
- To sign a cooperation treaty,
- To outsource the development, production and marketing of the product,
- To realize all steps connected with developing and marketing the products alone (and maybe protect the idea by a patent) or
- Hybrid models with partially adding value on your own.

While the robotics industry in the US naturally uses all six models, US universities protect their scientific findings by patents, facilitate the creation of spin-offs in order to realize and market the product/service or sign licensing agreements with other partners. The Bayh Dole Act (1980) enabled universities to market the results of publicly funded scientific research. Prior to the adoption of this law, it was nearly impossible for companies to gain exclusive rights of patents owned by the government. Thus, companies only had a limited motivation to place further investments into turning relatively simple research approaches into marketable products or services. Due to the Bayh-Dole Act, more than 200 universities are nowadays involved in technology transfer. And this regulation inspired a lot of European countries to take similar steps. [30]

The results since then have been remarkable: new technologies and industries appeared, often as a direct result from university patents; new products based on university licensed discoveries came on the market and scientific studies became a significant factor of earning one's living in the US. One reason for the success of academia-industry cooperation is that they allow both sides to benefit from the synergic effects and use their respective strengths to a maximum extent.

A very innovative approach to efficiently transferring knowledge from an industrial company into a wide range of different applications was created by Willow Garage, a fully privately funded company. By offering all software solutions as open source, they might have developed a successful new venture capital model which could be adopted by organizations beyond the US.

Apart from Open Source Software there is a novel concept of also offering hardware as open source. This can be regarded as a promising step. Currently there are only few examples for open hardware. The benefit may be tremendous since hardware is needed in robotics and this increases the failure chances of many projects. Open source mitigates the risk and reduces the costs. The ECHORD project demonstrates that there is a demand for standardized hardware to be used also in university labs. Open source hardware would be a step in the right direction.

The counterpart to Willow Garage is NASA JPL, who is working with a closed environment and very careful with collaborations, but this is a special case that cannot be generalized.

3.8.1. Technology Transfer between academia and industry

One important aspect when discussing the pros and cons of industry-academia collaboration and – on a larger scale – technology transfer between them is the lack of a method to properly measure and evaluate the impact of science on society. Godin and Doré [31, p. 13] point out that "the measurement of impact is actually at the stage where the measurement of R&D was in the early 1960s: data has to be collected from scratch".

This aspect has also had an impact on public funding. As Cozzens [32, p. 101] argues: "The majority of the [measurement effort] has studied the process of innovation and not its outcomes. Traditional innovation studies still focus narrowly on making new things in new ways rather than on whether the new things are necessary or desirable, let alone their consequences for jobs and wages".

Prototypes, publications and patents were identified by the experts we visited in the US as being the most appropriate indicators to measure the success of knowledge transfer between academia and industry. For academic labs the number of former students working in the industry after their studies is another indicator of importance. In addition they ask for experiments to analyze the capabilities of production robots and extending their use to novel applications.

The feedback of the labs on the tour on their modes of collaboration between partners from industry and university was heterogeneous. The majority of the industrial as well as academic labs confirm that academia-industry collaboration is desirable. The attempt to figure out a line in the answers, the collaboration between industrial and academic labs mainly concentrates on the experimental end, for idea creation and prototype generation. Industry claims that researchers should be more user-focused. Naturally, for university labs the collaboration with industrial partners offers the opportunity to work with experienced engineering teams (which reduces the amount of infrastructure that academics have to develop) and is a good way for students to gain experience. Partnerships with the public sector lead to industrial partnerships (again, this is a tool which the EC is likely to strengthen in Horizon 2020, too).

The following obstacles of academia-industry collaboration were identified:
By industrial representatives:
- Misalignment of incentives
- Industry wants to push research results into the real world, while academia wants to publish papers

By academic representatives:
- Coming to an agreement about our respective roles
- Intellectual property
- Contracts
- Matching of timelines
- Industry has short-term goals, while academia is working on the long-term gain (tension between basic research and the quickest path to product)
- Difference in goals

When asked for the most important issues when collaborating with industrial/academic partners, the following aspects were raised:
By industrial representatives:
- Try to ensure that the result of the collaboration is made manifest (publicly available code)
- Aim for more than just a co-authored paper

Academic representatives see a potential for technology transfer and commercialization of their results, but industrial partners have to better understand the true benefit of collaborating with research: academics have to be “grounded”, but also think many years into the future with big ideas and should not try to develop something new for the next manufacturing iteration.

Synergy in resources and expertise was raised by both. Academia is typically good at approaching ill-defined research problems, while industry is typically strong at efficiently implementing and mass-producing solutions. For academia, working with industrial partners can provide access to hardware support and applications that motivate the basic research, guiding academic research to more relevant directions. Relevance of the research for government and society is another aspect that is valued by both parts.

In order to make academia-industry collaboration a success story a written agreement of how to handle IP is mandatory (IP sharing agreement). Industry should approach academic labs for problems, which do not have straightforward solutions, while academics typically require close collaboration with the industry to produce results that are good for the market.

The following routes of knowledge transfer are considered most efficient:

- Presentations and free dissemination
- Research collaborations and joint projects based on public funding
- Ventures and Spin-offs
- Exchange of personnel

On the other hand, sale of services, data and software to universities is not considered to be a successful instrument for facilitating knowledge transfer between academia and industry.

In order to increase the degree of knowledge transfer from academia to industrially relevant applications, industry as well as academia recommended expanding research collaborations by increasing the number of publicly funded joint projects. In addition to this, academia is seeking more assistance for technology spin-offs.

3.8.2. IP Handling and Patents

The question of whether Intellectual Property Rights (IPRs) and patents are conducive or obstructive to innovation is a subject of great controversy. The "opposite" of IPR are open source products – and the field in which the two advice credos collide, the most is in the area of software development.

The defenders of IPRs argue that innovation gains pace if inventors disclose their inventions quickly, in order "to prevent other firms from spending on duplicate R&D and to minimize the time used for advanced research. Simultaneously the government awards the assignee the exclusive right to use, make, and sell the technology during a limited time" [33].

The defenders of open source software (OSS) are convinced that software patents and even copyrights are a barrier for technology improvement [33]. All code should be open for using, modifying and sharing. Some OSS-utilities proved evidence by helping advance the fast development of the internet. There are studies confirming that OSS is more important in the software industry than traditionally acknowledged. Moreover, there is the economic point of view which states that the open-source market is a classic example of a competitive market and hence provides the best requirements for constant and fair improvement [34]. The OSS market is rapidly growing and so-called OSSg2 (Second Generation Open Source Software) firms have popped up. These companies are mostly a hybrid between corporate distribution and sponsored OSS and provide professional open source software [35].

An example of OSS in robotics is the CLARAty (Coupled-LAyer Architecture for Robotic Autonomy) project, initiated by various institutions in the US. CLARAty is a robotic software framework that enables different participants the leveraging of robotic software – taking into account that without sharing software across institutions, invented capabilities could be lost only because of the fact that the innovation tool takes place in another research institution [36].

There are no studies yet on how IPR will affect science in the future. A majority of the experts visited are concerned about this development but without considering the possibility of reciprocal effects on industry-driven research. Though there have been meetings on different models of openness and their relationship to existing features of IPR law and institutionalized scientific practice, questions about where IP rights lines exactly should be drawn are still open.

Even though OSS is a special case, some observations can be transferred to robotics in general.

ECHORD's lab tour to North America showed that even universities which currently own patents doubt the relevance of this instrument. Despite this uncertainty about the real value of IPRs to innovation, Bessen et al. [37] state that there has been a global trend toward stronger intellectual property rights (IPR) over the past (then) twenty years.

Irrespective of this gain in IP momentum, Kortum [38] observes a steady and ubiquitous decline of the patent-R&D ratio in the United States over a period of three decades (from an investment of one million 1982-dollars for three patents in the late 1950's to down to one patent in the 1980's). This phenomenon can be observed across industries and across countries. According to his opinion there are three main reasons for this development:

- The exhaustion of technological opportunities has reduced the productivity of the research sector [39 and 49, in: 38].
- The expansion of markets has raised the value of patents and the competition within research has resulted in higher investments per patent.
- The rising costs of handling the patent system prevent some researchers from patenting their innovations.

Although some of the American Ivy League Universities (like the University of California or Stanford University) were very active in marketing their scientific findings even before the Bayh-Dole Act was adopted, it is a non-disputed fact that the Bayh-Dole Act has been a strong driving force behind this development, also provoking a strong debate about the impact IPRs & patents have on science.

Royalties do, of course, contribute to the financial resources of an organization. There are several modi to finance a research institution: basic funding by public sources or university, financing by donation (in the US a lot more common than in Europe), third party funding (public or cooperation with industry, some of which are publicly supported).

Some observers refer to these new industry-academia cooperation schemes - as 'Academic Capitalism and Marketization' and 'Academic Entrepreneurship'.

On the other hand, the analysis of Cohen et al. [41] suggests that the impact of patents on knowledge transfer is overestimated. They claim publications, conferences, informal exchange of experiences and consulting to be the main channels of knowledge transfer.

The experts visited during the tour stated that the majority of the industry-driven publications come from Europe.

Schibany et al. [42] suggest for Austria that highly skilled human capital and personal contacts build the paths of knowledge transfer, which are the most valuable instruments for companies.

This reflection is strongly confirmed by some of the experts visited during the ECHORD lab tour.

Schibany et al. [30] demonstrate that US universities can be extremely successful in generating royalties without issuing a high number of patents. Sometimes it is just luck that counts. Florida State University probably gives the most prominent example. The university holds a relatively limited number of patents, but nevertheless occupies one of the national top ranks when it comes to the generation of royalties, since the semi-synthetic production of a pharmaceutical agent paved the way for a very prosperous cooperation with a strong industrial partner.

It is important to note that patents are not evenly spread throughout the US academic research community. As an average, about 50% of all patents owned by academic institutions are in the hands of the 25 top-ranked American universities, while the 100 top-ranked account for about 80% of all patents.

The North American lab tour revealed major differences between the patentability of scientific research between North America and Europe. While Europe only allows for patents of technical solutions, algorithms and ideas are patentable in the US. This wider scope and more liberal approach naturally results in a higher number of patent applications and issues.

3.8.3. Start-Ups

Spin-offs play a very important role in marketing academic research and transferring scientific results into added value. Normally spin-offs are technology-orientated foundations, which face a high level of uncertainty. Out of 50 spin-offs of the MIT between 1980 and 1996, only 17 successfully launched a product or carried out a clinical test. Therefore, it is extremely important to make end users part of the technological development.

The ECHORD lab tour revealed that there is a huge difference in the success rate of start-ups based on pure software engineering and those based on the commercialization of hardware. The reasons are: hardware development requires significant financial investments; debugging is time-consuming and expensive; dependence on suppliers and lead times. In addition to this, hardware requires maintenance and a long-term commitment (for instance, supply of spare parts) which is risky. Compared to Google, Facebook, etc. who have low fixed costs, robotics is much more difficult. Furthermore, hardware often carries the obligation to meet standards and obtain certification.

The research institutions that are specialized in service robots as well as young start-up companies in this area are confronted with various obstacles. On the one hand there needs to be a stronger network between research, development, production and sales (business models) and on the other hand binding, obligatory requirements are missing (standardization). One of the hindrances for universities in creating spin-offs in the US is the fact that professors cannot become company managers. This is different in Europe. Therefore, the preferred model of knowledge transfer for academia may be to create patents and license innovative products/services to the industry instead of founding a spin-off.

For Canada, though, Greg Dudek at McGill University stated that there is a surprisingly large number of small companies in Canada.

A unique way of supporting academic spin-offs is the University of Waterloo model [47]. Researchers retain the rights to their development, but universities still support them to issue a patent. The payback for the university often consists of donations from their alumni and can then start a successful, long-term collaboration.

4. Individual Lab Reports

4.1. Stanford Biomimetics and Dexterous Manipulation Lab

4.1.1. Research topics

The current research includes the following topics:

- Advanced materials
- Tactile sensing
- Tactile displays
- Bio-inspired robots

The current areas of research are motivated by the following factors:

- Curiosity
- "Bottom-up vision" (in contrast to many other university labs which start with a big scene as vision)

The lab sees the following areas as future trends:

- Actuation as mid-term research challenge
- Reasonable computation power, e.g. on small air vehicles
- Use of sensing technology in mass markets, e.g. touch-screens or smart-phone components
- Integration of hands and tactile sensors
- Perception as success factor for future applications, especially robustness in perception
- Future systems will combine light-weight structures and compliant components

4.1.2. Results and innovation

Scientific/technological outcome

The lab is characterized by an attitude, which focuses on bottom up research of bio-inspired solutions rooted in mechanics and materials science advancement. The lab's current research is based on a number of focused researches on the applications of advanced materials, tactile sensing and bio-inspired solutions. As challenges for mid-term research, they see actuation and the availability of a reasonable computation power (weight and power consumption, e.g. on small air vehicles). They are developing sensing technology with some interesting early results, with an expectation for mass-market application of new applications similar to touch-screen or innovative smart phone applications.

The adorable robot Asimo and the tour group

More specifically, in robotics three short-middle term trends are envisioned: 1) the integration of hands and tactile sensors 2) robust perception as a pivotal success factor for applications 3) light weight structures and compliant components.

During the lab visit, the ECHORD expert saw a number of interesting prototype systems: a bio-inspired gecko, bio-inspired bird claws, and an interesting haptic device technology (patent request filed).

