

CCC/Robotics - Roadmap f. Service Robotics

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1. Introduction

Service Robotics is defined as those robotics systems that assist people in their daily lives at work, in their houses, for leisure, and as part of assistance to handicapped and elderly. In industrial robotics the task is typically to automate tasks to achieve a homogenous quality of production or a high speed of execution. In contrast, service robotics tasks are performed in spaces occupied by humans and typically in direct collaboration with people. Service robotics is normally divided into professional and personal services.

Professional service robotics includes agriculture, emergency response, pipelines and the national infrastructure, forestry, transportation, professional cleaning, and various other disciplines.

[Professional service robots are also used for military purposes but their application in this area is not included in this report.] These systems typically augment people for execution of tasks in the workplace. According to the IFR/VDMA World Robotics more than 38,000 professional robots are in use today and the market is growing rapidly every year. Several typical professional robots are shown in figure 1.

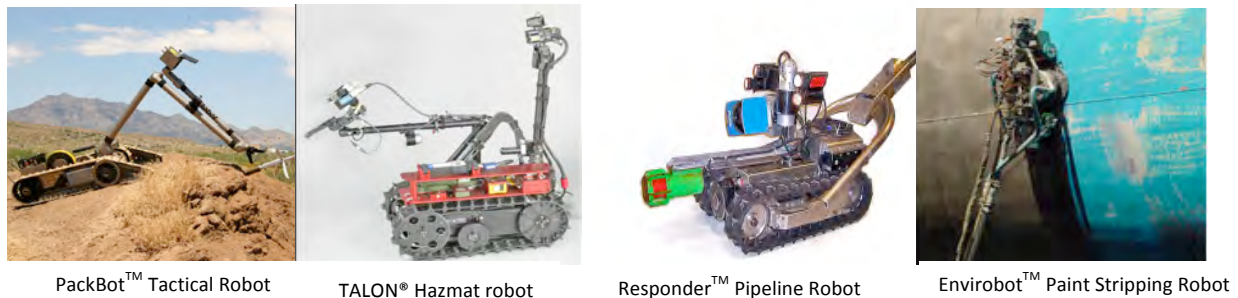


Figure 1: Typical service robots for professional applications.

Personal service robots on the other hand are deployed for assistance to people in their daily lives in their homes or as assistants to them for compensation for mental and physical limitations. The by far largest group of personal service robots consists of domestic vacuum cleaners; over 3 million iRobot Roomba's alone have been sold worldwide and the market is growing 60%+ / year. In addition, a large number of robots have been deployed for leisure applications such as artificial pets (AIBO), dolls, etc. With more than 2 million units sold over the last 5 years, the market for such leisure robots is experiencing exponential growth and is expected to remain one of the most promising in robotics. A number of typical personal service robot systems are shown in figure 2.



Figure 2: Typical service robots for personal applications.

The service robots panel included both professional and personal services and as such covered a highly diverse set of applications and problems.

2. Strategic Findings

After much discussion, there was general agreement among those present at the meeting that we are still 10 to 15 years away from a wide variety of applications and solutions incorporating full-scale, general autonomous functionality. Some of the key technology issues that need to be addressed to reach that point are discussed in a later section of this report. There was further agreement among those present, however, 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. Commercial products and applications based on existing technology have already begun to emerge and more are expected as entrepreneurs and investors realize their potential. The participants identified several markets where these early commercial solutions are appearing and where service robotics is likely to have the greatest impact. Among the areas identified are healthcare, national infrastructure and resource management, energy and the environment, security, transportation and logistics, and education and entertainment.

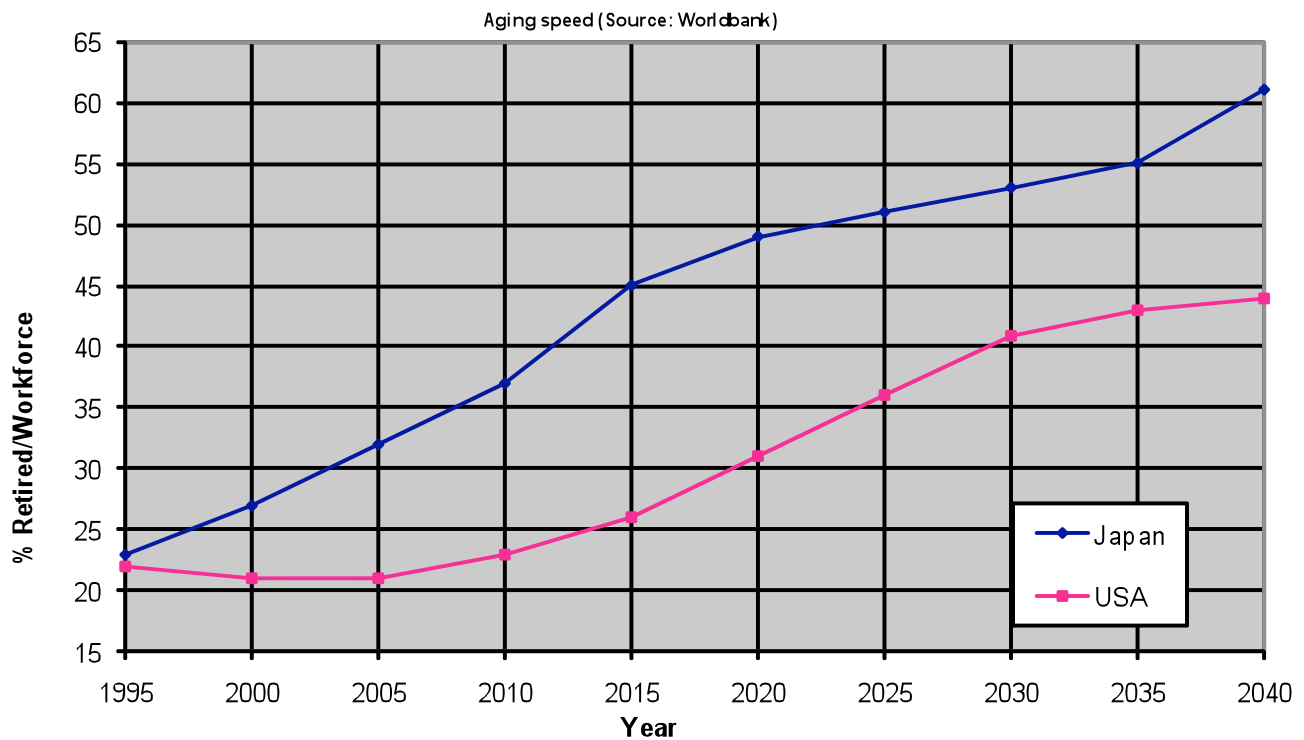


Figure 3. The changes in demographics in USA and Japan respectively.

