

## **From Internet to Robotics: The Next Transformative Technology**

Henrik I Christensen, Georgia Tech (PI)

Oliver Brock, UMASS

Ken Goldberg, UC Berkeley

John Hollerbach, Utah

Seth Hutchinson, UIUC

Leslie Kaebbling, MIT

Vijay Kumar, UPENN

Matt Mason, CMU

Gaurav Sukhatme, USC

Sebastian Thrun, Stanford

Jeff Trinkle, RPI

### **Introduction**

The present proposal outlines an effort to develop and promote a unified agenda for robotics R&D across US agencies, industries and universities.

Robotics is a set of ideas and technologies that will transform our lives by enabling computers to interact intimately with the physical world.

The transformational potential of robotics is already evident. Manufacturing technology saw the earliest and most thorough introduction of robotics. Robots now perform almost all welding and painting tasks in the automotive industry. The resulting improvements in quality and productivity are essential to compete with producers in Asia and Europe. At present more than 150,000 industrial robots are in use in the US, and the market is growing at a rate of 14% annually.

More recently, robotics has begun to transform the cars themselves. Both Toyota and Lexus produce cars that can park themselves automatically. Some manufacturers' current production models incorporate radar and sonar systems that provide advanced distance-keeping cruise control, collision warning, and even adjust the vehicle when a collision is anticipated. The rapid advance of driving technology is attested by the DARPA Urban Grand Challenge, predicated on the thesis that much of the key technology for fully autonomous driving can be demonstrated today. Further advances have enormous potential. Every year traffic accidents kill about 43,000 people and injure close to 2.7 million people<sup>1</sup>. The resulting economic cost is very significant. Additional economic gains would follow from autonomous driving, because of the enormous amount of time we spend driving. Today the average commute time for people going to work is 30 minutes. If this time could be spent more effectively it would have significant economic implications.

Robotics is also beginning to affect our home lives. Vacuum cleaners are the first significant market in home service robots. Close to 3 million autonomous vacuum

---

<sup>1</sup> NHTSA's National Center for Statistics and Analysis

cleaners have been sold across the 112 million homes in the US. In the domestic segment a large number of entertainment robots are expected to follow Sony's AIBO, LEGO MindStorm, Papero, RoboSapiens, and others.

Robotics is also beginning to impact health care. Telerobotic systems such as the Da Vinci system are performing heart and prostate surgery, resulting in shorter recovery times and more reliable outcomes. The potential in rehabilitation is even greater. When people experience a stroke it is essential that they start rehabilitation and physical therapy as soon as possible, but there aren't enough physical therapists to meet the need. Experiments have demonstrated that robotic systems can provide therapy with little or no supervision by therapists, and can continue therapy in the home after hospitalization. Health care, rehabilitation, and elder care are especially important application areas given the aging population both inside the United States and in other developed countries.

These examples are all early indicators of the likely impact of robotics. The growing breadth and accelerating pace of applications have led many to believe that we are entering an age of robotics. (See the feature article "Robotics" by Bill Gates in the March 2007 issues of Scientific American, for example.) Robotics technology has reached the point that the American business community is making substantial commitments. The recent creation of a Congressional Caucus on Robotics is evidence of increasing interest and commitment by governmental leadership.

There is an international competition for leadership in robotics research. We lost the previous competition: the robotics industry started in the United States, but as a result of sustained commitment by our competitors, 80% of the present industrial market is served by European and Asian companies. If robotics technology is now poised to transform other industries, including information technology, the stakes are much higher. It is essential that the robotics research community proceed in a strategic and coordinated way to produce the continuing basic research advances, and the resulting technology that our business and government communities expect and require.

The proposed program would develop a robotics research agenda that relates strategic applications to underlying basic research, addresses the roles of the different funding agencies, and presents a program that serves the economic and social needs of the nation.