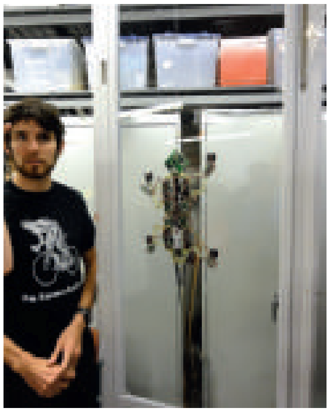
Business models

The lab seems clearly oriented to stimulate bottom up, highly individualized research leveraging on mechanics insight and materials. The main driver of 'business' seems to be the side effect of excellence and reputation among the peers coming from pursuing 'real research'. They patent novel and potentially wide applicability results like the quoted haptic sensors.

4.1.3. Funding modes and statements regarding funding

The lab funds mainly come from DARPA (seen as shifting from short-middle term military application oriented research to long-term basic research) and from industry (company funding going 'up and down'). They have high hopes for the National Research Initiative, which was launched by the US government in 2011. They cooperate with some European companies: a Norwegian oil company, Tekes, Nokia, Volvo, etc. In the US they have/had projects with Meka and Willow Garage. DARPA and government agencies provide 'continuity'.

DARPA has its own research labs and big projects: The 5 year program RCTA (Robotics Collaborative Technology Alliance), such projects usually involving CMU, Stanford,



Boy, that's a big house fly!
No – it's a robot! The Gecko
as it climbs up a glass surface

other first tier universities and companies. The IRCCL program it is also worth mentioning.

More in detail, funding originates from various sources linked to the military: AFOSR, ARL (MAST), the already quoted DARPA (DSO), then DraperLabs, various NSF branches (RI, CMMI, CISE, CPS, MRSEC), ONR. They cooperate with the DARPA initiative on manufacturing.

4.1.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

Cooperation with industry is structured in an ECHORD-like manner based on specific problem solving targeted by small-middle sized projects. They have or had co-operations with a Norwegian oil company, Tekes, Nokia, Volvo, Meka, Willow Garage and others. In academia, they have ongoing cooperation activities with Wyss Institute (Harvard) for Biologically Inspired Engineering and the Harvard Microrobotics lab. The diverse project topics are, for example, small ToF sensors for UAV. In particular, they mentioned the optical flow sensor on RobotBee prototypes (Centeye).

Commercial activities

The commercial activities are 'case by case', based on scientific excellence and reputation, and very engineering oriented. As mentioned before, they seek and find targeted application projects dealing with scientific issues in an ECHORD-like manner. The lab cooperates with a Norwegian oil company, Tekes, Nokia, Volvo, Meka, and Willow Garage.

In this perspective, it is interesting to see where they see opportunities and challenges. They believe that semi-autonomous cars could be a driver and a market that could push robotics research. Another opportunity lies in the fact that sensing has become smaller, lighter and cheaper. On the other hand, light weight arms are still far from human arms and muscles, and they see difficulties in the systematic exploitation between mass producers (e.g. phone chips) and robotic start-ups for the advancements in tactile sensors.

Spin-offs

We were not made aware of significant spin-off activities (although we see some significant potential, in particular in haptics and sticking systems).

IP handling

They patent results that they deem as novel and that show a potential for commercial application. No objections have been raised against current patent regulations.

4.1.5. Education

The model they pursue is the traditional way of preparing highly knowledgeable, open-minded students by involving them in intellectually demanding research.

4.1.6. Statements by the people visited

'Compared with Google, Facebook, etc., which have no fixed costs, robotics is much harder, also with respect to the curve of absorption of capital during the startup phase.'

4.2. Stanford Artificial Intelligence Lab – Robotics

4.2.1. Research topics

The current research includes the following topics:

- Whole body operational space control for humanoid robots
- Reconstruction of the human motion atlas
- Development of novel actuation systems, notably pneumatic muscle actuation
- Detailed controllable biomechanical simulations of human musculoskeletal models
- Software for controlling robots and haptic devices
- Tele-operation of robots using haptic devices
- Multi robot control: controlling groups of (humanoid) robots to navigate across obstacles in real-time detailed physics-based simulations of robots

The current areas of research are motivated by the following factors:

- Long term humanoid research
- Compliant human inspired underactuated future humanoids
- Human-friendly and human-centered humanoids

The lab sees the following areas as future trends:

- Force controlled humanoid robot platform
- Tactile and vision sensors for robots
- Sensor fusion software
- Software standards for robot programming interfaces
- Manipulation ability for humanoids
- Solving the discrepancy between safety and performance

The expert group in Stanford

4.2.2. Results and innovation

Scientific/technological outcome
Among the many interesting results are the developments (in cooperation with Honda) on the ASIMO humanoid platform. The results related to the control of anthropomorphic human body models and pneumatic muscle driven robots are very interesting.

Other applications are focused on motion control, ball-throwing into bins, or anticipative motion control for robots fighting with a sword against humans.

They chase a unified mobility and manipulation framework for multi-contact manipulation. The aim is to understand why humans move, not to reproduce individual movements, in order to be able to generate motions from criteria, not from a pre-described trajectory (human strategy: along the lines of maximum acceleration). One goal is to achieve a “sitting Asimo”.

Business models
The business model of the lab is clearly based on pursuing excellence in research and clear ‘vision’ as a way to attract sponsors and applied research partners.

The cooperation work with industry is seen as an important way to foster research, too.

Another relevant success factor is considered the integration with business schools. Moreover, academic teams are typically good at approaching ill-defined research problems, while industrial teams are typically good at efficiently implementing and mass-producing solutions. The close cooperation with industrial companies has another advantage: experienced engineering teams, which reduce the amount of infrastructure that academics have to develop.

4.2.3. Funding modes and statements regarding funding

The funding comes mainly from industry or business (95%). This reflects the huge impact of commercial activity. This may come from the ‘brand value’ of Stanford and of Khatib. Another reason might be the openness and correct evaluation of the role of research in driving business revenues in the US business environment. Companies include GM, Sony, Honda (12 year funding!), Boeing, and also European companies, such as Kuka, Siemens, Yaskawa, and Hansen Medical.

The remaining 5% of funding comes mainly from NSF. NSF funds are often integrated by in-kind contributions from companies (35-40% for HW from companies).

4.2.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

The funding structure naturally leads to close cooperation in applied research projects with business partners, which provide 95% of the funds. While most cooperation is done with industrial partners, the work on biomechanics is done with other academics.

This tight cooperation leads to a large amount of technology transfer due to the direct interaction of the sponsoring industries. On the other hand, this has not generated successful spin-offs so far.

Commercial activities

As mentioned above, excellence in research and clear ‘vision’, as well as the ‘brand value’, attract sponsors and applied research partners.

Spin-offs

So far, there haven’t been many in robotics - as said above, the technology transfer is huge, but in the form of knowledge transfer to the established corporate partners in the form of research. The general model, as it is common in the US and especially in California, is based on long standing relationship with partners, university sponsors, alumni, VC/PE. Up to now, there have been no significant spin-offs.

IP handling

The lab follows the standard approach of patenting what seems useful for applications (e.g. the haptic interface for virtual reality). They aren’t asking for changes in current IP policies and regulations.

4.2.5. Education

They have extremely motivated students, they strongly pursue the connection with business schools (as opposed to with highbrow basic academic research) and they value and practice a strong collaboration between AI and engineering departments.

4.2.6. Statements by the people visited

‘We have the platforms, but we have no safety, no deployment’.

Safety is deemed as necessary in robotics.

4.2.7. Additional comments

The lab has a clear, long-term vision heading toward the exploitation of compliance and bio-inspired underactuation in humanoid robotics. Moreover, it benefits from the outstanding contribution of O. Khatib.

Oussama Khatib’s lab

4.3. Willow Garage

4.3.1. Research topics

The company's current research includes the following topics:

- Hardware and open source software for personal robotics applications
- Open source Robotics Operating System (ROS). ROS initiative as de-facto standard.
- Focus on home robotics

These current areas of research are motivated by the following factors:

- Creation of / enabling a large base of service robotics applications (supposed to create a big market)
- Studying what users want a robot to perform at home

The lab sees the following areas as future trends:

- Software will play a paramount role and will lead to advantage
- Reduction of wiring, cables as biggest challenge for long term reliability
- Home automation
- Interested in Planning Library

4.3.2. Results and innovation

Scientific/technological outcome

The Personal Robot PR2 is the most prominent outcome. It is sold to companies and research institutions. Willow garage also develops robotic hardware that is released as 'open-source' in the sense that their full technical specification and design can be freely obtained. The TurtleBot is one example. Their hardware is still being produced with a huge amount of manual labor. They see the reduction of wiring and cables as the biggest challenge for long-term reliability.

The group in front of the Willow Garage

Business models

Despite being an industrial lab, Willow Garage has an "academic" mindset. The goal of the company is to first generate impact in the robotics market and secondly to generate a return on capital. More specifically, the aim is to enable a large base of service robotics applications (which are not open source) that should create a market of sufficient size. The company sees the long term potential to become a Tier 1 supplier to the robotics industry. Eleven PR2s were issued for free to research organizations to support co-development and encourage market development.

In other words, the company's aim is to initiate a robotics market based on standardized programming schemes.

4.3.3. Funding modes and statements regarding funding

In terms of funding, Willow garage relies on the financial support of a portfolio of private investors. There is, however, also a small amount of public funding.

4.3.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

Willow Garage's policy is dictated by the open source concept. And exactly this is their attitude towards cooperation. The company is generally open to cooperating with anyone who is interested and acts as a small-scale funder of appropriate research. Currently, most of the cooperation is with universities and public sector institutions, in order to comply with the openness paradigm, but also to limit the cost. The company is also looking for strategic alliances with universities.

The PR2 program led to close contacts and an (open) user feedback. In this program, 10 international universities received a PR2 robot for free, based on evaluation of their proposals.

There are few contacts with industrial companies with emphasize on local industry that evaluates prototypes.

Willow Garage has collaborates with Google. Furthermore, as they see sensing as crucial, they also cooperate with Motoman on putting ROS in industrial robots.

Commercial activities

Willow Garage operates as an independent research lab, which is not market-driven and with few direct commercial activities. The company does not intend to become

Prof. Knoll and Henrik Schunk and a Fraunhofer CareOBot with Schunk arms

a mass product company, so does not need to establish customer support. The only commercially available product is the PR2, of which 30 units were built. Ten are in the company, ten have been given away, and ten have been offered for a sales price of $400k. A 30% discount is available to teams with a track record. This strategy paves the way for spin-off companies that commercialize outcomes of Willow Garage's development. One example is the Turtlebot robot 8 open hardware development with free BSD hardware license. It costs $1500 and 400 units have already been sold.

Spin-offs

The first spin-off is Suitable Technologies, which developed a telepresence platform based on Willow Garage's Texai project. Twenty-five prototypes have been built to date.

IP handling

The company has a transparent IP policy; everyone can have completely open (BSD), or partially open (GPL) licenses. Before starting a project, the objectives are clarified and how to handle intellectual property is stated in a written agreement. It is aimed at creating an open relationship during and after the conclusion of projects.

The ROS system is completely open so to allow for additional ROS distributions and thus to initiate active participation in its development. The TurtleBot design is open, allowing for highly flexible usage. Furthermore, Willow Garage has equity in exchange for IP related to Suitable Technologies.

4.3.5. Education

Students yield the main influx of innovation and are the principal medium for knowledge transfer. Willow Garage is very attractive for students due to its reputation as robotics software "think-tank".

4.3.6. Statements by the people visited

One strategy is to team up with robotics start-ups.

There is no clear view on when the mass robotics market will develop. Currently there is a slow adoption rate.

4.3.7. Additional comments

All in all, Willow Garage is very unique as a privately funded company without a dedicated commercial ambition. It exhibits a special case of Silicon Valley culture in that it combines an open research environment with sufficient unconditional funding. On the other hand, it is certainly a long-term investment.

In order for a service robot to be successful in a home environment, special attention must be paid to all aspects of its design, from functionality to aesthetics and user interaction. Willow Garage works with professional industrial designers from the early stages of developing new hardware.

As with any product, robots must be designed to survive for an appropriate length of time in the target environment. To take the PR2 as an example, a goal was set of 2–3 years of operation before a significant repair is required. An estimate was made of how and how often the robot would be used in a research lab environment, and then tests were designed to simulate 2–3 years of that usage pattern.

Willow Garage takes testing very seriously, in both hardware and software. The PR2 was tested extensively during its design, and new PR2s are thoroughly tested before shipping. On the software side, support is provided to easily integrate standard testing tools and to see reports on tests. Unit tests and regression tests are the norm in the ROS code base, and even some graduate students are following the pattern by developing tests for their own code.

ROS comprises a large variety of libraries and tools, many of which evolve independently. While it is possible to manually pick a collection of versions of these modules, it would be difficult and time-consuming to do so in a way that ensures compatibility and correct functionality. So instead a new ROS release is made every six months, with the goal of providing a standard “platform” to which the entire community can refer when writing new code. This release model was inspired by Ubuntu, which performs a similar function for Linux by bundling particular versions of tools and libraries.