One of the key factors contributing to the identified trends is our aging population. This impacts service robotics both in terms of the need to address a shrinking work force as well as the opportunity to develop solutions that will meet their healthcare needs. As shown in figure 3, the United States is on the threshold of a 20 year trend that will see a near doubling of the number of retire workers as a percentage of the current workforce; from just over 2 retirees for every 10 workers today to just over 4 retirees for every 10 workers in 2030. In Japan the situation is even worse and has fueled a major national initiative to develop the robotics technology needed to help care for their rapidly aging population. Generally speaking, *professional* service robotics is expected to serve as a workforce multiplier for increased economic growth, while *domestic* service robotics is expected to enable sustained personal autonomy.

While increasing productivity and reducing costs are the common denominator of service robotics, each system is expected to uniquely provide a compelling solution to certain, critical market specific issues or needs. For example, a key, primary driver in using robotics technology to automate the automobile factories was the desire to obtain consistent, day-to-day quality and avoid the “built on Monday” syndrome.

2.1 Principal Markets and Drivers

Healthcare & Quality of Life – the current application of robotics technology to provide tele-operated solutions such as Intuitive Surgical’s daVinci surgical system represents the tip of the iceberg. Robotics technology holds enormous potential to help control costs, empower healthcare workers, and enable aging citizens to live longer in their homes.

Energy & Environment – the attendees identified these two closely linked issues as both critical to the future of our country and ripe for the emergence of robotics technology applications, especially in the areas of automating the acquisition of energy and monitoring the environment.

Manufacturing & Logistics – beyond the traditional application of robotics technology to automate certain assembly line functions, the meeting participants agreed that there is tremendous potential to further automate the manufacture and movement of goods; as fully explored in the parallel roadmapping effort in this area. In particular, robotics technology promises to transform small scale, or “micro”, manufacturing operations and in the process help accelerate the transition of manufacturing back to America. This belief has since been substantiated by the formation of a new start-up robotics company, Heartland Robotics, organized specifically for that purpose.

Automotive & Transportation – although we are still decades away from the fully autonomous automobile, robotics technology is already appearing in the form of advanced driver assistance and collision avoidance systems. Public transportation is another area that is expected to become increasingly automated. As robotics technology continues to improve and mature, 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.

Homeland Security & Infrastructure Protection – participants in the meeting agreed that robotics technology offers tremendous potential for applications in border protection, search and rescue, port inspection and security, and other related areas. In addition, robotics technology is expected to

be increasingly used to automate the inspection, maintenance, and safeguarding of our nation's bridges, highways, water and sewer systems, energy pipelines and facilities, and other critical components of our nation's infrastructure.

Entertainment & Education – this area, perhaps more than any other has seen the early emergence of robotics technology enabled products. In particular, robotics has the potential to significantly address the science, technology, engineering, and math (“STEM”) crisis facing the nation and to become the veritable “fourth r” of education. This is evidenced by the tremendous success of FIRST, a non-profit organization founded in 1999 that runs national robotics competitions to inspire young people to be science and technology leaders, and other robotics inspired educational initiatives. Robotics provides kids with a compelling and tactile avenue to learn and apply both the underlying key mathematics and science fundamentals and the engineering and system integration principles required to produce intelligent machines to accomplish certain missions.

2.2 Near Term Opportunities and Factors Effecting Commercialization

Significant investment is required for expanded research and development of robotics technology if the full promise of what can be achieved in each of the above areas is to be realized. As noted above, we are still a long way from the fully autonomous robotics technology required to automate processes to the extent that no human attention or intervention is required. That said, it was the collective opinion of those in attendance that enough progress in robotics technology has been made to enable the development and marketing of a wide variety of initial applications and products in each of these areas to achieve significant levels of “human augmentation”.

Such solutions will be capable to varying degrees of automatically performing the following types of functions: monitoring defined, yet dynamic physical environments, identifying objects, detecting changes, or otherwise perceiving the status of their assigned environments, analyzing and recommending actions that should be taken in response to detected conditions, taking such actions in response to human commands, and/or automatically performing such actions within certain pre-authorized boundaries not over-ridden by human operators.

Examples of such robotics solutions today include tele-operated systems such as the daVinci surgical system and autonomous, specialized productivity tools such as the Roomba. As the Internet continues to evolve, it will inspire a natural progression from sensing at a distance to taking action at a distance. This extension of the Internet into the physical world will serve to further blur the boundaries among community, communication, computing, and services and inspire new dimensions in telecommuting and telepresence applications. Hybrid solutions are likely to emerge that enable distributed human cognition and enable the efficient use of human intelligence. Such solutions will combine the robotics-enabled capability to remotely and autonomously perceive situations requiring intervention with the Internet-enabled capability for human operators to take action from a distance on an as-needed only basis.

As referenced above, our aging population will result in a future labor shortage. As workers seek to move up the job hierarchy, there will be a growing need to augment and increasingly automate jobs at the bottom because the workers to perform them may not be readily available and eventually may not exist. While the challenge of achieving fully autonomous solutions in the long run remains primarily technological, the challenge in the near term is one of investing in the science of developing requirements and otherwise determining 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.

2.3 Scientific and Technical Challenges

Workshop participants worked in three break-out groups to identify technical and scientific challenges pertinent to the applications and business drivers described in the previous section. The first break-out group focused on **application and systems design**; the second group discussed **action, cognition, planning, and other elements of robotic intelligence**; and the final group identified challenges in **human robot interaction**. This section summarizes their findings. Because the challenges identified by the three groups span the boundaries between the respective topic areas, we will present the technical and scientific challenges identified by the break-out groups in an integrated manner. The emphasis of this section is on describing the challenges, not on laying out a roadmap towards addressing these challenges—such a roadmap will be outlined in the next section.