### **Societal Context**

Recent demographic studies suggest that we will go through a period of significant aging over the next 2-3 decades. Japan will see a doubling in the number of elderly<sup>2</sup> people, Europe will have a 50% increase and USA will experience a ~40%<sup>3</sup> increase in the number of elderly by 2030. An additional aspect is that the number of people with an age above 80 will increase by more than 100% across all continents<sup>4</sup>. Advances in

---

<sup>2</sup> Elderly are here defined as people of age 65 and older.

<sup>3</sup> U.S. Census Bureau, 2004, "U.S. Interim Projections by Age, Sex, Race, and Hispanic Origin,"

<sup>4</sup> Data from Paul Wallace, AgeQuake, Bredslley Publishing, UK 1999`

medicine result in a longer life-span and this in combination with reduced birthrates imply that we will be seeing a significant aging of society in general. Such an aging will impact many aspects of society such as industrial production, housing, continued education, and healthcare. Many of these aspects could be directly impacted by use of robotics. As an example, continued economic growth as we know it today will require at least a 50% increase in productivity per capita, which can only be achieved through increased automation. If the productivity increase were to happen with manual labor then US would have to double its present immigration rate<sup>5</sup>. In terms of healthcare and elderly care, institutionalized care is not considered a viable alternative. People will want to have a choice in terms of where they live and who is taking care of them. In general people will want to feel independent. Technology offers solutions to allow them to take care of basic functions such as “getting out of bed”, “getting dressed”, “preparing a meal”, “going to the restroom”, “cleaning” etc.

### **International Context**

Our foreign colleagues are organizing strong coherent R&D programs. In Europe, robotics has seen a tremendous growth over the last decade. In 1995 the research was fairly uncoordinated but through the setup of a network across the 200 most important R&D actors in Europe it has been possible to define a joint research initiative that involves all the major industries and universities. The initiative has generated a higher degree of cohesion and a strong push for the robotics industry. As an example ABB and KUKA today are some of the primary providers of manufacturing systems. At the same time new defense initiatives have also required the main providers (SAGEM, Diehl, Daimler, Finmeccanica, ...) to coordinate their efforts to compete against US based companies. To ensure an adequate basic research volume the European Commission has, as part of its 7th Framework Programme, defined a so-called Technology Platform for Robotics (European Robotics Platform - EUROP). The initiative has enabled a number of different EU offices to launch robotics research programs such as the robotics / cognitive systems program (200 M\$ in funding) and the Manufature program (170 M\$).

In South Korea, robotics has been identified as one of the 10 most important economic drivers for the future. Korea has in the past been heavily dependent on outside technology to drive their electronic and automotive industries. The present push is directed at making Korea a major provider of the core technologies in robotics. Various agencies have defined significant programs on robotics across automotive assembly, domestic robotics, electronics, etc. To support these initiatives basic research is also pursued by agencies such as MOCIE (180 M\$), MIC (80 M\$) and MOST (70 M\$). The Korean program is a 10-year initiative with the objective of making Korea the second largest provider of robotics worldwide (after Japan). The Korean program is driven forward according to a detailed national roadmap for robotics.

In Japan, the Ministry of Industry and Economic Development (MITI) has for a long time sponsored robotics. Over the next 2 decades the number of elderly people in Japan will

---

<sup>5</sup> Paul Wallace, “AgeQuake” Bredslley Publishing, UK 1999

double, while the overall population growth is very limited. This situation challenges the general economic growth for Japan. To address this generational imbalance, robotics is seen as an enabling technology to increase productivity, to assist in home-care, etc. The Humanoid program (150 M\$) was an attempt to build robots that are well suited for operation in environments designed for human by humans (i.e. without a need to change the environment to accommodate the robots). More recently new initiatives have been launched on service robotics (80 M\$) and intelligent environments (120 M\$).

In the US, corresponding initiatives are not in place. Significant efforts are sponsored by DoD related agencies but these programs are of a much more applied nature with little room for basic research that could be the foundation for a new industry. In addition the DoD programs lack efforts related to domestic services and manufacturing.