4.4. Bosch - Technology and Research Centre

4.4.1. Research topics

The current research includes the following topics:

- ASIC design and MEMS technology
- Energy conversion and energy storage technologies, modeling simulation and controls
- Wireless Technologies
- Software and Internet Technologies
- Algorithms for Robotics, Autonomous Systems and Data Mining
- User Interaction Technologies

The current areas of research in robotics are motivated by the following factors:

- Existing gaps
  - Affordable manipulation
  - Long-term autonomy and dependability
  - Quality of software and metrics (static analysis vs. functional analysis)
  - Safety

The lab sees the following areas as future trends for robotics:

- Personal robots
- Navigation
- Affordable manipulation
- Standardization of software
- Software quality measures
- Publication of metrics to encourage academia to write better code
- Sensor expertise for robotics applications
- Shared autonomy (autonomous vs. tele-operated, shared autonomy / human in the loop)
- Long term: autonomy, robustness, dependability

4.4.2. Results and innovation

Scientific/technological outcome

Bosch's robotics research work is part of the Corporate Research effort and has a mid to long-term aim to establish Bosch as a Tier 1 supplier for the emerging service robotics industry. They collaborate strongly with both Willow Garage and Stanford University. Their current research themes are the application of sensors (particularly low cost ones from other major application areas such as automotive), sharing of hardware resources over the internet to facilitate a remote robot laboratory and the general robustness of robot systems, with particular emphasis on humans in the loop and shared autonomy.

Business models

Bosch has the mid to long-term business aspiration of becoming a Tier 1 supplier for robot manufacturers, which fits the role they undertake in other markets, such as automotive. As such their long term niche will be in the supply of sensor and actuator systems, maybe going as far as small sub-systems. They are also investigating the possibility of putting aspects of autonomy into current (non-robotic) product lines. There is currently no dedicated business unit for robotics, nor is there any short term return on investment imperative. However, they are open to other opportunities presenting themselves to the Company as the market develops. Robert Bosch Venture Capital is involved in Aethon, a company providing logistics robots for hospitals and care institutions.

Jan Becker discussing the role of Bosch in service robotics market of the future

4.4.3. Funding modes and statements regarding funding

Bosch Corporate Research is corporately funded. The lab is open to collaborative research (collaborations on-going with Ken Salisbury at Stanford on safe manipulation, and with Willow Garage on open source software) but these are for strategic technology reasons. Bosch is also open to the potential for providing venture capital investment for robotic start-ups.

4.4.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

Bosch undertakes collaboration on the basis of strategic technology decisions. The lab sees the need for ROS (Willow Garage's Robot Operating Software) to be put into a foundation to secure its independence and future and to provide confidence to the robotics community. Bosch has had discussions about this and would like to collaborate with others in securing the future of ROS. They interact with the community through the PR2 remote lab. Bosch collaborated with Stanford University in the 2007 DARPA Urban Challenge, and then founded the robotics group in 2007.

Bosch is the only industrial lab which received a Willow Garage's PR2 Robot (here getting ready to set a table) through the PR2 Beta program

Commercial activities

The research lab does not pursue any direct commercialization of its work. Commercialization is undertaken by business units and there is not a dedicated robotics business unit today. However, there are activities looking at the possibility of commercialising aspects of autonomy through its incorporation in existing products. They are specialized in high volume, but are now also active in custom developments with Bosch Engineering GmbH.

Their short-term vision includes Bosch products influenced by robotics (i.e. evolution of existing product portfolio towards robotics technologies/autonomous systems). In the mid-term they want to become, just like in the car-industry, the largest components provider for robotics. There is, however, need for a developed value chain.

Spin-offs

Robert Bosch Venture Capital currently has a $5m stake in Aethon, a Pittsburgh based company specializing in robotic hospital delivery systems. Although this corporate venturing route is regarded as a possibility, generally commercialisation will be through the development of product lines within Bosch.

IP handling

As a private lab, all IP of internal developments is held by Bosch. No mention was made of how IP in collaborative projects was handled. They are however keen on open source software as a key enabler for building a strong robotics industry, e.g. in the context of PR2 activities.

4.4.5. Education

Bosch actively seeks collaborations with universities in the form of strategic technology alliances and sees this as a key resource for encouraging its own innovation.

4.4.6. Statements by the people visited

- Affordable navigation exists (e.g. Neato vacuum cleaner).
- Key roadblocks are affordable manipulation, achieving long term and dependable autonomy, the lack of an identified pipeline from academia to industry in robotics and the lack of metrics.
- Guaranteed safety will be the key to opening the domestic marketplace for robots.
- Personal robots may be like the “next car”.
- You should publish papers and software code. This should be encouraged.
- The quality of code and corresponding documentation from academia can often be improved.

4.4.7. Additional comments

Bosch has a clear market orientation in their objectives and has a mid to long-term agenda. In terms of robot systems, Bosch was the only organisation with a clear view of the position within the value chain they wished to occupy.

4.5. University of Southern California

4.5.1. Research Topics

The labs' current research includes the following topics:

- Robotic Embedded Systems Lab (RESL) (Gaurav Sukhatme)
  - » Robot networks and large-scale, distributed, robotic systems
  - » Strong application focus on environmental robotics, particularly aquatic environmental monitoring
  - » Optimization and planning for ocean surveillance (e.g., coordination of multiple robots and sensor networks bloom tracking) based on ocean dynamics models
  - » Focus on estimation, sensing and planning, with some work in control with real-time requirements under communication constraints
  - » Additional topics: Perception for manipulation, manipulation-aided perception, and estimation of physiological parameters using mobile sensing
  - » Fleet: PR2 and 12 Naos (shared with Interaction Lab and CLMC), Sarcos Humanoid (shared with Interaction Lab and CLMC Lab, through NSF Major Research Infrastructure grant), UGVs (Segways, Creates and Pioneers), USVs (Q-boats) and AUVs (Slocum gliders and Ecomapper)
- Computational Learning and Motor Control (CLMC) Lab (Stefan Schaal)
  - » Autonomous systems research
  - » Statistical Learning
  - » Reinforcement Learning
  - » Imitation Learning
  - » Motor Primitives
  - » Nonlinear Control

University of Southern California

Gaurav Sukhatme and George Bekey during a lab visit

- » Humanoid Robotics
- » Legged Locomotion
- » Computational Neuroscience for motor control
- » Planning, self-organization, life-long learning
- » Adaptation and learning through HRI
- » Participation in DARPA ARM-S competition, among the two top performing teams who received continued funding
- » Bottom-up research approach, bootstrap intelligence by e.g. learning, increasingly 3D perception learning
- » Fleet: 12 Naos (shared with Interaction Lab and RESL), Hubo humanoid (Korea) through NSF Major Equipment Grant, Sarcos Humanoid (shared with Interaction Lab and RESL, through NSF Major Research Infrastructure Grant), 2 Barrett WAM Arm/Hand systems for bimanual manipulation, one Sarcos Master-Slave Arm System, one Sarcos Active Vision Head, PR2 (shared with Interaction Lab and Robotics and Embedded Systems Lab)

- ▪ The Interaction Lab (Maja Mataric)
  - » Socially assistive robotics
  - » Human-robot interaction (HRI)
  - » Human-robot team interaction
  - » Human activity modeling
  - » Imitation learning and teaching
  - » Therapeutic and educational uses of socially assistive robots
  - » Multi-modal interaction
  - » Pre-clinical and clinical studies are used to demonstrate evidence of the effectiveness of the developed methods and systems with real-world user populations (stroke patients, Alzheimer's patients, elderly users, children with autism spectrum disorders, and others)
  - » Objective assessment of acceptability and effectiveness of socially assistive robotics for health interventions
  - » Long-term user modeling and adaptation
  - » Studies of embodiment, embodied communication, and influencing interaction dynamics and human behavior change toward improving human health and performance
  - » Fleet: 12 Naos (shared with CLMC Lab and RESL), Sarcos Humanoid (shared with CLMC Lab and RESL, through NSF Major Research Infrastructure grant), PR2 (shared with Interaction Lab and Robotics and Embedded Systems Lab), 6 custom-designed mobile humanoids (Bandits) used for HRI studies, Giraff tele-presence and autonomous platform, Sparky Minimatronic Figure courtesy of Walt Disney Imagineering Research and Development, ESRA II head from Robodyssey Systems LLC, 2 Sony AIbo dogs

Applicable work has been done, but the labs' main interest is a. to create intellectual work, and b. to graduate thought leaders who will have long-term impact. According to their approach, the work needs to stay academic, but there are industrial contacts to transition the research out of the lab. The labs' current areas of research are motivated by the following factors:

- ▪ Main motivations: Fundamental questions and social problems outside robotics:
- ▪ Science (e.g., how does the brain work, how do we change human behavior?)

Alois Knoll and Henrik Schunk in Stefan Schaal's lab looking at the DARPA ARM-S set-up

- Health (e.g., how to monitor behavior & design intervention for people with special health needs)
- Environment (e.g., how are the world's oceans changing due to anthropogenic impact?)
- Robotic Embedded Systems Lab
  - Environmental Surveillance (one of the big challenges in environmental monitoring is staying under water for long periods of time, e.g., 100 days) and 'googling' the planet.
- Computational Learning and Motor Control Lab
  - Understand neural computation, i.e., how neuroscience can help technical domains, and how technical science can enable new insights and methods in neuro and clinical sciences. "The back and forth between technology and brain science can be very productive."
- The Interaction Lab
  - Developing socially assistive robotics methods (specifically assistive non-contact human-robot interaction) for monitoring, coaching, training, and rehabilitation. Validating with real-world populations and problems, including the elderly, stroke patients, children with autism spectrum disorders, Alzheimer's patients, etc. Research focused on understanding human behavior and influencing it toward therapeutic goals (recovery, rehabilitation, training, improved performance).
  - "There are large and growing populations that need care, and there is already a shortage of doctors and nurses. This gap in care will only get worse. Intelligent personalized socially assistive robots can help to fill this gap by aiding human care but not replacing it."

The labs see the following areas as future trends (Robotics seen in a wider sense):

- Robotic Embedded Systems Lab
  - Sensorizing the natural environment (a planet scale Google for the physical world)
  - Using robotics to gather reliable data for public policy (especially environmental policy)
  - Closing perception, action loops where the sensing is engineered (e.g., on phones) but the actuation is human – a new world of mobile sensing
- Computational Learning and Motor Control Lab
  - Biological substrates (Not machines anymore)
  - Bio-hybrid systems (Mechanical systems do not always scale, and are not very robust)
  - Coming up: 3D perception and see-and-act-and-see.
  - Interactive robotics, integration of tactile and vision sensing
  - Probing the world through sensing
  - Perception-action-learning. Usable perception is active perception.
  - Finding learning methods for closed loop, from nano- to macroscopic to biosynthetic
  - Biggest challenge: Learning in perception-action loops, automatic bootstrapping of supporting representations (associative skill memories)
- The Interaction Lab
  - Robot therapy for autism: Many (not all) children as well as adolescents with autism respond more socially to robots than to people; this opens up an avenue for therapy and training social behaviors. With autism rates being 1 in 100 children in the US, there is a shortage of resources for diagnosis and therapy.

» Aging society: Complementary to service robots that perform physical labor, socially assistive robots that do not do physical work but provide so

The "Robot Exercise Instructor" at Maja Mataric's lab interacting with a human.

cial and emotional support, and reduce isolation and depression. Mataric's lab has shown that the elderly, including those with Alzheimer's, respond very positively to socially assistive robots, and consistently prefer them to computers.

» Rehabilitation for stroke patients and related motor disorders (Parkinson's, traumatic brain injury, etc.): 1.6M strokes are expected per year in the US in about a decade. There is already a shortage of nurses and there is a need for in-home rehabilitation. Mataric's work has shown that robot therapists motivate stroke patients; there is great potential for these systems for in-clinic and in-home use.

4.5.2. Results and innovation

Scientific/technological outcome

The Robotic Embedded Systems lab works mainly on decision making and planning algorithms for robot networks and large-scale distributed robotic systems. Application foci include environmental monitoring, urban security, and military reconnaissance. This includes research on the cooperation of mobile robots and sensor networks as teams, with a focus on underwater vehicles. The fact that the individual robots are extremely expensive puts a lot of responsibility on the shoulders of the PhD students. The lab also works on algorithms for perception and calibration for robots such as the PR2.

The Computational Learning and Motor Control Lab focuses on neural networks/statistical learning, dynamic movement generation, the investigation of human performance, and humanoid robotics. Their probabilistic reinforcement learning approach generates unparalleled, robust and fast learning. Research employs a large number of different robot platforms (e.g. Sarcos, PR2, various robot arms and hands). The lab participates in various challenges, e.g. the "Little dog" challenge, and the DARPA Manipulation Challenge (together with Robotic Embedded Systems Lab), and ended up the top ranked team in both of these challenges.

The Interaction Lab focuses on socially assistive robotics, which involves three major dimensions of basic research: 1) embodiment: the role of the robot's embodiment, its use in communication and engagement, and its power relative to alternatives (computers, PDAs, smart phones, etc.); 2) influencing social dynamics: how the robot can use its embodiment and communication strategies to influence the user's behavior effectively; and

3) long-term adaptation: unlike current machine learning approaches, which focus on converging on a particular policy/learning a particular function, socially assistive robots must adapt to the user as the user's behavior changes even during a single interaction session (due to mood swings, fatigue, familiarity), and more so over weeks, months, and even years (due to long-term familiarity, recovery, deterioration, aging, etc.); this is a new area of embodied and situated machine learning. These research dimensions are not independent and methods developed in the Interaction Lab span multiple dimensions. The methods include learning through interaction, imitation, and demonstration, modeling social properties and dynamics such as personality and dominance, and using controlled user studies with different embodiments and user populations.