Mobility

Mobility has been one of the success stories of robotics research. This success is exemplified by a number of systems with demonstrated performance in real world environments, including museum tour guides and autonomously driving cars, as in the DARPA Grand Challenge and Urban Challenge. Nevertheless, workshop participants agreed that a number of important open problems remain. Finding solutions to these problems in the area of mobility will be necessary to achieve the level of autonomy and versatility required for the identified application areas.

Participants identified **3D navigation** as one of the most important challenges in the area of mobility. Currently, most mapping, localization, and navigation systems rely on two-dimensional representations of the world, such as street maps or floor plans. As robotic applications increase in complexity and are deployed in every day, populated environments that are more unstructured and less controlled, however, these 2D representations will not be sufficient to capture all aspects of the world necessary for common tasks. It will therefore be important to enable the acquisition of three-dimensional world models in support of navigation and manipulation (see next section). These 3D representations should not only contain the geometry layout of the world; instead, maps must contain task-relevant **semantic** information about objects and features of the environment. Current robots are good at understanding where things are in the world, but they have little or no understanding of *what* things are. When mobility is performed in service to manipulation, environmental representations should also include **object affordances**, i.e. knowledge of what the robot can use an object for. Achieving **semantic 3D navigation** will require novel methods for sensing, perception, mapping, localization, object recognition,

affordance recognition, and planning. Some of these requirements are discussed in more detail later in this section.

One of the promising technologies towards semantic 3D mapping, as identified by the participants, is using different kinds of sensors for building maps. Currently, robots rely on very high precision laser-based measurement systems for learning about their environment, using mapping algorithms known as "SLAM" algorithms. The participants identified a desire to move away from lasers to cameras, to develop a new field of "visual SLAM" (VSLAM). This technology relies on cameras, which are robust, cheap, and readily available sensors, to map and localize in a three-dimensional world. Already today, VSLAM systems exhibit impressive real-time performance. Participants therefore believed that VSLAM will likely play a role in the development of adequate and more affordable 3D navigation capabilities.

Participants identified additional requirements for 3D navigation that will be critical to meet the requirements of targeted applications. **Outdoor 3D navigation** poses a number of important challenges that have to be addressed explicitly. Among them is the fact that current 2D environmental representations cannot capture the complexity of outdoor environments nor the changing lighting conditions that cause substantial variability in the performance of sensor modalities. Participants also identified robust **navigation in crowds** as an important mobility challenge.

Manipulation

Substantial progress in manipulation is needed for almost all of the service robotics applications identified in the previous section. These applications require a robot to interact physically with its environment by opening doors, picking up objects, operating machines and devices, etc. Currently, autonomous manipulation systems function well in carefully engineered and highly controlled environments, such as factory floors and assembly cells, but cannot handle the environmental variability and uncertainty associated with open, dynamic, and unstructured environments. As a result, participants from all three break-out groups identified **autonomous manipulation** as a critical area of scientific investigation. While no specific directions for progress were identified, the discussions revealed that the basic assumptions of most existing manipulation algorithms would not be satisfied in the application areas targeted by this effort. **Grasping and manipulation** suitable for applications in open, dynamic, and unstructured environments should leverage prior knowledge and models of the environment whenever possible, but should not fail catastrophically when such prior knowledge is not available. As a corollary, truly autonomous manipulation will depend on the robot's ability to **acquire adequate, task-relevant environmental models** when they are not available. This implies that—in contrast to most existing methods which emphasize planning and control—**perception** becomes an important component of the research agenda towards autonomous manipulation.

Participants identified novel **robotic hands** (discussed in the subsection on Hardware), **tactile sensing** (see Sensing and Perception), and highly-accurate, physically realistic simulators as important enablers for autonomous manipulation.

Participant suggested that competent "**pick and place**" operations may provide a sufficient functional basis for the manipulation requirements of a many of the targeted applications. It was therefore

suggested that pick and place operations of increasing complexity and generality could provide a roadmap and benchmark for research efforts in autonomous manipulation.

Planning

Research in the area of motion planning has made notable progress over the last decade. The resulting algorithms and techniques have impacted many different application areas. Nevertheless, participants agreed that robust **dynamic 3D path planning** remains an open problem. An important aspect of this problem is the notion of a robot's **situational awareness**, i.e. the robot's ability to autonomously combine, interleave, and integrate the planning of actions with appropriate sensing and modeling of the environment. The term "appropriate" alludes to the fact that complete and exact models of the environment cannot be acquired by the robot in real time. Instead, it will be necessary to reason about the objectives, the environment, and the available sensing and motor actions available to the robot. As a result, the boundary between planning and motion planning is blurred. To plan a motion, the planner has to **coordinate sensing and motion under the constraints imposed by the task**. To achieve task objectives robustly and reliably, planning has to consider **environmental affordances**. This means that the planner has to consider interactions with the environment and objects in it as part of the planning process. For example: to pick up an object, it may become necessary to open a door to move into a different room, to push away a chair to be able to reach to a cabinet, to open the cabinet door, and to push an obstructing object out of the way. In this new paradigm of planning, the **task and constraints imposed by the task and the environment** are the focus; the "motion" of "motion planning" is a means to an end. Constraints considered during planning can arise from **object manipulation, locomotion (e.g. footstep planning), kinematic and dynamic constraints of the mechanism, posture constraints, or obstacle avoidance**. Planning under these constraints must occur in **real time**.

Some of the constraints on the robot's motion are most easily enforced by leveraging sensor feedback. Obvious examples are **contact constraints** and **obstacle avoidance**. The area of **feedback planning** and the integration of **control and planning** are therefore important areas of research towards satisfying the planning requirements identified by the participants. A feedback planner generates a policy that directly maps states to actions, rather than generating a specific path or trajectory. This ensures that sensor, actuation, and modeling uncertainties can adequately be addressed using sensory feedback.

The increased complexity of planning in this context will also require novel ways of capturing **task descriptions**. While in classical motion planning the specification of two configurations fully specified a planning task, the view of planning described here has to handle much richer task representations to address the richness of manipulation tasks and intermediate interactions with the environment.

Participants also perceived the need for formal methods to perform **verification and validation** of the results of planners. Such guarantees may be required to ensure safe operation of robots in environments populated with humans.

Sensing and Perception

Sensing and perception are of central importance to all aspects of robotics, including mobility, manipulation, and human-robot interaction. Participants were convinced that innovation in sensing and perception will have profound impact on the rate of progress in robotics.