### **The Vision**

Robotics encompasses several technologies to enable computers to interact more effectively with the real world. A computer today has no awareness of its physical surroundings, and is largely unable to react to physical events. Robotics is developing techniques allowing computers to perceive their surroundings, to interpret those perceptions, and act effectively to accomplish physical tasks. And while robots may not exhibit human-level performance for many years, it is becoming evident that human-level perception and intelligence is not necessary for numerous high-impact applications.

For example, an essential part of the drug discovery process is testing of promising drugs on lab mice. This step is so expensive that it creates a bottleneck that adversely affects the entire drug discovery pipeline. The reason for the expense is not the mice; it is the people who have to monitor the mice and record their behavior in excruciating detail. Instrumented animal cages have now been combined with perceptual software, behavior recognition, and machine learning to automate this step<sup>6</sup>.

The example illustrates the profound disruptive transformation robotics introduces. We simply have no experience with extremely inexpensive perception or intelligence. Even the most inexpensive human labor can be orders of magnitude more expensive than a robotic system. There will be numerous unanticipated applications.

There are a wide variety of important potential applications. Some applications have already been described: telerobotic surgery, physical therapy, autonomous driving, and manufacturing automation. However, this is just the beginning. As the cost of cameras and processors continue downward, the performance vision algorithms improve, and the communications bandwidth increases, it will be a simple matter to have semi-intelligent monitoring of any space one cares to monitor. This includes drug testing, security doors, international borders, environmental monitoring, elderly and sick people, infants, pets, and one's home. We are also seeing very promising educational applications. For example, speech recognition has been combined with cognitive modeling to develop

---

<sup>6</sup> United States Patent 7209588

automated reading tutors that can listen to a child read and interact with the child to encourage it (Project Listen). While the system is not as good as the best human tutors, it is about as good as an average tutor, and significantly better than reading alone. The system has also been adapted to teach English as a second language in Ghana.

Perhaps the most profound change will be an extension to the internet. The internet now provides access to sources of information all around the world, and connects human users in sometimes very surprising ways. Networked robots will likely play a significant role in the development of a 'Google for the physical world'. And yet, the internet is still limited mostly to information that has been entered by humans. There is an enormous amount of latent information in the physical world, which will become accessible through robotics technology. At the same time the internet becomes a more effective interface between humans, enabling communication through physical media, not just abstract symbolic messages and images.

This vision involves many advances in the basic foundations of robotics, and many new technologies. It also requires substantial continuing investments by the business community, and significant training and re-training of the human workforce. We aim for a society one or two decades in the future, where the constant demands for increasing productivity will combine with the aging population and social imperatives for a clean environment to create an absolute requirement for robotics.

### Process

The objective of the proposed program is to formulate a research agenda on robotics across several different agencies such as NSF and NIH. To enable this, the definition of key problems will be pursued both from an applications and a basic theory perspective. One may envisage the needed process as composed of basic theoretical models for physical interaction, simulation, model based control, perception, etc and competencies through which key functionality is made available and finally integration of competencies into applications. The basic building blocks are shown in figure 1.

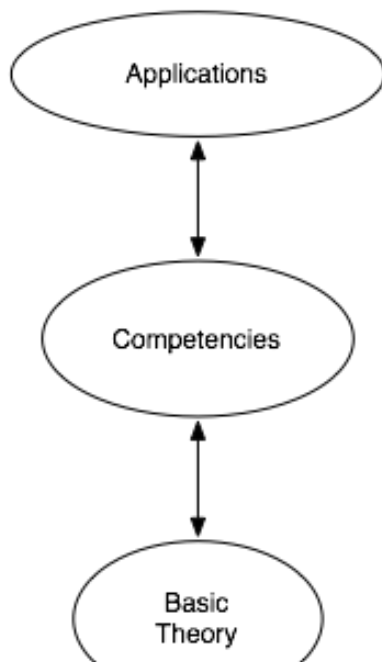


Figure 1 Basic building blocks from theory to applications.