Business models

The USC labs all focus on basic research, motivated by major societal challenges (health, the environment, etc.). At this time, their primary focus is not on starting companies. However, some interesting opportunities are at hand which the individual PIs and their students are pursuing.

4.5.3. Funding modes and statements regarding funding

The main funding sources are NSF, ONR, NIH, NOAA, NASA, and DARPA. The labs are strongly focused on academic research, and there is little funding from companies. In general, industry funding is welcomed, but only if it supports the intellectual challenges for the PhDs, postdocs and faculty.

The Computational Learning and Motor Control Lab receive its funding mostly through NSF and DARPA. There has been also major funding from Japan, mostly through JST/ERATO and the ATR Computational Neuroscience Labs, but funding has recently shift away to more US-based sources.

The Interaction Lab is funded by NSF, ONR, NIDRR, Robert Wood Johnson Foundation, several other foundations, and small-scale industry partnerships on grants from the Department of Defense and NIH.

The Robotic Embedded Systems Lab's underwater work is funded by ONR, NOAA (National Oceanic and Atmospheric Administration), and NSF. The remaining projects in the lab are funded by NASA and DARPA.

All the USC robotics labs are active and founding partners in NRI (the National Robotics Initiative). All three PIs (Mataric, Schaal, Sukhatme) participated in the NRI development and Mataric is one of the senior team that authored the US Robotics Roadmap on which the NRI is based.

4.5.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

The USC labs are all well connected to other university groups (e.g., Daniela Rus at MIT, Vijay Kumar at UPenn, Manuela Veloso at CMU, Brian Scasselleti at Yale, Cynthia Breazeal at MIT), oceanographic institutes, and medical clinics. Since their focus is on academic research, they do not cooperate with industry to a large extent. There used to be a formal cooperation with Intel, which ceased when Intel shut down their robotics activities.

Commercial activities
For the better part, the focus is on basic research and so there are no general cooperation modes. If there are cooperations, the cooperation mode is decided case by case.

Spin-offs
The USC Stevens Institute is the commercialization gateway for the university as a whole. Individual PIs and students are currently pursuing some commercial spinoffs via this route. Maja Mataric' has received a USC Stevens grant (from the competitive Ideas Empowered program) to explore commercializing her technologies related to stroke rehabilitation. USC is also the home of the first awarded Alfred Mann Institute (AMI), which facilitates research commercialization. AMI has reached out to Maja Mataric' and they are starting to discuss potential avenues for commercializing health-related developments from the Interaction Lab.

IP handling
Because of the focus on basic research, IP is not a core issue. Most software in the labs is done in ROS, which is free public domain software intended to further code sharing and thereby facilitate research. IP issues, when they arise in dealing with industry, are handled via the USC Stevens Institute.

4.5.5. Education

There is a connection to the Interact program at KIT (Karlsruhe, Germany), an exchange network for students. According to Gaurav Sukhatme (Robotic Embedded Systems Lab), there has been a change in the past 20 years: PhD students are no longer solely interested in theoretical work (e.g., algorithms) and just using a robot for a video at the end. Today, the robot and the real application are of interest right from the beginning.

Student training at all levels (undergraduate and PhD) is a major priority of the PIs. Mataric' has placed a large number of students in academia (in the US and in Europe) and in leadership positions in the fledgling US robotics industry (e.g., leading positions at iRobot and Willow Garage).

4.5.6. Statements by the people visited

Stefan Schaal (Computational Learning and Motor Control Lab): "Understanding autonomous robots will require a concerted effort in understanding learning in perception-action loops."

Maja Mataric (Interaction Lab): "Socially Assistive Robotics will play a major role in people's lives starting in a couple of decades, spanning across ages (kids, elderly) and needs (healthy exercise, recovery, rehabilitation, ageing)."

Gaurav Sukhatme (Robotic Embedded Systems Lab): "Robots will provide information in real time about the natural environment, so it will be possible to 'Google' the planet."

4.5.7. Additional comments

There is a strong and growing outreach program to use robots as tools for promoting STEM (Science, Technology, Engineering, and Math) learning in younger students (kindergarten and up). Mataric maintains a pre-university web resource (http://robotics.usc.edu/interaction/k-12/index.html) and also heads the pre-university efforts for the USC Viterbi School of Engineering.

4.6. SynTouch LLC

SynTouchLLC is a spin-off of the Medical Device Development Facility of USC.

4.6.1. Research topics

The current research includes the following topics:

- Focus on sensor hardware
- Provide (finger) sensors to the robotics market

The current areas of research are motivated by the following factors:

- Proof that bio-inspired methods give rise to commercial products

The lab sees the following areas as future trends:

- Applications in areas such as tele-operation, food-handling, medical

4.6.2. Results and innovation

Scientific/technological outcome
SynTouch is a startup founded on the vision to provide sensors to the market. Today, they concentrate on biologically inspired finger sensors for the robotic market. Their solution embeds a contact sensor, which measures pressure, vibrations, and temperature in a robotic finger.

Business models
Their business model is to sell the sensor, (which is based on an invention USC made 4-5 years ago), while providing functionality/algorithms as open source to enable the market. Today, they produce in small quantities, with a price tag of 12,000 $ for one finger kit.

4.6.3. Funding modes and statements regarding funding

In contrast to the EU model, their research is fully executed within the company, including Masters and PhD students. This takes place in collaboration with USC, but enables people to live and learn about the culture of the company while performing research.

The money for the company SBIR comes through different agencies: SME funding from NIH, NFS, DARPA and the US Dept. of Agriculture, including DARPA "revolutionizing prosthetics" funding.

SynTouch has been begun in 2011 to work on two Phase 2 Small Business Innovative Research (SBIR) Grants: one from the NIH for prosthetic hand integration (automated grip adjustment reflexes and conscious tactile feedback) and one from DARPA to develop haptic exploration and object discrimination robots. SynTouch is also building a BioTac interface kit for the Barrett and Shadow Robot hand (see e.g. June 2011 TC on Mobile Manipulation Newsletter, distributed through the robotics-worldwide mailing list [43]).

A SynTouch employee explaining the manufacturing process

4.6.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes
Surprisingly, SynTouch does not work with USC technology transfer office at all. The knowledge transfer takes place by having Master and PhD students working in the company, but collaborating with USC.

The company cooperates with independent academic laboratories, incorporating feedback to improve their product. The university tech transfer center is not considered helpful at all by the company.

Commercial activities
They participate in conferences (IROS San Francisco), and other events to get in touch with researchers who can then buy their touch sensor kits. The software will be open source.

The company also acts as a consultant on bio-mimetic signal processing and control algorithms for haptic tasks.

Spin-offs
They are a spin-off.

IP handling
They mainly work on patenting for the hardware, and open-source for the software.

The Syntouch fingertip sensor

4.6.5. Education

The company collaborates with USC by employing Master and PhD students directly in the company.

4.6.6. Statements by the people visited

“Dexterity depends on rich sensory information from our fingers ... There were no artificial sensors that could provide this information to a mechatronic hand with the sensitivity, dynamic range, and robustness that humans take for granted in their own hands. Until now...” [44].

4.7. NASA – Jet Propulsion Lab

4.7.1. Research topics

The current research includes the following topics:

- Construction and operation of robotic planetary spacecraft
- Earth-orbit and astronomy missions
- CLARAty – open platform for reusable robotic software and module integration
- Approach and instrument placement
- Visual aids for landing
- Operations tools, Microsurgery manipulation
- Rover platforms, e.g. for Driving on Mars
    - » Stereo vision, visual odometry
    - » Navigation, GESTALT (Grid-based Estimation of Surface Traversability Applied to Local Terrain)
    - » Use of CMU's D* algorithm
    - » Mars rover drill demo

The current areas of research are motivated by the following factors:

- Program driven research
- Long-term perspective

The lab sees the following areas as future trends:

- Physics-based simulation
- Advanced mobility systems
- Sampling/handling/caching and dexterous manipulation
- Reusable robotics software architectures
- Steep terrain mobility and anchoring systems
- Robotic airships for planetary and terrestrial use
- Fast vision hardware for fast and power-efficient driving
- Airborne surveillance and 3D terrain reconstruction

Demonstrating rock sample mechanisms for the Mars robot

4.7.2. Results and innovation

Scientific/technological outcome

JPL has a clear focus on the production of high reliability, low volume components and systems for space applications. To achieve this they have a very structured development approach, even extending back to low Technology Readiness levels. The primary focus is on planetary rovers but there is also work on support of landing systems as well as earth orbit and terrestrial applications.

JPL have also developed the CLARAty architecture for robotics which includes capabilities for both teleoperated and autonomous robots. However, while it was planned to put this into the public domain, only 10% has currently been made public and there is no active programme supporting its development and release process.

Autonomy for robots is pursued to the extent that it is needed for mission effectiveness or for non-NASA customer applications.

4.7.3. Funding modes and statements regarding funding

The sky is the limit at JPL

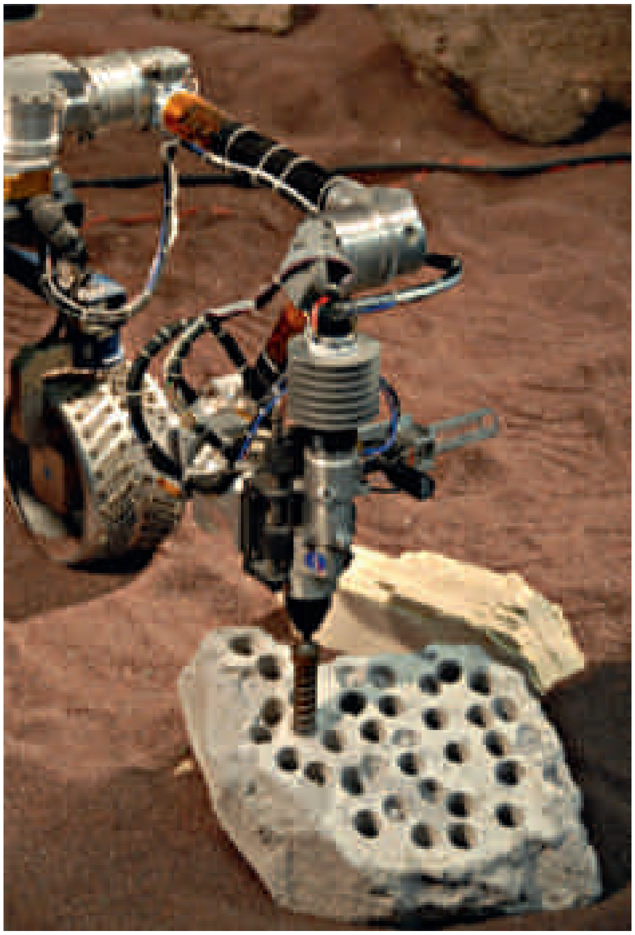
The Jet Propulsion Laboratory (JPL), California Institute of Technology, is a Federally Funded Research and Development Center (FFRDC) with a prime contract to NASA. JPL Robotics is approximately 80% funded by NASA and has a clear focus on space robotics and, in particular, future NASA requirements. The rest of the funds come from the DoD or commercial sources. Research directions are consistent with NASA objectives, which are subject to decadal guidance from the National Academy of Sciences and are primarily driven by future mission objectives. JPL is regarded as NASA's lead centre for science-driven robotic exploration.

4.7.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

JPL does have a responsibility put on it by NASA to make science and research results available to the wider community and to industry. Moreover, NASA and JPL are expected to engage the research community through its various programs. One such example is the Mars Technology Program during the first decade of the new millennium. The competed portion of this program funded universities and other organizations to develop robotic software autonomy. To facilitate the development and integration of capability from disparate organizations, the Mars Technology Program developed the CLARAty reusable robotic software that was open to the participants in the program. A further effort was made to put the CLARAty robotic software architecture in to the public domain to facilitate further collaborations among robotic software developers – however, NASA's funding of this project has ended along with completion of the competed Mars Technology Program.

CLARAty features an object-oriented design with an emphasis on clear interface definition and managing heterogeneity. While 95% of the CLARAty software has been cleared by the U.S. State and Commerce departments, only about 10% of the CLARAty software was



Drilling holes

released in the public domain due to funding constraints. The released portion represents 44 modules of the 450+ total modules. CLARAty has over a million logical lines of software (excluding documentation).

Commercial activities
JPL collaborates with university and industrial partners for research sponsored by NASA and non-NASA programs. JPL is not a commercial entity, but does partner with commercial companies. Additionally, JPL licenses technology it develops.

IP handling
Please contact JPL for details.

4.7.5. Education

JPL robotics has several modes of interaction with education institutions. First, JPL itself is part of a major university, the California Institute of Technology. Many JPL employees also participate in education at Caltech and other nearby universities to teach courses or mentor students. Additionally, throughout the year but particularly in the summer, JPL robotics hosts a large number of students to help with on-going research activities. These students are at all levels of education, from high school to graduate school.

4.7.6. Statements by the people visited

-

4.7.7. Additional comments

The special feature of this lab, which made it stand out from all other labs visited, was the focus on high reliability of low volume systems that entered the thinking and processes very early in the development process. This is driven by the extreme consequences of mission failure.

JPL employs approximately 5,000 people, with approximately 3,000 of these being engineers. Approximately 100 are robotics engineers.