Participants believed that **new sensing modalities** as well as more **advanced, higher-resolution, lower-cost** versions of existing modalities would be areas of important progress. For example, participants expect important advances in manipulation and mobility alike from **dense 3D range sensing**, possibly by LIDAR. Advances in dexterous manipulation are likely to require **skin-like tactile sensors for robotic hands**. But also specialized sensors, for example for safety, termed **safety sensors**, were discussed by the participants. These sensors could take various forms, such as range or heat sensing to detect the presence of humans, or could be implemented by special torque sensors as part of the actuation mechanism, capable of detecting unexpected contact between the robot and its environment. **Skin-like sensors for the entire robotic mechanism** would also fall into this category.

The data delivered by sensor modalities must be processed and analyzed by algorithms for perception in complex and highly dynamic environments under varying conditions, including differences between day and night and obscurants like fog, haze, bright sunlight, and the like. Participants identified the need for progress in **high-level object modeling, detection, and recognition, in improved scene understanding, and in the improved ability to detect activities and intent**. Novel algorithms for **affordance recognition** are required to support the type of planning described in the previous subsection. Participants also discussed the need for **accurate sensor models** in support of perceptual algorithms.

Architectures, Cognition, and Programming Paradigms

The discussions on the topics of mobility, manipulation, planning, and perception revealed that these issues cannot be viewed in isolation but are intricately linked to each other. The question of how to engineer a system to effectively integrate **specific skills from those areas to achieve safe, robust, task-directed, or even intelligent behavior** remains an open question of fundamental importance in robotics. Research towards this objective has been conducted under the name of **architectures, cognition, and programming paradigms**. This diversity in approaches or even philosophical viewpoints may reflect the lack of understanding in the community on how to adequately tackle this challenge. This diversity of viewpoints is also reflected in the diversity of tools currently brought to bear on this issue: they range from imitation learning to explicit programming of so-called cognitive architectures. Some participants felt that a mixture of these would probably be required to achieve the desired outcome.

One of the classical approaches towards the overarching issue of generating robust, autonomous behavior is the **sense/plan/act loop** usually employed by modern control systems. While sense/plan/act has been a constant in robotics research over the last several decades, some participants felt that novel approaches would likely deviate from this approach in its simplest form. Possible alternatives are multiple nested or hierarchical loops, the behavior-based approach, combinations of the two, or possibly even completely novel approaches.

All participants agreed that this area of investigation will require substantial attention and progress on the path towards autonomous robotic systems.

Human Robot Interaction (HRI)

Given the ultimate goal of deploying mobile and dexterous robots in human environments to enable coexistence and cooperation, substantial progress will be required in the area of human robot interaction. These interactions could also become an important component in an overarching approach to robust robot behavior, as discussed in the previous subsection. Robot might learn novel skills from their interactions with humans but under all circumstances should be cognizant of the characteristics and requirements of their communication with humans.

In addition to the **modes of communication** (verbal, nonverbal, gesture, facial expression, etc.), participants identified a number of important research topics, including **social relationships, emotions** (recognition, presentation, social emotional cognition/modeling), **engagement**, and **trust**. An understanding of these aspects of human robot communication should lead to an automatic structuring of the interactions between humans and robots where robotic systems' ability to operate independently rises or falls automatically as both the task and the human supervisor's interaction with the system change.

Progress towards these objectives will depend on **effective input devices** and **intuitive user interfaces**. Participants also advocated the development of a variety of **platforms** to study HRI, including humanoid robots, mobile manipulation platforms, wheelchairs, exoskeletons, and vehicles. Participants identified a **design/build/deploy cycle** in which HRI research should progress. The design process should consider input from a number of relevant communities, including the basic research community and end users. The build process integrates numerous components and research threads into a single system; here there is an opportunity for industry collaborations and technology transfer. Finally, the integrated system is deployed in a real-world context. Participants suggested the notion of a **Robot City** (see next subsection) as a promising idea to evaluate HRI in a real-world context. The cycle is closed by incorporating end user feedback into the experimental design of the next iteration of the design/build/deploy cycle.

Research Infrastructure

Workshop participants felt strongly that rapid progress towards the identified scientific objectives will critically depend on the broad availability of adequate research infrastructure, including hardware and software. To address the research challenges given above, it will be necessary to construct robotic platforms that combine many advanced and interacting mechanical components, providing adequate capabilities for mobility, manipulation, and sensing. These platforms will be controlled by a multitude of independently developed, yet interdependently operating software components. As a result, these integrated robotic platforms exhibit a degree of complexity that is beyond what can easily be designed, developed, tested, and maintained by many independently operating research groups. The lack of standardization of hardware and software platforms may also result in a fragmentation of the research

community, difficulties in assessing the validity and generality of published results, and the replication of much unnecessary engineering and integration effort.

To overcome these challenges, workshop participants advocated coordinated community efforts for the development of hardware and software systems. These efforts should include the development of an **open experimental platform** that would—preferably at low cost—support a broad range of research efforts on the one hand, while enabling **technology and software reuse** across research groups on the other hand. One example of such an open platform is ROS, a robot operating system being developed by Willow Garage that enables code reuse and provides the services one would expect from an operating system, such as low-level device control, implementation of commonly-used functionality, and message-passing between processes. Ideally, such platforms would be complemented by **physical simulation software** to support early development and testing of algorithms without compromising the safety of researchers and hardware. Development efforts could also benefit from **robotic integrated development environments (IDEs)**; these IDEs enforced modularity in software development thereby facilitating reuse and documentation.

Participants noted that research in robotics is rarely thoroughly evaluated and tested in well-defined, repeatable experiments. Other fields, such as computer vision, have greatly benefited from publicly available data sets, which enabled an objective comparison between multiple algorithms and systems. The participants therefore suggested the creation and expansion of **repositories of experimental data**, which could then serve as community-wide benchmarks. However, as much of the research in robotics is focused on the physical interaction between the robot and its environment, electronic data sets are not sufficient. They should be complemented by **skill-specific benchmarks consisting of physical objects**. For example, a number of readily available objects can be selected as a benchmark for grasping research. Furthermore, entire **benchmark environments** were suggested to develop, evaluate, and compare the performance with respect to a particular application or implementation. Such environments could range in size and complexity from a simple work space (an office desk or a kitchen counter) to an entire room, a house, or an entire city block. In this context, the notion of a **Robot City** was mentioned: a regular urban environment in which all inhabitants are part of the experiment and help in the evaluation process as well as with the definition of adequate requirements for everyday application environments.