Innovations can both be driven forward by a market pull or by a technology push. This corresponds to two different flows of ideas in the diagram in figure 1. It can be anticipated that different application areas have different requirements and the drivers for growth vary tremendously. However it is envisaged that many of the same competencies can be utilized across different applications. I.e. navigation systems are required on all mobile systems, and vision-based recognition is required in many manipulation tasks, etc. Finally one would expect that the theoretical basis for competencies and applications is a relatively well-defined set of models.

Several different competencies will exploit the same theoretical tools. As an example hybrid control theory is utilized both for manipulation systems and as part of mobile robot systems. Consequently, analysis of requirements across several different application domains will result in an R&D supply chain as shown in figure 2.

An important part of the roadmapping process is thus to identify the key competencies for continued growth of the robotics industry but also to identify the main theoretical challenges to be addressed to ensure future growth. Commercial interests will often sponsor application development if the payback is evident in a short-term perspective and if the associated risk is manageable. Research into basic theoretical models on the other hand carries a higher risk and the payback is over a significantly longer time scale. Consequently the studies of basic theory and fundamentally new competencies are in more need of support in a comprehensive robotics program.

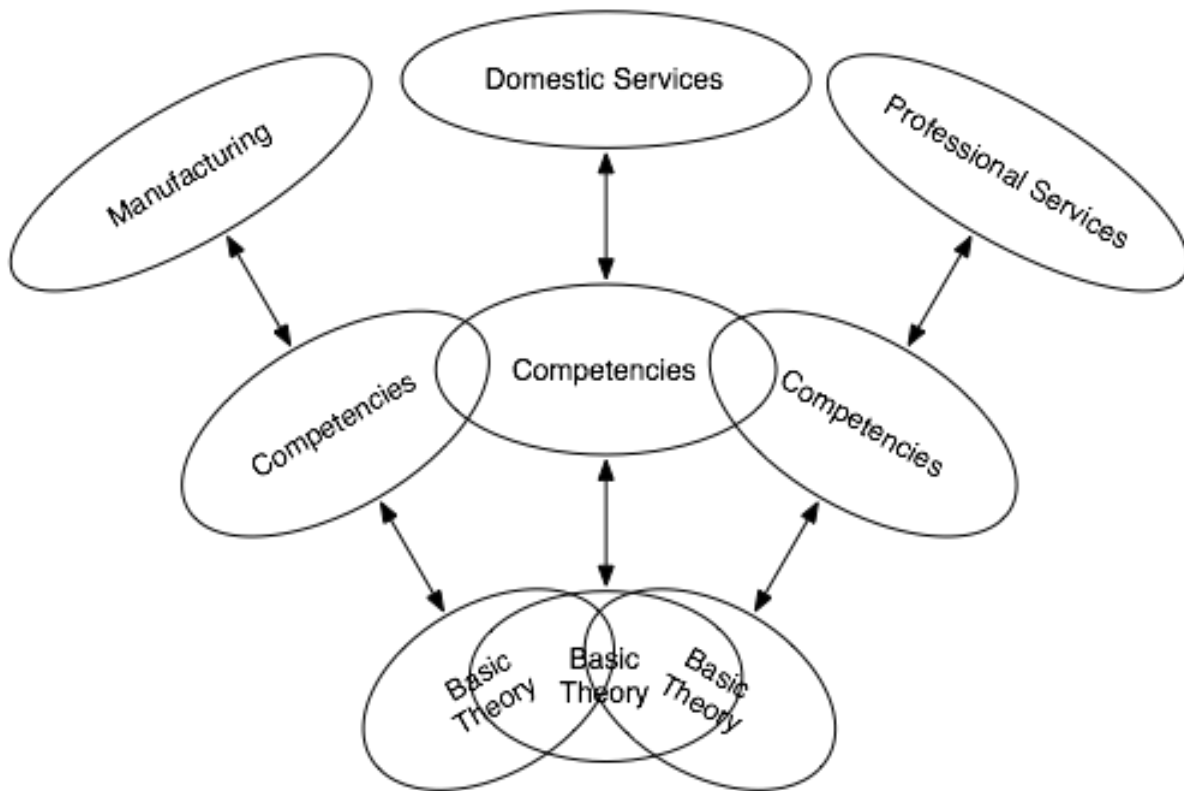


Figure 2: The relation and overlap across a number of different applications and related competencies and basic theories.

As part of the process to define a program in robotics topical workshops will be organized across

- Manufacturing
- Domestic Services and Healthcare
- Professional Services

Each topical workshop is to identify key application / economic drivers and specify the main obstacles to progress. What are the most basic competencies needed to deliver on such applications? Once competencies have been identified the associated set of missing theoretical tools/models will be specified.

In parallel, a workshop will pursue identification of the key science results expected to appear over the next decade based on extrapolation from current state of the art in robotics and IT in general. What are the key inventions anticipated that could radically change the premises for deployment and use of robotics?