4.8. University of Washington

4.8.1. Research topics

The labs' current research includes the following topics:

- Biorobotics Laboratory (Blake Hannaford)
  - » Surgical robots (Development of reference hardware platform RAVEN for minimally invasive surgery)
  - » Technology improvements, such as motor controller for RAVEN
  - » Haptic interfaces
  - » Tissue testing device
- Robotics and State Estimation Lab (Dieter Fox)
  - » 3D perception and modeling
  - » RGB-D perception
  - » Interactive systems
  - » Scalable object pose tree
  - » Active object learning
  - » Inverse reinforcement learning
  - » Control of imprecise HW (arm), handling of uncertainties
- Sensor Systems Research Group (Joshua R. Smith)
  - » Advanced sensing
  - » Wireless power transmission
  - » Seashell effect pre-touch sensing

The current areas of research are motivated by the following factors:

- Biorobotics Laboratory (Blake Hannaford)
  - » There is a need for another platform for research on robotics surgery, which is cheaper than Da Vinci.

Blake Hannaford in his lab

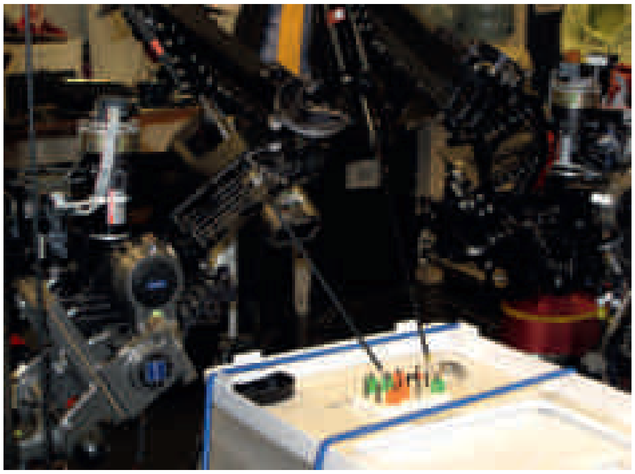
The labs see the following areas as future trends:

- Long-term learning for use in home service robotics.
- Open source software and hardware have a very high impact, but there is not as much money in the market as in social networking. Robotics is more disruptive. There is not yet enough capital available for investment.
- Open source hardware is a novel concept, positive for everybody. However, there are only few examples of open hardware.
- Robotics and State Estimation Lab (Dieter Fox)
  - » Richer representations
  - » Cloud connection of robots (e.g. when sporadic peak performance is needed)
  - » Building and sharing of object models
  - » Not only object class recognition, but rather instance recognition needed in robotics (“Bring me MY mug”)
  - » No need to be as precise in hardware, solution on software side
  - » For quadcopters: The best representation of the environment (e.g. surface, full 3D) is still unclear.
  - » Manipulation with lots of sensors.
  - » Machine learning
  - » Continuously learning, e.g. for robots at home: ML for robots.
  - » Human-robot interaction
  - » Natural language (UW)
- Sensor Systems Research Group (Joshua R. Smith)
  - » Proximity sensors (seashell effect with reference microphone)

4.8.2. Results and innovation

Scientific/technological outcome

The Biorobotics Laboratory pursues cutting edge research in the area of surgical robotics and haptic interfaces. The main achievement is the RAVEN, a surgical robotic manipulator system intended as a reference platform for research on minimally invasive surgery that also has a high market potential. It is intended for the development of software for robotic surgery systems using the open source ROS development platform. Currently, the RAVEN is not planned for use on humans, due to certification requirements. Rather it will be used as a low-cost training platform.



Surgical robot

There is more brain surgery in China than in the rest of the world altogether. RAVEN can be used as an alternative to Da Vinci. Two systems in China are even more comprehensive, but Da Vinci is no longer being purchased in China because it is too expensive.

Another outcome of the lab is the award winning EDGE surgical skills training system, which is open source. It allows the recording of movements and forces of the instruments recorded from exercises.
The lab also developed impressive vision-based force feedback using Kinect, as well as a tissue-testing device. There has also been a lot of research done on equipping grippers with different sensors, based on Stars instruments.

The Sensor Systems Research Group is working on novel sensors and wireless power supply concepts for robotics and medical applications. These include a wireless power supply for heart pumps, a wireless identification and sensing platform, as well as sound-based, pre-touch recognition systems. The Group's specialty is its dedication to application of wireless power transmission systems in various areas.

The Robotics and State Estimation Lab focuses on computing systems interacting with their physical environments. It develops advanced methods for low level estimation, active object and inverse reinforcement learning.

The lab also develops methods for the representation of complex environments and for the handling of uncertainties. These methods are applied to human robot interaction, activity recognition, people tracking, navigation through crowded environments, and the control of parametrically uncertain robots. The lab did experiments with prime sense sensor (Kinect) one year before Kinect came out. Some of the work is related to RoboEarth. Recently, the lab developed techniques for 3D mapping combining both depth and color information from a Kinect depth camera. The approach works robustly without any odometry information and is integrated into an interactive mapping system. Additional research resulted in novel kernel descriptors and feature learning techniques for object recognition based on depth and color, a large-scale RGB-D object dataset, and a scalable, tree-based approach to object class and object instance recognition.

Business models

The Biorobotics Laboratory does not aggressively push their developments on the market. Their most successful implementation is the RAVEN, sales of which have been low so far. Currently, eight RAVEN platforms are being manufactured for use in other academic institutions, funded by the NSF. Other universities, one of which is in Montpellier, France, will purchase three RAVENs. The lab licensed the company Simulab for marketing their EDGE training system. The maturity of the developed systems and level of application focus will allow the lab to increase its commercial activities. However, a long-term business models has not yet been developed.

The Sensor Systems Research Group operates as a classical university lab.

The Robotics and State Estimation Lab carries out basic research that is mainly based on funding from Intel. The lab itself does not market or commercialize their findings.

4.8.3. Funding modes and statements regarding funding

All three labs receive mainly public funding (NSF, SBIR program). The main funding source of the Biorobotics Laboratory is the National Science Foundation. The development of the RAVEN minimally invasive surgical systems has been largely financed by NSF. Furthermore, NSF paid for the development of eight RAVEN systems. The lab also capitalizes on the use of open source software and hardware, such as ROS.

The Robotics and State Estimation Lab is affiliated with the Intel Science and Technology Centre for Pervasive Computing at the University of Washington. Main funding sources are Intel, NSF, DARPA, and ONR. The lab collaborates with other departments and in the framework of the Intel Science and Technology Center for Pervasive Computing.

4.8.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

The Biorobotics Laboratory closely collaborates with the medical school of UW, which is indispensable in the area of minimally invasive surgery. It has links with the Simulab, a company that is also marketing EDGE, a training device for minimally invasive surgery. Collaboration with other universities is fostered by the installation of eight RAVEN systems.

The Sensor Systems Research Group mainly collaborates with the university's Robotics and State Estimation Lab and the Neural Systems Laboratory, the Yale School of Medicine, and Willow Garage. The lab is running the classical system of knowledge transfer through common projects.

The Robotics and State Estimation Lab collaborates with other departments and in the framework of the Intel Science and Technology Center for Pervasive Computing.

Commercial activities
The Biorobotics Laboratory does not endeavor to commercialize their findings itself. As such, there is no collaboration with companies for the RAVEN, and the EDGE training system is being marketed by the company Simulab.

The technological achievements of the Sensor Systems Research Group allow for commercializing their findings and for founding startup companies. The university's technology transfer initiative should be an advantage.

The Robotics and State Estimation Lab does not pursue an affirmative plan for commercializing their findings.

Spin-offs
The University of Washington is fostering technology transfer, provides support services to set up businesses, and has entrepreneurs in residence. However, there is not sufficient capital in the area of robotics.

All research programs have an SBIR support. For example, a neurosurgery startup was able to acquire substantial funding through an SBIR grant after it the company was launched in 2007.

IP handling
The Biorobotics Laboratory and the Robotics and State Estimation Lab strictly respect intellectual property rights. In particular, the RAVEN was built to circumvent the many Da Vinci patents. Patents are filed for their own developments. The university pays to file the patent and the patent is given to the researchers. RAVEN's HW design as open source could be an option, but a decision has not yet been made.

There was consensus among the experts that open source software and hardware have a very high impact. Open source hardware is a novel concept, which is positive for everybody. Working on hardware, there are more ways to fail, but open source mitigates risk and keeps the cost down, and should be used more in labs. Currently there are, however, only few examples of open source hardware. In medical robotics, once open source frameworks are approved in general, only additional approvals for new additional modules are needed.

Group together with Blake Hannaford and the RAVEN surgical robot

Standardized robot platforms will make it possible to test ideas.

The University of Washington is getting better at Tech Transfer. They provide support services to business set ups, and they have “Entrepreneurs in residence” who try to fix the cultural problem of engineers starting a business. One goal is to get business students together with engineers.

At UW, a company on neurosurgery is being started (one year to set up), which is developing new IP. This is not supported by the university.

The Biorobotics Laboratory has licensed Simulab for a training device and members own a patent on an innovative wrist design.

4.8.5. Education

The department has active involvement of students from other departments. For example, the medical department has projects with the Biorobotics Laboratory.

Student competitions are being used as a way to pave the way towards a serious robotics education.

Given the Sensor Systems Research Group's innovative character, students may work on very interesting and multidisciplinary projects. This can be expected to trigger lateral thinking of students, hence, inspiring them to think in new directions.

The Robotics and State Estimation Lab provides an excellent environment for students to work on cutting edge methods. They are exposed to challenging problems but are embedded in a vivid research environment with direct contact to Intel.

4.8.6. Statements by the people visited

- Robotics is potentially more disruptive than social networking, but has higher financial risk.
- No need to be as precise in hardware, because the solution will be on the software side.
- Biorobotics Laboratory (Blake Hannaford)
    - Computer vision is further ahead in machine learning than robotics.
    - ROS open-source initiative is helping robotics research and also very probably existing markets such as surgery.

4.8.7. Additional comments

Dieter Fox emphasized that there is a need for robots that can tolerate imprecision and have good hand, a key will be adaptive algorithms for noisy sensor data. A robot arm has more potential the lower the system cost. This is in contrast to the emphasis on most precise hardware.

In a discussion about openness and reference platforms there was consensus that PR2 and other widely known platforms are beneficial, as each lab can increment and does not need to start from scratch. The researchers at UW claimed that the work with the PR2 is very productive in terms of papers.

4.9. Microsoft Research

4.9.1. Research topics

The current research includes the following topics:

- Microsoft did not reveal the own current research besides developing new versions of the Robotics Studio ™

The current areas of research are motivated by the following factors:

- Microsoft wants to enter the robotics mass market.
- Interaction modules are needed. Thanks to Microsoft's Kinect gestures are now more accessible, but verbal communication is still to come.
- Autonomy and rich interaction may create interesting value

The lab sees the following areas as future trends:

- Market will change if manipulation is possible in home environments.
- Autonomous navigation first, then manipulation
- Autonomously navigating in the house
- Contributions by other hardware providers are needed.
- Cloud computing will be available for future robotics.

Branch Hendrix outlines Microsoft's involvement in robotics

4.9.2. Results and innovation

Scientific/technological outcome

One of the main outcomes is the Kinect system (low cost, 3D, standardized hardware), which was actually not developed for robotics, and gives new impetus and capability to human interaction. Parallax has produced a reference platform Eddie with Kinect (a 1'000$ non-manipulating device for consumer market).

Other outcomes are, for example the Robotics Studio, which has a public awareness, but is not widely used in the academic world (> 50 partners, > 500.000 downloads, V4 Nov. 2011).

Business models

Microsoft Research is focused on the mass consumer market. Its business model is to provide development platforms for applications. After reaching the consumer market with simple applications, Microsoft expects increase of market for products with manipulation.

Broad consumer usage is, according to Microsoft, hard to achieve because of fragmented hardware and the high complexity of such systems. In their opinion software is the key, but better development tools are needed (similarity to early PC industry). Additional the creation of new markets depends on Technology disruption (sensors, battery, etc.), high-speed internet for cloud services, and added value.

4.9.3. Funding modes and statements regarding funding

Funding for the 850-people research department is undertaken on an annual basis. The internal roadmaps foresee work in 3 time-scales, working on the future generation on product groups with a time horizon of up to 4 years, pre-development in Microsoft Labs; within 2–5 years, and the work on technology rather than products at Microsoft Research in a 5-10 year's perspective.

4.9.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

Microsoft monitors the robotics sector with respect to science, technology, and markets. They established an early adopter program for the Kinect and initiated the competition robotics@home [48].

Commercial activities

Commercial activities mainly include the sale of the Kinect system and Eddie (through Parallax), mentioned in the section "Scientific/technological outcome". Rapidly transfer innovative technologies into products.

Stewart Tansley

Spin-offs

There are no spin-offs the authors are aware of.

IP handling

Microsoft uses closed IP and patents.

4.9.5. Education

Microsoft collaborates with the world's top academic research institutions but does not have a commitment for non-profit research.

4.9.6. Statements by the people visited

"Interact with Microsoft Research the way you would interact with an academic".

4.9.7. Additional Comments

Microsoft research has a 20 year history and today employs almost 900 people. It seems that there is lack of an actual developer team for robotics and that no long-term perspective is established yet. Current activity seems to be centered on Kinect. Microsoft needs contributions by other hardware providers.