Many of the proposed efforts—and in particular **hardware or software integration** efforts—fall outside of the scope of existing funding programs. Participants noted that a policy change in this regard would be necessary to ensure that the availability of research infrastructure does not represent a bottleneck in the progress towards autonomous robotic systems in everyday environments.

Mechanical Hardware

Safety is a critical factor for the deployment of robotic systems in human environments. Inherently safe robots would also enable modes of human robot interaction that can increase acceptance of robotic technology in everyday life. Participants therefore felt that **inherently safer motors and mechanisms** with increased strength to weight ratio would represent an important enabling technology. In such mechanisms **variable compliance** would be a desirable property. The concept of variable compliance

refers to a mechanisms ability to adjust its behavior to reaction forces when contacting the environment. These reaction forces can be varied for different tasks. Such mechanisms enable safe operation, especially when interacting with humans, as well as flexible, robust, and competent motion when in contact with the environment. Furthermore, **energy efficiency** was identified as a critical concern for many applications, as robots will have to operate without tethers for extended periods of time. Finally, **novel or improved modes of locomotion beyond wheels** are needed to enable safe and reliable operation in indoor and outdoor environments. Outdoor environments oftentimes exhibit highly variable terrain properties while outdoor may contain stairs, ladders, ramps, escalators, or elevators.

Participants identified **highly dexterous and easily controllable robotic hands** as an important area for research. Progress in robotic grasping and manipulation very likely will go hand in hand with the development of novel hand mechanisms. At the same time, participants felt that the potential of current hand technology were not fully leveraged by existing grasping and manipulation algorithms. It is therefore conceivable that many interesting and relevant applications can be addressed with available grasping and manipulation hardware.

3. Key Challenges / Capabilities

3.1 Motivating Scenarios

Quality of Life

Robotics technology is expected to make a tremendous contribution to the lives of the elderly and disabled. One such example of an existing application is a revolutionary transportation mobility solution that enables



ATRSTM Robotic Wheelchair

those with limited mobility who use wheelchairs to independently get into and out of their vehicles and remotely load and unload their wheelchairs from a wide range of vehicles. This system makes it possible for those dependent on wheelchairs to transport their wheelchair using an ordinary passenger van and to access it whenever needed without assistance from others offering

them a degree of freedom and independence heretofore unavailable. This system provides significant benefits over existing transportation mobility solutions, including lower cost of ownership, ability to use standard crash-tested automotive seats, greater choice of vehicles, no required structural modifications, and ability to re-install on subsequent vehicles.

Agriculture

Robotics technology is expected to impact a myriad of applications in agriculture and address farmers' constant struggle to keep costs down and productivity up. Mechanical harvesters and many other agricultural machines require expert drivers to work effectively, while factors such as labor costs and operator fatigue increase expenses and limit the productivity of these machines. Automating operations such as crop spraying, harvesting, and picking offer the promise of reduced costs, increased safety, greater yields, increased operational flexibility, including night time



Autonomous Tractor

operations, and reduced use of chemicals. A number of such prototype systems and applications, including automated fruit crop spraying and field crop harvesting, have been developed and the technology has now matured to the point where it is ready to be transitioned for further commercialization and field deployment within the next few years.

Infrastructure

Robotics technology has tremendous potential to automate the inspection and maintenance of our nation's bridges, highways, pipelines, and other infrastructure. Already, the technology has been adapted to develop automated pipeline inspection systems that reduce maintenance and rehabilitation costs by providing accurate, detailed pipe condition information. Such systems, based on advanced multi-sensor and other robotics technology, are designed for underground structures and conditions that are otherwise difficult to inspect, including large diameter pipes, long haul stretches, invert, crowns, culverts, and manholes, and in-service inspections. These robotic platforms navigate this critical wastewater infrastructure to inspect sewer pipe unreachable by traditional means and produce very accurate 3D images of the pipe inside surface. The inspection information, captured in digital form, serves as a baseline for future inspections and as a result can automatically calculate defect feature changes over time.

Responder™ Pipeline Robot



Mining

Robotics technology is already starting to have a dramatic impact on both the underground and surface mining industries. An innovative belt inspection system that uses a high-speed "machine vision" system and software algorithms to monitor the condition of conveyor belts and help operators detect defects, for example, is in everyday use at several underground coal mines. The patented system is designed to reduce costly downtime caused by the degradation and eventual rupture of conveyor belt splices. On a larger scale robotics technology is being used to develop autonomous versions of large haul trucks used in mining operations. Caterpillar recently announced that it is developing an autonomous mining haulage system with plans to integrate autonomous haul trucks, each with payload capacities of 240 tons or more, into some mine sites by 2010. The autonomous technology is designed to provide productivity gains through more consistency in processes and minimize environmental impact by both improved efficiency and overall mine safety.



Autonomous Haul Truck

Transportation

Robotics technology will significantly affect every aspect of how we transport people and goods in the coming decades; from personal transportation systems to intelligent highways to autonomous public transportation systems. Companies such as Segway and Toyota have introduced personal transportation robots that are ridden in standing position and controlled by internal sensors that constantly monitor the rider's position and automatically make the according adjustments. Meanwhile, carmakers and device manufacturers are creating "smart cars" by installing more powerful computers and sensors, giving drivers a better idea of their [environment](#) and car performance.



Top Three Finishers in the 2008 DARPA Urban Grand Challenge

ago, the roads they are driving on have increased in capacity by only 5 percent, resulting in 3.7 billion hours of driver delays and 2.3 billion gallons of wasted fuel. To address this issue highway agencies are attempting to create “smart roads” by installing sensors, cameras and automatic toll readers and a public-private national initiative called Vehicle Infrastructure Integration (VII) has been launched to merge smart cars and smart roads to create a virtual traffic information network and bust up gridlock. Mass transportation systems are also expected to adopt robotics technology to provide operators with greater situational awareness and navigation assistance in crowded urban corridors thereby helping to control costs and increase safety.