Broad involvement across the research community is essential for this process to be successful. Consequently it is anticipated that four proposed topical workshops will have a significant number of participants. A core group will then be asked to synthesize the main findings from each workshop in terms of key applications, key competencies and associated theoretical models/tools. Reports from the workshops will be published on a web facility and requests for comments will be circulated over a period of one month.

Once the topical reports are available, a smaller workshop will be organized to identify common needs for competencies and also the corresponding set of theoretical needs. Again a synthesis process will be used to identify the main findings from the workshops. A workshop report will be made available to the wider community for comments and suggestions.

Finally based on the full set of reports, a proposal for a research program will be put forward for presentation to CCC and to the wider community. It is anticipated that a number of different program proposals will be generated. Each of them will target a specific agency such as NIH, NSF, DHS, etc. However it will be characteristic that all of them will be based on the community wide plan for R&D in robotics and with a clear view to how different efforts will be complementary and feeding into a common vision for the field in general.

### **Timeline**

It is anticipated that the effort will get underway Spring 2008. The topical workshops will all take place during Spring 2008 with reports available for comments by June 2008. The synthesis workshop is then expected to take place during Fall 2008 with a joint program statement available before the end of 2008. During the Spring of 2009 a number of different program proposals will emerge and direct meetings with different agencies will take place.

Jan 2008	Initiation of effort Formal organization of effort with an executive council
Feb 2008	Web facility online with information about the initiative Call for Participation in topics Workshops
Mar 2008	Topical workshops
Apr 2008	Draft reports from topical workshops

May 2008	Reports available for comments on community web facility
Jun 2008	Revised version of topical reports Internal review of the process to ensure cohesion
Sep 2008	Synthesis workshop organized
Oct 2008	Draft version of synthesis workshop report Request for comments from community
Nov 2008	Revision of Synthesis Report Identification of program priorities
Dec 2008	Report on the overall process for robotics
Jan 2009	Organization of groups to formulate agency specific program proposals
Mar 2009	Draft versions of agency specific proposals
Apr 2009	Meetings with different agencies jointly with CRA/CCC
Jun 2009	Final report on initiative on the web facility
Dec 2009	The effort is closed and a final report is submitted to CCC.