4.10. University of Pennsylvania – GRASP Laboratory

4.10.1. Research topics

The current research includes the following topics:

- Multi-robot coordination and networked control
- Locomotion and Mobility
- Learning-based Integrated Robots
- Haptic Perception
- Reconfigurable robotics
- Machine Learning
- Tele-operation
- Autonomous Robots
- Vision for navigation and manipulation

The current areas of research are motivated by the following factors:

- Addressing fundamental questions on perception, control, and mobility
- Addressing society needs on robotic helpers in defense, rescue, security, and manufacturing

The lab sees the following areas as future trends:

- Navigation challenges
  - Real-time 3D SLAM in complex terrains (no walls)
  - Bio-inspired navigation and perception for swarms
  - Human-robot interaction and navigation
- Manipulation/mobility challenges
  - Active perception for grasping
  - Dexterous mobile manipulation

4.10.2. Results and innovation

Scientific/technological outcome

The following table provides an overview of the laboratory's numerous research activities, which cover many areas in the field of robotics:

- Multi-robot coordination and networked control
- Locomotion and mobility
- Autonomous navigation and exploration with MAVs
- Very impressive dynamic control of Quadrotors
- Learning-based integrated robots (Magic 2010, Urban Challenge, Soccer),
- (Haptic) perception (use of accelerometers)
- Modular and reconfigurable robotics
- Machine learning
- Coordination of legged robots (for example for climbing)
- Optical detection of objects by moving monocular camera
- Laser/Kinect mapping, Incremental EKF-based SLAM

After the 2010 earthquake the lab went to Sendai and showed their research to Mitachi.
VICON motion capture replaces perception and enables control at 180Hz.

Mark Yim with a modular robot

Business models

Although they point out that technology transfer and cooperation with industry is not at center stage (but academic research), they do have several successful industrial cooperations and a substantial number of projects with corporate funding.

Michael Nathan explaining his quadcopter technology

4.10.3. Funding modes and statements regarding funding

As the oldest US University, founded in 1780, the University of Pennsylvania has a research budget of $ 1 Billion.

The School of Engineering and Applied Science, with 6 departments, 13 institutes, and 1600 students, has a research budget of $ 80 Million (30% NFS, 21% DoD, 15% NIH, Industry).

The Grasp Lab, with 77 PhDs, 9 Postdocs, 69 Masters, and 6 Visitors, has a budget of $ 12 Million.

Funding for the GRASP Lab is mostly from DoD (90%) and NSF (10%), but there are also several successful cooperations with companies (e.g. Moss Rehabilitation Research Institute, Dragonfly Pictures Inc., Lockheed Martin, Boston Dynamics, Susquehanna International Group, and Honeywell International) and some foundations (ONR for Heterogeneous unmanned networked teams, the Army Research Office, and the Army Institute of Collaborative Biotechnology for swarm research).

The lab receives a Da Vinci robot for free, for manipulation and 3D vision.

4.10.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

Knowledge transfer, though not a major focus (as pointed out by GRASP members), takes places through cooperations with corporations, which provide some funding for projects. Some of the faculty has many years of industrial experience.

The lab is well connected with companies.

Commercial activities

Again, commercial activities are not at center stage. Still, there are some spinoff companies, some product developments (e.g. a robust version of the Rhex robot, built and marketed by Boston Dynamics), and patents.

Spin-offs

There are several patents; among them are two or three by Daniel E. Koditschek, and at least 20 by mark Yim.

From discussions during the ECHORD Lab Tour, we concluded that their spin-offs have not been successful and have failed for various reasons. Their first spin-off lost out to iRobot. The next one, SandBox, failed because of internal conflicts. KMel Robotics is a new spin-off producing small UAVs and UGVs.

IP handling

Two patents have been filed (one for surgery). Mark Yim has several patents, from which apparently a lot of revenue has been generated. Apparently not all faculties are convinced that patents are the right way to go.

4.10.5. Education

UPenn has had an excellent Master's program in robotics since 2007, with 15 top faculties in robotics alone. They established an IGERT (Integrated Graduate Education and Research Traineeship) PhD Trainee Program. Students choose from core areas (robotics, control, perception, AI), and engineering electives (which includes "entrepreneurship"). The program is surprisingly non-interdisciplinary (little neuroscience, biomechanics, ethology, materials, etc.).

There are also intern exchanges with Willow Garage, which is attractive for students.

Since 1980 there has been a Speaker Series, to which everyone is invited.

K-12 Education: Mentoring Middle Schools and High Schools and organizing the finals of the regional First Lego League (more than 500 middle-schoolers)

Expert group is scrutinizing a prototype at GRASP Lab

4.10.6. Statements by the people visited

- "The two most interesting things in the last two years have been: Willow Garage's ROS and Microsoft's Kinect."
- "Willow Garage is an enabler company, not a transitional company."
- "iRobot and Microsoft were trying to create a research platform, but they both lost out to ROS."
- "In a conference, most of the industry-driven publications come from Europe."
- "A professor can't be a company manager."
- "Maybe the model is to create patents and license to the industry instead of spin-offs."

4.10.7. Additional comments

Mark Yim created over 100M$ with patents on vibrating devices he filed in a former company, which then suited Microsoft and Sony's gaming devices. There are more than 60 patents, but the challenge is to find an application for them.

4.11. Carnegie Mellon University Robotics Institute

4.11.1. Research topics

The current research includes the following topics:

- Space robotics (Lunar X price participation)
- Mobile robot teams (RoboCup)
- Snake-like robot´s
- Surgery robots
- Agricultural robots
- Skin-based force control
- Human motor control of locomotion
- Rehabilitation robotics
- Understanding animal performance
- Soft and safe robots (inflating systems)
- Humanoids (stability, balance, human interaction)
- Aerial robotics

The current areas of research are motivated by the following factors:

- Field Robotics - Develop, Secure, and Feed the World

William „Red“ Whittaker explaining the Google Lunar X PRIZE activities at CMU

The lab sees the following areas as future trends:

- Robotics markets: Defense, mining, agriculture, service, energy, space, and transportation
- Agriculture is the future. In agriculture 50% of costs is labor (by low cost immigrants).
- Open space autonomy
- Surgical applications
- Perception in non-perfect environment
- Robot in manufacturing will not be important in future as it was in the past

4.11.2. Results and innovation

Scientific/technological outcome

Scientific and technological outcomes of the lab include:

- The Robotics Initiative (started at CMU and was then brought forward by Henrik Christensen)
- A theory of legged dynamic systems (Legged systems for humanoid and rehabilitation)
- A tour-guide robot (quite simple, but “has already performed 100km”)
- Soccer robots (small size league)
- A 3D laser scanner for obstacle avoidance, up to real size helicopters
- A balancing ball-robot - Cobot
- A haptic device based on magnetic levitation principle

Business models

Instead of venture capital the department receives financial support when a return of innovation is expected. Several spinoffs emerged from the department. “You have to take risks to create new things and win” (e.g. invest $40k and receive millions).

4.11.3. Funding modes and statements regarding funding

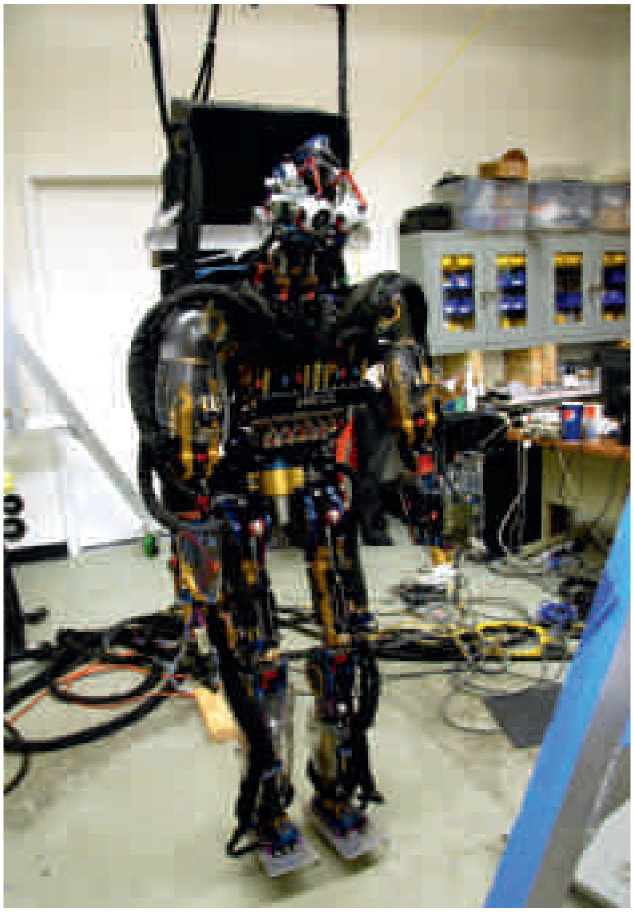
The Robotics Institute receives significant of $ (65M$ research + 10M$ education). Currently 50% of the funding comes from DoD, and the rest from NASA, NSF, NIH, Department of Agriculture, Department of Homeland Security, and Industry (e.g. Caterpillar, INTEL, DISNEY). DoD funding is decreasing while industrial funding is increasing (in particular agriculture, mining). RI generate 20% the total CMU budget (1 M$ per person per year). As an example RI invested 4M$ into the Urban Challenge, and after winning the 2M$ prize the RI signed a 6M$ contract.

4.11.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

The lab has extensive collaboration with spin-offs, for example sharing project funding, etc. Its reputation (prizes, excellent publications) brings CMU RI many sponsors and project cooperations.

Commercial activities
Commercial activities include the National Robotics Engineering Center (NREC): "A proof-of-concept demonstration followed by an in-depth development and testing phase that produces a robust prototype with intellectual property for licensing and commercialization" [49].



The SARCOS humanoid robot

Spin-offs
The lab has several spin-offs, including RedZone (National Robotics Engineering Center), MedRobotics (Spin-off in cardiac surgery started by Howie Choset, 1M$ institutional investment) and Butterfly Haptics (a haptic device based on magnetic levitation) [50]. The robotics foundry (a mechanism to support the creation of companies), is now merged into www.techcollaborative.org and aims at "incubating and mentoring early-stage companies".

IP handling
CMU RI is generating a large number of patents each year, and IP protection seems crucial. It filed 12 patents from a 18 months development only.

4.11.5. Education
CMU is the largest robotics education entity in the US (Obama announced the NRI after visiting CMU). The RI has more non-tenured research faculties than tenure track faculties.

4.11.6. Statements by the people visited
Chris Akinson: "Why don't you visit the companies – as opposed to 10 years ago they are now there!"

4.11.7. Additional comments
The Robotics Institute started in 1979 and became a department in the '80. It is now the world's largest robotics research and development organization and has over 600 employees (45 faculties). There are separate groups, each with people ranging from conception to field tests. Marcel Bergerman is IEEE co-chair agriculture robotics. The institute is involved in the Congressional Caucus. Differentiation is the key: Bring something different to the congress, and you get 0.5M$ directly.

4.12. Massachusetts Institute of Technology

4.12.1. Research topics

The current research includes the following topics:

- Smart Power devices
- Fuel cells
- Adaptive mirrors

The current areas of research are motivated by the following factors:

- Overall reason for robotics: do things for society
  - » Medical applications
  - » Robotics for the elderly
  - » Clean energy, water
  - » Military: ground vehicles, rough terrain robots

The lab sees the following areas as future trends:

- Most important areas
  - » Medical applications and assistive robotics for elderly, healthcare
  - » Energy, environment, especially fuel cells
  - » Military
- Smart systems instead of classical robotics, e.g. weapons

4.12.2. Results and innovation

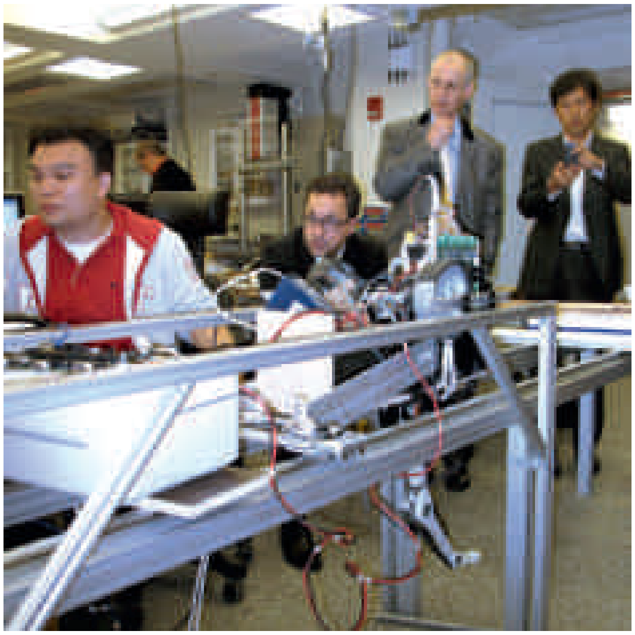
Scientific/technological outcome
The Field and Space Robotics Laboratory has been mainly working on industrial robotics in the past, but has now moved to smart vehicles outside the factory. The reason is that factory automation is a mature field and Prof. Dubowsky thinks the USA will have little to do with factory automation in the future.

The main categories explored in the lab are healthcare and help for the elderly, energy and environment, and military applications.

The lab does fundamental research, even if it is not related to robotics, e.g. on fluid dynamics and other basic research, and their application to "smart systems". They trigger innovation by performing long term, basic research.