Education

Robotics has already commenced transforming the American classroom. Robotics puts academic concepts in context and is being used at all levels in K-12 and college education. Robotics provides students with a

FIRST Lego League™ Participants



tactile and integrated means to investigate basic concepts in math, physics, computer science and other STEM disciplines, while enabling teachers at the same time to introduce concepts about design, innovation, problem solving, and teamwork. Robotics curriculums have been developed, teachers have been trained, and scores of competitions are held every year across the country. Perhaps the best known robotics competition programs are operated by FIRST, a non-profit organization founded in 1999 to inspire young people to be science and technology leaders. As a measure of the

growing popularity of robotics competitions, FIRST is expecting over 195,000 students to participate in its competitions in the coming year. Even more significantly, a recent Brandeis University survey found that FIRST participants are more than twice as likely to pursue a career in science and technology as non-FIRST students with similar backgrounds and academic experiences. Although much progress has been made, the surface has only been scratched in terms of the potential impact of robotics in education. To more fully realize this potential, robots need to be made more accessible, affordable and easy to use for both students and teachers.

Homeland Security and Defense

The use of robotics technology for homeland security and defense continues to grow as innovative technology has improved the functionality and viability of search and rescue efforts, surveillance, explosives countermeasures, fire detection, and other applications. Unmanned surveillance, detection

Disaster Site Application



and response systems will be able to make use of robotic platforms, fixed sensors, and command and control networks to potentially monitor and patrol hundreds of miles of rough border

terrain, to sniff out and locate chemical / biological / radioactive / nuclear / explosive threats, and survey large perimeters associated with borders, power plants or airports. Such systems will enable security personnel to automatically detect potential threats, to take a close-in first look from a safe distance, and to provide initial disruption and interdiction at the point of intrusion if necessary. While other “man-packable” robots equipped with instruments including infrared cameras, night vision sensors and millimeter-wave radar have been used at disaster sites, including the World Trade Center, to search for victims.

3.2 Capabilities Roadmap

In the following, we identify the key challenges that have to be met and the key capabilities that have to be developed in order to deliver service robots capable of addressing the aforementioned motivating scenarios. Figure 4 provides an overview of the proposed roadmap and the remainder of this document. The right column in the figure lays out the application areas, many of which are described in the motivating example scenarios above. High-impact advances in these application areas can only be enabled if a number of capabilities for autonomous service robots become available. These capabilities are listed in the middle of the figure and described in more detail in Section 3. To achieve the required level of competency in those areas, sustained investment in research and developments in a number of basic research areas and technologies is required. Figure 4 shows these research areas and technologies in the left column; they are described in more detail in Section 4.

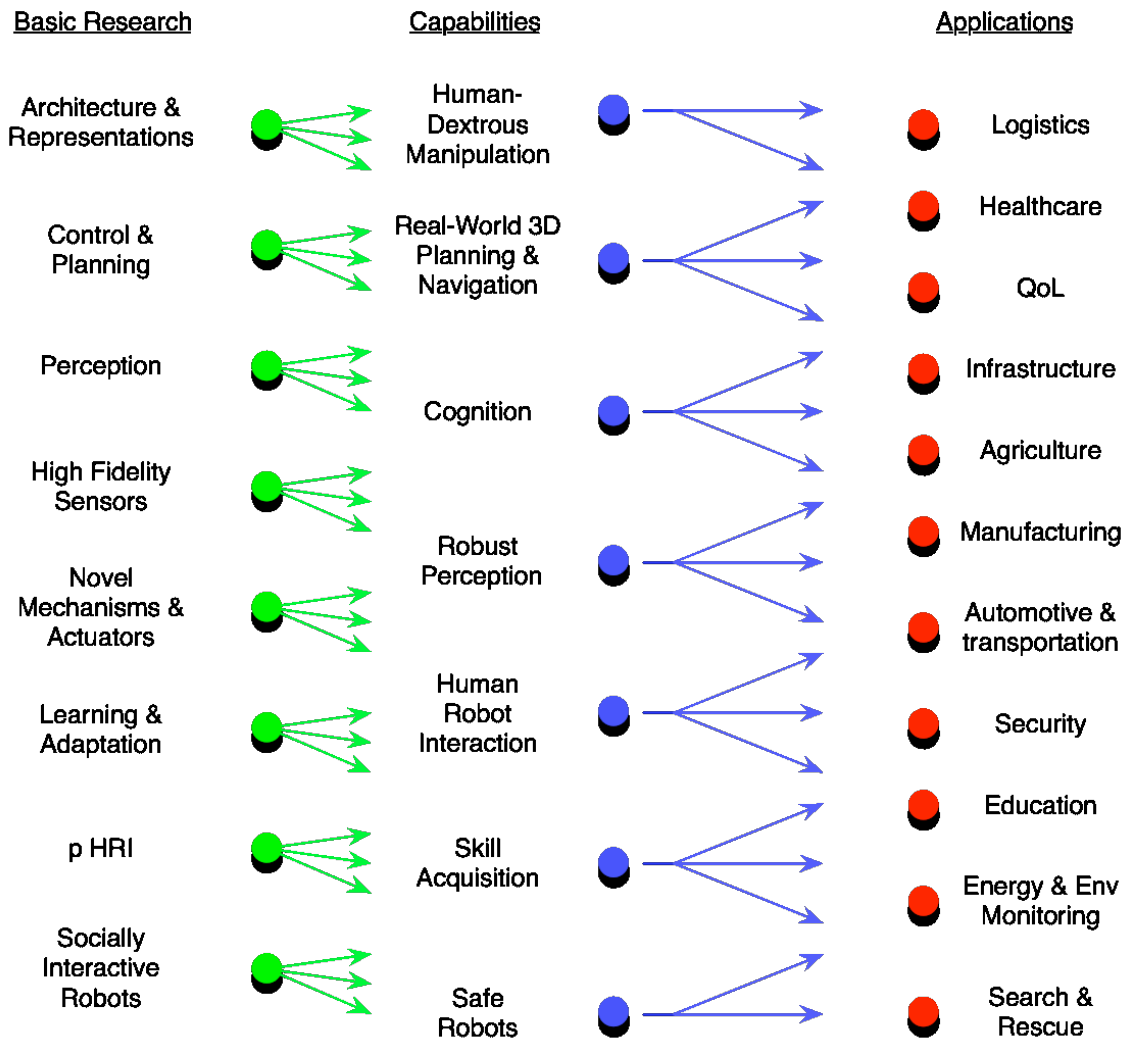


Figure 4. Overview of the roadmap for domestic and industrial service robotics: Sustained research and development in the basic research areas in the rightmost column of the figure will enable a number of elementary capabilities, shown in the middle column of the figure. These capabilities in turn enable progress in the application areas on the right.