**Budget**

	Year 1	Year 2	Total
<u>PERSONAL SERVICES</u>			
Faculty	\$0	\$0	\$0
Faculty	\$0	\$0	\$0
Faculty	\$0	\$0	\$0
Faculty	\$0	\$0	\$0
Total Senior Personnel	\$0	\$0	\$0
Post Doc	\$0	\$0	\$0
Research Scientist	\$0	\$0	\$0
TBA-mo	\$0	\$0	\$0
GRAs @ 50%	\$4,876	\$5,120	\$9,995
GRAs @ 37.5%	\$0	\$0	\$0
Secretarial	\$7,500	\$7,875	\$15,375
Total Other Personnel	\$12,376	\$12,995	\$25,370
Total Personal Services	\$12,376	\$12,995	\$25,370
<u>FRINGE</u>			
@26.4%	\$1,980	\$2,079	\$4,059
Total P.S. & Fringe	\$14,356	\$15,074	\$29,429
<u>EQUIPMENT</u>			\$0
<u>TRAVEL</u>	\$10,000	\$4,000	\$14,000
<u>OTHER DIRECT COSTS</u>			
Materials & Supplies	\$40,000	\$25,000	\$65,000
Publication Costs	\$4,000	\$6,000	\$10,000
GRA Tuition \$583/mo	\$1,312	\$1,312	\$2,624
Consulting			\$0
Computing Charge	\$1,570	\$1,570	\$3,140
Total Other Direct	\$46,882	\$33,882	\$80,764
<u>TOTAL DIRECT COSTS</u>	\$71,238	\$52,955	\$124,193
<u>INDIRECT</u>			
@ 51.0%	\$35,662	\$26,338	\$62,000
<u>TOTAL DIRECT &amp; INDIRECT</u>	\$106,900	\$79,294	\$186,193

## **Budget Motivation**

A majority of the costs are related to organization and reimbursement of people for participation in the meetings. The initiative will provide partial reimbursement of travel and accommodation expenses for the meetings. Meeting expenses in terms of facilities and meals/food will also be covered from the “materials & support” part of the budget. People will be invited as needed for these meetings and open access is the operative concept – the expectation is to have 10-25 people per workshop. In addition resources are requested for a part-time graduate assistant to maintain a web facility. The administrative staff person will be responsible for handling the logistics of the workshops, and pulling together the various reports from these workshops.

Direct payment for faculty time is not included in the budget as priority has been to provide participation support for as wide a community as possible.

## **CV for Process Coordinator – Henrik I Christensen**

Dr. Henrik I Christensen received his initial training in Mechanical Engineering and subsequently spent time with MAN B&W Diesel building automation systems. He received M.Sc. and Ph.D. EE degrees from Aalborg University, 1987 and 1990, respectively. Upon graduation he has held positions with Aalborg University, Swedish Royal Institute of Technology and Georgia Institute of Technology. Dr. Christensen does research on human-robot interaction, estimation and mapping, systems integration and vision. He has published more than 230 contributions across computer vision, robotics and artificial intelligence. Results from his research has been commercialized by companies such as Electrolux, ABB, Siemens, Daimler, KUKA, WEDA, Intelligent Machines, PerMobil, and iRobot. Dr. Christensen is also the co-founder of 4 companies across health care, entertainment, robotics and IT-Systems.

Dr. Christensen has participated in a large number of international projects across 4 continents. For the period 1999-2006 he was the founding chairman of the European Network of Excellence in Robotics – EURON, which includes more than 200 universities and companies across all EU member states. EURON was the main driver for the new robotics/cognition initiative by the European Commission. In addition he was the research coordinator of the EU network on excellent in computer vision – EcVision (2000-2004). Dr. Christensen has also served as a consultant to a large number of governmental agencies and companies across 4 continents.

Henrik Christensen is at present the KUKA Chair of Robotics and a Professor of Computing at the Georgia Institute of Technology where he also is the director of the cross disciplinary Center for Robotics and Intelligent Machines.

Dr. Christensen has served/serves on the editorial board for many journals in the field of computer vision, robotics and artificial intelligence such as IEEE PAMI, IJRR, RAS, AI Magazine, IJPRAI, AutRob, Service Robotics. Dr. Christensen is a member of IEEE and an officer of IFRR. He also serves as a government appointee on the board of trustees for the Swedish Foundation for Internationalization of Research and Education – STINT (2003-2007)