Some examples of the lab's research outcome:
- A water purification system with 75% efficiency improvement
- Novel solar reflectors, fuel-cell improvement
- "Coffee bean bolloon" grippers in several labs
- Magnets that change state with current (the current is needed only to change the state)
- Small satellites, as a response to the challenge: "do it in space"
- Smart systems, controller

Steven Dubowsky's lab



Experiments with a robot leg

Business models
The Field and Space Robotics Laboratory clearly performs long term, basic research, which is then patented to create value. The valorization takes place by selling licenses or creating spin-offs.

4.12.3. Funding modes and statements regarding funding
The lab has a collaborative internal competition with Boston Dynamics. There is a DARPA mandate with Boston Dynamics for high speed running (MIT using electric and Boston Dynamics using hydraulics). MIT has an alliance with Ford.

Space robotics was a major funding source, but in recent years, the budget for space robotics was reduced.

4.12.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes
The knowledge transfer is directly embedded in the lab's business model, and takes place either via patent licenses, or spin-offs.

Commercial activities
-

Spin-offs
The lab has several spin-offs, including iRobot, Boston Dynamics, and PAMMs (Personal Aids for Mobility and Monitoring), which is now in Singapore.

IP handling
IP is mainly handled via patenting.

4.12.5. Education
There is an integrated Bachelor product design course by Richard Wiesman (Chief Technology Officer and Executive Vice President of QinetiQ North America & Technology Solutions Group), where groups of students have to get to create a prototype by finding a competitive application, evaluating the market, and developing small projects close to reality.

Steven Dubowsky

4.12.6. Statements by the people visited
Steven Dubowsky: “Do you think one can compete with Asia in manufacturing?”

4.12.7. Additional comments
It was impressive to see how large the spectrum of research topics is, from mechanics to fluid dynamics, to chemistry. This is really what makes this lab unique: basic research for long term results.

4.13. MIT – Computer Science and AI Laboratory

The Computer Science and Artificial Intelligence Laboratory (CSAIL) is the largest lab at MIT with more than 800 members and about 450 students.

4.13.1. Research topics

The current research includes the following topics:

- Broad range of research topics, structured in 3 core areas: Artificial Intelligence, Systems, and Theory.
- Individual research areas range from Robotics locomotion over vision to learning and distributed robotics.

The current areas of research are motivated by the following factors:

- Promote robotics as next disruptive technology
- Work on important challenges to achieve pervasive robotics
- Work with industry to go from theory to prototype to deployable technology
- Be at the forefront of this robotics revolution

The lab sees the following areas as future trends:

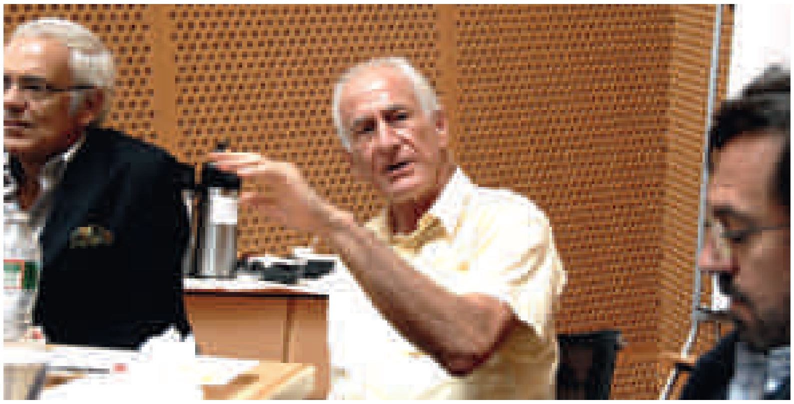
- High dynamic UAV
- Manufacturing (collaboration with Boeing)
- Group robotics
- SMAL vs. SLAM
- Challenges in mapping
- Large scale lifelong visual SLAM
- Lozano-Perez: Back to older principles

4.13.2. Results and innovation

Scientific/technological outcome

CSAIL's scientific and technological outcome includes results in the following areas:

- Learning, graph methods, programmable matter
- Stability control
- SLAM (first results)
- Soft robotics
- Human robot interaction
- Unmanned Underwater Vehicles
- Natural language commands for UAV, navigation with natural language. (Impressive UAV mapping around the campus)
- DARPA urban challenge



Bruno Siciliano and Jeffrey Hoffman

Business models

CSAIL has developed alliances with companies such as Ford and Boeing ans also pursuing spin-offs when appropriate

4.13.3. Funding modes and statements regarding funding

CSAIL has 40M$ funding, which is a significant amount for a lab, if you keep in mind that all of MIT has 500M$.

The funding comes 1/3 from the government, 1/3 from industry, and 1/3 from other countries. Funding from the DoD comes especially for logistics.

4.13.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

CSAIL seems to be a big single lab. Their members really give the impression that it is a collaborating team, not a competing one like in many other places.

CSAIL has several collaborations with the industry (Boeing, Ford, etc.). With Boston Dynamics there is a collaborative internal competition (DARPA mandate to Boston Dynamics).

Commercial activities
-

Spin-offs
CSAIL has nearly 100 spin-offs, such as Akamai, Ascent Technology, Boston Dynamics, Bluespec, Determina, iRobot, ITA Software, Meraki, Open Market, RSA, Sandburst, Sight Path, Scalable Display, Speechworks, StreamBase, Tilera, and Vertica.
iRobot and Boston Dynamics have been a huge spin-off success.

IP handling
The IP strategy was not really discussed, but one can imagine that patenting and spinning-off is most likely the approach they use.

4.13.5. Education
CSAIL clearly fosters interdisciplinary collaboration within CSAIL and MIT as well as collaborations with industry. This can be a good driver for successful innovation.

4.13.6. Statements by the people visited
"We want to promote robotics as the next disruptive technology."

"Startups are not a goal; they come about through serendipity. Students take up ideas, but not as easily in the last few years."

4.13.7. Additional comments
CSAIL also played a major role in standards setting, including TCP/IP, GNU, X-windows, and the Worldwide Web.

MIT buildings

4.14. McGill University – Centre for Intelligent Machines

4.14.1. Research topics

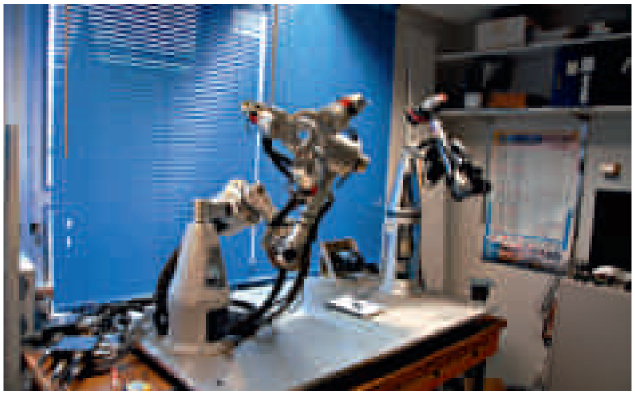
The current research includes the following topics:

- Systems & control
- Human-machine interaction, in particular visual language (motion capture of the hands or tags)
- Dynamics modeling
- Characterization and operation of mobile platforms
- Robustness against changing environments and safety
- Terramechanics for mobile platforms
- Design of robotic mechanical systems
- Aerospace mechatronics
- Artificial perception

The current areas of research are motivated by the following factors:

- Excelling in the field of intelligent machines with basic research, technology development and education.
- Robotics in manufacturing (especially aerospace manufacturing) as one of the priorities for the Canadian Science and Engineering program

Jorge Angeles and Benoit Boulet with the lab tour participants



Research on mechanical devices

The lab sees the following areas as future trends:

- Assistive systems (personalized healthcare, car automation, …)
- Opportunities with increasing computing devices (smart-phone, camera)
- Smart systems rather than humanoid robots
- Aerospace (important for manufacturing)
- Goal: Robustness against changing environments, safety
- Mechanical Engineering: miniaturization, turn into a science rather than an industrial activity
- 15 years ago: not enough data from sensors. Now: a lot of data that has to be computed intelligently.

4.14.2. Results and innovation

Scientific/technological outcome

The Mobile Robotics Laboratory is a top-notch robotics and mechatronics laboratory. The most interesting result is the Aqua amphibious robot, which merges advanced mechatronic, bio-inspired underactuated design and machine learning (capable of swimming underwater in the sea and of legged movement on challenging terrains, and 3D maneuvers). They got many interesting results in the mechatronic line:

- ASTEC UAV (fixed wing)
- Post-capture control and stabilization
- MAV funded by DRDC Suffield and the Canadian Space Agency.
- Landing Draganflyer X8 simulated on Gazebo and on ROS
- Dynamic locomotion of PAW, a jumping wheeled/legged robot (firstly funded by DRDC)
- Kinesthetic and haptic interfaces

The Robotic Mechanical Systems Laboratory excels in the design and control of mechanical systems, with special focus in robots, sensors and remote intervention. A sample of projects:

- Beating heart emulator
- A surgery project for percutaneous mitral valve annuloplastry
- Optimal design of accelerometers
- Schönflies Motion Generator (four-degree-of-freedom parallel robot)
- Innovative clutching mechanism for hybrid vehicles.

Business models

-

4.14.3. Funding modes and statements regarding funding

Canada's funding scheme is comparable to the Spanish or UK national budget, without the benefit of the continental level framework represented by FPs in the EU (they have a limited participation in DARPA calls). Huge funding comes from the public effort to rescue the car industry with huge applied research funding (two of three big US car companies went bankrupt and were nationalized by the US government, and are still being heavily supported, Chrysler is now owned by Italian FIAT).

User robotics in manufacturing is one of the priorities for the Canadian Science and Engineering program.

They have 13 labs, 18 members, 9 associates, 160 graduate students and visiting researchers, and a $3.5 Million budget, which adds to direct student funding (20-30 students financed).

According to Gregory Dudek, there is a surprisingly large number of small companies, showing that there is no lack of entrepreneurial attitude.

PRECARN, a non-profit company supporting pre-commercial development, is going to be closed by the end of 2011.

Although basic research on robustness is required, this kind of research is not easily funded. Canadian companies have a parochial vision of 'collaborative research'. The funding comes from industry (CMLabs / Quanser), the government, Canadian Space Agency / NRC Aerospace Centre. Their cooperation within cooperative research programs is mainly with other Universities in CA.

MAV research is funded by DRDC Suffield and the Canadian Space Agency.

4.14.4. Knowledge Transfer, Cooperation, and IP handling

Cooperation modes

The McGill Office of Technology Transfer aims at big hits like RIM (Blackberry's producer), a Waterloo University

Jorge Angeles showing an innovative transmission mechanism spin-off. McGill is highly medical oriented and the model for medical/pharmacology is very different with respect to technology, as it is longer term and more capital intensive. This should be integrated into a spin-off program aiming at creating smaller sized successful companies. Also, they believe that if the patent/IP ownership could stay with the inventor, not the university, as in Waterloo, it would make the spin-off process more effective. In this case, the pay-off for the university would come from donations. Draganflyer is quoted as a good example of cooperation with industry. The hiring of students by the industry is seen as a very effective way of transferring knowledge to the industry.

As mentioned above, there is cooperation with GM on a very specific mechatronic topic: innovative clutching mechanism for hybrid vehicles.

There is also a program branded i2i- an idea-to-innovation technology transfer program (with the limitations, with respect to robotics and smart systems quoted above.

Commercial activities

The spin-offs (most notable Aqua) follow a 'European (traditional) model'. As mentioned above, they see opportunities in the 'smart systems' domain and in the car-manufacturing sector.

Spin-offs

So far the most promising spin-off comes from the Aqua amphibious robot, thanks to its bio-inspired underactuated dynamics and advanced perception based on machine learning methods, which allowed designing a viable system and gave rise to a potentially successful spin-off.

Independent Robotics Inc. focuses on an 18 months vision selling Aqua to academia as a research platform. Later it will be marketed for use in environmental inspection, and similar applications.

They have a large number of spin-offs, although this might be a consequence of the lack of big employers.

Various factors are seen as affecting the process of tech transfer and spin-offs. According to Jorge Angeles, the basic ingredients are fundamental research and patents. Others still see a lack of sensor data and computation power.

From an economic sector point of view, opportunities for mainly smart systems but also robotics are in demand in factory automation, and a potentially huge medical market, where there are still no big players.

McGill is the only entity in Canada, which has the critical size to put a robotics network in place, and they want to!

IP handling

The IP management at McGill is standard (patents on supposedly interesting solutions paid for by the university, with a percentage of revenues going to the inventor).

CIM has many patents, for example, in mechatronics and mechanisms (such as a patent of J. Angeles on dual-wheel transmission). CIM thinks the open IP approach, (giving full benefits to the inventor, and the university would be compensated by donations from successful inventors) would increase the commitment of researchers (this is University of Waterloo's approach, which led to various extremely successful spin-offs, for example RIM).

4.14.5. Education

CIM sees education in a standard way and an important tool for technology transfer (when students are hired by business).

Many of the people from robotic labs go to graphics, intelligent devices. Thus, robotics seems to provide good preparation for other areas.

4.14.6. Statements by the people visited

-

4.14.7. Additional comments

“Manufacturing went out of North America, only automation can change that.”