Human-like Dexterous Manipulation

Even simple tasks, such as picking up unknown objects, still represent major research challenges. The level of dexterity and capabilities in physical reasoning required for autonomous manipulation in the context of professional and domestic service robotics seems far out of reach. Pressing problems in this area include adequate sensors and associated perceptual capabilities, dexterous hands and safe manipulators, planning under uncertainty, advanced control, skill learning and transfer, and modeling and simulation.

Some participants believed that the required competency in manipulation can only be achieved when these different areas are advanced in a coordinated fashion rather than in isolation. For example, novel, skin-like tactile sensors hold great promise for dexterous in-hand manipulation. However, we lack the algorithms to process the data from such sensors. It is conceivable that techniques from computer

vision could interpret the tactile information as an image and therefore are able to compute useful abstractions of the high-dimensional tactile data. At the same time, inspiration from computer vision algorithms may enable the design of simpler tactile sensors that contain simple local pre-processing tailored to the specific algorithms they support.

In 5, 10, and 15 years the following goals are possible with sustained research and development:

- *5 years:* Robots perform limited pick and place task in the home and in industrial settings; robots are able to reliably open doors and cabinets. These manipulation tasks are accomplished partially by engineering the environment, partially by equipping robots with specialized (or at least not very general purpose) end-effectors, and by making simplifying assumptions regarding the environment.
- *10 years:* Robots robustly manipulate large, graspable, rigid, possibly articulated objects and tools without possessing a priori models. Robots improve the robustness and applicability of manipulation and grasping skills with experience. Robots acquire generalized manipulation knowledge to give them information about the use of objects and tools, even if they have not encountered them before.
- *15 years:* Robots possess hands with nearly human levels of mechanical dexterity. Hands are covered with high-resolution tactile skin. Robots are able to perform robust, sensor-based, prehensile and non-prehensile manipulation of objects. They possess rudimentary capabilities of manipulating flexible objects.

Real-World 3D Planning and Navigation

Autonomous service robots accomplish tasks by moving about their environment and by interacting with their environment. These motions and interactions need to achieve a given task by changing the robot's pose and by moving objects in the environment. The accomplishment of a task may require complex sequences of motions and interactions; the robot may have to move from one room to another or it may have to open doors, clear obstacles out of its path, remove obstructions, or use tools. To achieve this level of competency, substantial advances at the intersection of motion planning, task planning, and control have to be made. Historically, these areas have progressed in isolation. The problems posed by service robotics, however, can only be addressed through a tight integration of these techniques.

Consider the task of picking up a cup to which access is obstructed by a box. To reason about pushing the box to the side to pick up the cup, the robot has to reason about its own capabilities, the geometry of the scene, constraints imposed by actuation and joint limits, the contact dynamics and friction that arise when pushing the box, etc.

To reason about the world in such a way that the appropriate sequence of actions and motions can be determined, the robot has to be aware of its environment. Not all of the required information can be provided to the robot beforehand, as service robots operate in unstructured and dynamic environments. The robot therefore has to possess capabilities to perceive and map its environment. "Semantic mapping" provides the robot with information about the environment that is required to

achieve a task. Object detection and recognition and related perceptual skills provide information for semantic mapping and for object manipulation.

In 5, 10, and 15 years the following goals are possible with sustained research and development:

- *5 years:* Robots in research laboratories can navigate safely and robustly in unstructured 2D environments and perform simple pick and place tasks. Relevant objects are either from a very limited set or possess specific properties. Robots learn semantic maps about their environment through exploration and interaction but also through instruction from humans. They are able to reason about tasks of moderate complexity, such as removing obstructions, opening cabinets, etc. to obtain access to other objects.
- *10 years:* Given an approximate and possibly incomplete model of the static part of the environment (possibly given a priori or obtained from data bases via the Internet, etc.), service robots are able to reliably plan and execute a task-directed motion in service of a mobility or manipulation task. The robot builds a deep understanding of the environment from perception, interaction, and instruction. The robot modifies its environment to increase the chances of achieving its task (remove obstructions, clear obstacles, turn on lights), and it can detect and recover from some failures.
- *15 years:* Service robots can perform high-speed, collision-free, mobile manipulation in completely novel, unstructured, dynamic environments. They perceive their environment, translate their perceptions into appropriate, possibly task-specific local and global/short- and long-term environmental representations (semantic maps) and use them to continuously plan for the achievement of global task objectives. They respond to dynamic changes in the environment in a way that is consistent with the global objective. They are able to interleave exploratory behavior when necessary with task-directed behavior. They interact with their environment and are able to modify it in intelligent ways so as to ensure and facilitate task completion. This includes reasoning about physical properties of interactions between objects and the environments (sliding, pushing, throwing, etc.) and the use of tools and other objects.

Cognition

In service robotics there is a need to operate in non-engineered environments, to acquire new skills from demonstration by users, and to interact with users for tasking and status reporting. Cognitive systems enable acquisition of new models of the environment and training of new skills that can be used for future actions. Cognition is essential for fluent interaction with users and deployment in domains where there is limited opportunities for user training. In addition an added degree of intelligence for coping with non-engineered environment is essential to ensure system robustness.

In 5, 10, and 15 years the following goals are possible with sustained research and development:

- *5 years:* Demonstration of a robot that can learn skills from a person through gesture and speech interaction. In addition acquisition of models of a non-modeled in-door environment.

- *10 years:* A robot that interacts with users to acquire sequences of new skills to perform complex assembly or actions. The robot has facilities for recovery from simple errors encountered.
- *15 years:* A companion robot that can assist in a variety of service tasks through adaptation of skills to assist the user. The interaction is based on recognition of human intent and re-planning to assist the operator.

Robust Perception

Service robots operate in relative unconstrained environments and as such there is a need to provide robust perceptual functionality to cope with the environmental variation. Perception is critical to navigation and interaction with the environment and for interaction with users and objects in the proximity of the system. Today perception is typically used for recognizing and interacting with single, known objects. To enable scalability there is a need to have facilities for categorization of percepts and generalization across scenes, event and activities. Already today there are methods for mapping and interpretation of scenes and activities and the main challenge is in scalability and robustness for operation in unconstrained environments.