5. Conclusions and Recommendations

The mission of the experts was to summarize their recommendations on "best practices" on the topics above in a final report. Based on our personal experience, here are the major findings of the tour:

- The window of opportunity for service robotics in industry is now open – all major laboratories are working on different kinds of applications.
- Professional service robotics is seen as a market, but domestic service robotics is not yet perceived as an opportunity.
- Platforms (= operational robots systems) are being used that make it possible to concentrate on application development – and not on classical robot development.
- The US is pushing very hard to bring technology forward – through DARPA and the National Robotics Initiative.
- The US is becoming aware of its leading role in manufacturing, and will invest heavily into its Advanced Manufacturing Program (US$ 2 BN).
- The „classical“ areas (elderly care, medical robotics, exoskeletons, …) may not perceived be as spectacular any more, but they are still being pursued with high pressure.
- There was little sign of specific programs for encouraging spin-offs, although there was clearly significant success in this area by some institutions. Factors for success appear to include sheer critical mass in a single geographical location (both of robotics research and of associated high technology resources) and the ongoing interaction with alumni based in entrepreneurial ventures.
- Although many of the larger robotics research facilities featured labs with different core disciplines and orientations, truly integrated and cross-disciplinary research was not commonplace, leaving the impression that the value of potential synergies was not being fully exploited.

- The degree of application orientation versus research orientation varied widely between institutions and even between labs within an institution. There was no apparent correlation between this and perceived success of the labs.
- In general, where collaborations were undertaken with industry this tended to be with organizations in the local area. There was some evidence that this allowed stronger and longer term relationships to be built.

In addition to this, when elaborating the funding schemes for Horizon 2020, the EC must be sure to take a closer look at the way the US is handling funding and the use of IP. Programs similar to the funding schemes dedicated to strengthening SMEs in the US will be integrated (PPP and PCP).

Open-Call projects like ECHORD, however, were invented in Europe and currently there is not any parallel initiative in the US.

6. Outlook

In order to get a complete overview of the situation and to be in the position to draw parallels and evaluate the differences – ending up with recommendations on "best practice" of knowledge transfer between industry and academia, ECHORD's expert group will tour Asia in June of 2012, while the structured dialogue will focus on Europe. The outlook chapter will therefore be made available in the subsequent report on the Asian lab tour.

7. References

[1] U.S. National Science Foundation, „NCSES New Estimates of National Research and Development Expenditures Show 5.8% Growth in 2007“, 2008. [Online]. Available: http://www.nsf.gov/statistics/infbrief/nsf08317/. [Accessed: 30-Jan-2012].

[2] U.S. Department of Health and Human Services, „Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs“, 2012. [Online]. Available: http://grants.nih.gov/grants/funding/sbirsttr_programs.htm. [Accessed: 23-Feb-2012].

[3] D. B. Audretsch, J. Weigand, and C. Weigand, „The Impact of the SBIR on Creating Entrepreneurial Behavior“, Economic Development Quarterly, vol. 16, no. 1, pp. 32 –38, Feb. 2002.

[4] U.S. Small Business Administration, „Small Business Technology Transfer Program (STTR)“. [Online]. Available: http://www.sba.gov/content/small-business-technology-transfer-program-sttr-0. [Accessed: 30-Jan-2012].

[5] Wikipedia, the free encyclopedia, „National Science Foundation“. [Online]. Available: http://en.wikipedia.org/wiki/National_Science_Foundation. [Accessed: 30-Jan-2012].

[6] U.S. National Science Foundation, „Full-year Appropriations Bill Passed, NSF Funded at $6.8 Billion for FY 2011“, 2011. [Online]. Available: http://www.nsf.gov/about/congress/112/highlights/cu11_0523.jsp. [Accessed: 30-Jan-2012].

[7] U.S. Army Research Laboratory, „Robotics“. [Online]. Available: http://www.arl.army.mil/www/default.cfm?page=392. [Accessed: 30-Jan-2012].

[8] U.S. Air Force, „AFOSR: International - AOARD“, 2011. [Online]. Available: http://www.wpafb.af.mil/library/factsheets/factsheet.asp?id=9477. [Accessed: 30-Jan-2012].

[9] „AFOSR: Educational, Outreach and Special Programs“, 2011. [Online]. Available: http://www.wpafb.af.mil/library/factsheets/factsheet.asp?id=8972. [Accessed: 30-Jan-2012].

[10] G. A. Bekey, Robotics: State of the art and future challenges. Imperial College Press, 2008.

[11] G. Bekey, R. Ambrose, V. Kumar, A. Anderson, B. Wilcox, and Y. Zhen, „WTEC Panel on International Assessment of Research and Development in Robotics - Final Report“, 2006. [Online]. Available: http://wtec.org/robotics/. [Accessed: 12-Jan-2012].

[12] [1] Computing Community Consortium, „A Roadmap for US Robotics: From Internet to Robotics“, 2009. [Online]. Available: http://www.us-robotics.us/reports/CCC%20Report.pdf. [Accessed: 12-Jan-2012].

[13] R. Brooks, „Robotics (Version 4)“, 2009. [Online]. Available: http://www.cra.org/ccc/docs/init/Robotics.pdf. [Accessed: 12-Jan-2012].

[14] IFR Statistical Department, Ed. “World Robotics 2011”. 2011.

[15] European Robotics Technology Platform, eds., „Robotic Visions - to 2020 and beyond. The Strategic Research Agenda for Robotics in Europe“. 2009.

[16] G. Bekey and J. Yuh, „The Status of Robotics - Report on the WTEC International Study: Part I“, IEEE Robotics & Automation Magazine, vol. 14, no. 4, pp. 76–81, Dec. 2007.

[17] G. Bekey and J. Yuh, „The Status of Robotics - Report on the WTEC International Study: Part II“, IEEE Robotics & Automation Magazine, vol. 15, no. 1, pp. 80–86, Mar. 2008.
[18] U.S. Department of Defense, „FY2009–2034 Unmanned Systems Integrated Roadmap“, 2009. [Online]. Available: http://www.acq.osd.mil/psa/docs/UMSIntegratedRoadmap2009.pdf. [Accessed: 23-Feb-2012].
[19] „DARPA Grand Challenge - Wikipedia, the free encyclopedia“. [Online]. Available: http://en.wikipedia.org/wiki/DARPA_Grand_Challenge. [Accessed: 23-Feb-2012].
[20] Object Management Group, „Robotics DTF“. [Online]. Available: http://robotics.omg.org/. [Accessed: 23-Feb-2012].
[21] ISO - International Organization for Standardization, „TC 184/SC 2 - Robots and robotic devices“. [Online]. Available: http://www.iso.org/iso/iso_technical_committee.html?commid=54138. [Accessed: 23-Feb-2012].
[22] LiGuo Huang and D. Port, „Relevance and alignment of Real-Client Real-Project courses via technology transfer“, in 2011 24th IEEE-CS Conference on Software Engineering Education and Training (CSEE&T), 2011, pp. 189–198.
[23] D. A. Abercrombie, „A case study of cooperative university/government/industry education and research“, in University/Government/Industry Microelectronics Symposium, 1993, Proceedings of the Tenth Biennial, 1993, p. 41–45.
[24] C. M. Brown, E. M. Sheppard, J. F. Vetelino, and M. P. Galin, „University-industry technology interchange through a unique engineering projects course“, IEEE Transactions on Education, vol. 32, no. 3, pp. 343–348, Aug. 1989.
[25] L. J. Curran, „`A’ for effort [technology transfer education]“, IEEE Spectrum, vol. 30, no. 2, pp. 50–52, Feb. 1993.
[26] F. Tasch, „Knowledge and technology transfer: a university experience and perspective“, in University/Government/Industry Microelectronics Symposium, 1995, Proceedings of the Eleventh Biennial, 1995, pp. 13-26.
[27] K. J. Nasr and B. AbdulNour, „An experience on Industry-University collaborative research“, in Frontiers in Education Conference, 1997. 27th Annual Conference. „Teaching and Learning in an Era of Change“. Proceedings., 1997, vol. 1, pp. 317–320.
[28] J. J. Pauli, „Incentive-Based Technology Start-Up Program for Undergraduate Students“, in Fifth International Conference on Information Technology: New Generations, 2008, 2008, pp. 841–844.
[29] M. Polczynski, „An International Engineering Research and Exchange Initiative“, in Frontiers in Education Conference, 36th Annual, 2006, pp. 7–12.
[30] A. Schibany, G. Streicher, and B. Nones, „Geistige Eigentumsrechte an Hochschulen: Evaluierung des Programms Uni:Invent (2004-2006)“, TeReg Research Report, vol. 74, Feb. 2008.

[31] B. Godin and C. Doré, „Measuring the Impact of Science: Beyond the Economic Dimension, INRS Urbanisation, Culture et Société“, presented at: 1) Helsinki Institute for Science and Technology Studies, HIST Lecture, 24 August 2007, Helsinki, Finland; 2) International Conference „Science Impact - Rethinking the Impact of Basic Research on Society and the Economy“, 2004.

[32] S. Cozzens, „Evaluating the Distributional Consequences of Science and Technology Policies and Programs“, Research Evaluation, vol. 11, no. 2, pp. 101–107, Aug. 2002.

[33] S.-B. Chang, „Positive or Negative? Patent Institution Impact on the Knowledge Creation of Computer Software“, in Proceedings of PICMET '11, 2011, pp. 1–5.

[34] M. Boldrin and D. K. Levine, „Open-Source Software: Who needs Intellectual Property?“, The Freeman. Ideas on Liberty, vol. 57, no. 1, pp. 26–28, Jan. 2007.

[35] R. T. Watson, M.-C. Boudreau, P. T. York, M. E. Greiner, and D. Wynn, „The Business of Open Source. Tracking the changing competitive conditions of the software industry“, Communications of the ACM, vol. 51, no. 4, pp. 41–46, Apr. 2008.

[36] A. D. Nesnas, „CLARAty: A Collaborative Software for Advancing Robotics Technologies“, Proceedings of NASA Science and Technology Conference 2007, pp. 1–7, Jun. 2007.

[37] J. Bessen and E. Maskin, „Sequential Innovation, Patens, and Imitations“, MIT Department of Economics Working Paper, vol. 00–01, Jan. 2000.

[38] S. Kortum, „Equilibrium R&D and the Patent - R&D Ratio: U.S. Evidence“, The American Economic Review, vol. 83, no. 2, pp. 450–457, May 1993.

[39] R. E. Evenson, „International Invention: Implications for Technology Market Analysis“, in R&D, Patents, and Productivity, Z. Griliches, ed., Chicago: University of Chicago Press, 1984, pp. 89–123.

[40] R. E. Evenson, „Patent Data by Industry: Evidence for Invention Potential Exhaustion?“, in Technology and Productivity: The Challenge for Economic Policy, Organisation for Economic Cooperation and Development, ed., Paris: OECD, 1991, pp. 233–248.

[41] W. Cohen, R. Florida, J. Randazzese, and J. Walsh, „Industry and the Academy: Uneasy Partners in the Cause of Technological Advance“, in Challenges to the Research Universities, R. Noll, ed., Washington, D.C.: Brookings Institution Press, 1998, pp. 171–199.

[42] Schibany, L. Jörg, and W. Polt, „'Towards realistic expectations. The science system as a contributor to industrial innovation', tip-Studie“, 1999. [Online]. Available: http://www.tip.ac.at/publications/schibany_towards_indu_innov.pdf. [Accessed: 30-Jan-2012].

[43] https://duerer.usc.edu/pipermail/robotics-worldwide/2011-June/004197.html

[44] http://www.lithiumstudios.com/Syntouch/home.htm

[45] http://www.nsf.gov/nri

[46] http://www.cra.org/ccc

[47] http://www.research.uwaterloo.ca/watco/uw_researchers_ip_protection.asp

[48] http://www.roboticsathome.com

[49] http://www.rec.ri.cmu.edu/about/overview

[50] http://www.cmu.edu/startups

[51] http://spectrum.ieee.org/automaton/robotics/industrial-robots/obama-announces-major-robotics-initiative

Editor
Prof. Alois Knoll
Technische Universität München (TUM)
Department of Informatics VI
Robotics and Embedded Systems
Boltzmannstraße 3
85748 Garching bei München, Germany

Responsible for the report
Prof. Alois Knoll, TUM
Marie-Luise Neitz, TUM (Coordinator of the tour)
Laura Voss, TUM
Anna Marcos-Nickol, TUM
Amy Bücherl, TUM

Tour participants contributing to the report
Dr. Andreas Müller, University Duisburg-Essen
Dr. Reinhard Lafrenz, TUM
Geoff Pegman, R U Robots
Prof. Rolf Pfeifer, University of Zurich
Dr. Nicola Tomatis, Bluebotics SA
Prof. Fabio Bonsignorio, Heron Robots srl

Experts travelling
Prof. Alois Knoll, TUM
Prof. Bruno Siciliano, UNINA
Henrik Schunk, Schunk GmbH & Co. KG
Dr. Reinhard Lafrenz, TUM
Geoff Pegman, R. U. Robots
Prof. Rolf Pfeifer, University of Zurich
Dr. Nicola Tomatis, Bluebotics SA
Prof. Fabio Bonsignorio, Heron Robots srl
Prof. Jianwei Zhang, University of Hamburg

Picture credits
All image copyrights reserved by the respective experiment partners.

Design
Technische Universität München
ITSZ–Medienzentrum
www.mz.itsz.tum.de
design.mz@tum.de

Printing
Pinsker Druck und Medien GmbH
Pinskerstraße 1
D-84048 Mainburg

Edition
200 units

Publication
May 2012, Version 1.0

The ECHORD Consortium acknowledges support by the European Commission under FP7 contract 231143.

SEVENTH FRAMEWORK PROGRAMME

The ECHORD Consortium acknowledges support
by the European Commission under FP7 contract 231143.

echord@in.tum.de, www.echord.info
May 2012, Version 1.0