In 5, 10, and 15 years the following goals are possible with sustained research and development:

- *5 years:* Demonstration of a robot system that can categorize spaces and automatically associate semantics with particular places. The sensing will be integrated over time for robust operation in large scale scales such as mall or a building structure. The robot will be able to recognize hundreds of objects.
- *10 years:* Demonstration of a robot system that can perceive event and activities in the environment to enable it to operate over extended periods of time.
- *15 years:* Demonstration of a robot that integrates multiple sensory modalities such as GPS, vision and inertial to acquire models of the environment and use the models for navigation and interaction with novel objects and events.

Physical, intuitive HRI and interfaces

Deployment of service robots both in professional and domestic settings requires the use of interfaces that makes the systems easily accessible for the users. Diffusion of robotics to a broader community requires interfaces that can be used with no or minimal training. There are two aspects to interfaces: physical interaction with users and people in the vicinity and the command interface for tasking and control of the robot. The physical interaction includes body motion to move/nudge objects and people and non-contact interaction such as change of motion behavior to communicate intent or state. The interface aspect is essential to tasking and status reporting for operators to understand the actions of the robot.

In 5, 10, and 15 years the following goals are possible with sustained research and development:

- *5 years:* Demonstration of a robot where task instruction is facilitated by multi-modal dialog for simple actions/missions and robots that can communicate intent of actions by the body language.
- *10 years:* Demonstration of a robot where programming by demonstration can be used for complex task learning such as meal preparation in a regular home.

- *15 years*: Demonstration of a robot that can be programmed by an operator for complex mission at a time scale similar to the actual task duration.

Skill Acquisition

Service robots must possess the ability to solve novel tasks with continuously improving performance. This requires that service robots be able to acquire novel skills autonomously. Skills can be acquired in many ways: they can be obtained from skill libraries that contain skills acquired by other robots; skills can be learned from scratch or by composing other skills through trial and error; skills can also be learned through observation of other robots or humans; furthermore, they can be taught to a robot by a human or robotic instructor. But skill acquisition also requires the robot to identify those situations in which a skill can be brought to bear successfully. Skills can be parameterized; learning and selecting appropriate parameters for a variety of situations is also included in the capability of skill acquisition. The ability to transfer skills from one domain to another or to transfer experience acquired with one skill to another skill can be expected to provide substantial advances in skill acquisition. Adequate capabilities in skill learning will be enabled by advances in perception, representation, machine learning, cognition, planning, control, activity recognition, and other related areas.

In 5, 10, and 15 years the following goals are possible with sustained research and development:

- *5 years*: Robots can learn a variety of basic skills through observation, trial and error, and from demonstration. These skills can be applied successfully under conditions that vary slightly from the ones under which the skill was learned. Robots can autonomously perform minor adaptations of acquired skills to adapt them to perceived difference from the original setting.
- *10 years*: As perceptual capabilities improve, robots can acquire more complex skills and differentiate specific situations in which skills are appropriate. Multiple skills can be combined into more complex skills autonomously. The robot is able to identify and reason about the type of situation in which skills may be applied successfully. The robot has a sufficient understanding of the factors that affect the success so as to direct the planning process in such a way that chances of success are maximized.
- *15 years*: The robot continuously acquires new skills and improves the effectiveness of known skills. It can acquire skill-independent knowledge that permits the transfer of single skills across different tasks and different situations and the transfer of skills to novel tasks. The robot is able to identify patterns of generalization for the parameterization of single skills and across skills.

Safe robots

Today safety for robots is achieved through a clear separation of the workspaces for humans and robots or through operation at speeds that do not represent a risk to humans in the proximity of the system. As the operation of humans and robots become more and more intertwined there will be a need to explicitly consider operation at higher speeds while operating in direct proximity to people. There is a need to consider standards for safety to enable certification. While technologically, safety involves several aspects including the need for: advanced perception capabilities to detect objects and persons and predict possible safety hazards, control systems that react to possible dangerous situations, and inherently safe actuation mechanisms to ensure that contact with a person or objects causes little or no damage.

In 5, 10, and 15 years the following goals are possible with sustained research and development:

- *5 years:* A safety standard for service robotics has been defined and accepted worldwide, which specifies allow impacts and energy transfers. Basic manipulation systems have first versions of safety standard implemented.
- *10 years:* An inherently safe robot for operation in proximity of humans is demonstrated for industrial application scenarios.
- *15 years:* A robot system that does mobile manipulation in cooperation with humans is demonstrated and the safety is demonstrated both for hardware and software components.

4. Basic Research and Technologies

Architecture and Representations

Over the last 20 years a number of established models for system organization have emerged. Characteristically, however, no agreement or overall framework for system organization has materialized. For autonomous navigation, mobility, and manipulation there are some established methods such as 4D/RCS and Hybrid Deliberative Architectures, but once interaction components are added such as Human-Robot Interaction (HRI) there is little agreement on a common model. Over the last few years the area of cognitive systems has attempted to study this problem, but so far without a unified model. For wider adoption of robot systems it will be essential to establish architectural frameworks that facilitate systems integration, component modeling, and formal design. Appropriate architectural frameworks may initially or inherently depend on the task, the application domain, the robot, or a variety of other factors. Nevertheless, a deeper understanding of the concepts underlying cognition can be expected from an incremental unification of multiple frameworks into more less problem- or robot-specific architectures. Any of the aforementioned architectural frameworks will be intricately linked to a set of appropriate representations that capture aspects of the environment and the objects contained in it, the robot's capabilities, domain information, as well as a description of the robot's task

Control and Planning

As service robots address real-world problems in dynamic, unstructured, and open environments, novel challenges arise in the areas of robot control algorithms and motion planning. These challenges stem from an increased need for autonomy and flexibility in robot motion and task execution. Adequate algorithms for control and motion planning will have to capture high-level motion strategies that adapt to sensor feedback. Research challenges include the consideration of sensing modalities and uncertainty in planning and control algorithms; the development of representations and motion strategies capable of incorporating feedback signals; motion subject to constraints, arising from kinematics, dynamics, and nonholonomic systems; addressing the characteristics of dynamic environments; developing control and planning algorithms for hybrid systems; and understanding the complexity of these algorithmic problems in control and motion planning.

Perception

Over the last few decades tremendous progress has been achieved in perception and sensory processing as is seen for example in web based searches such as Google images and face recognition in security applications. Mapping and localization in natural environments is also possible for engineered environments. Over the last decade in particular use of laser scanners and GPS has changed how navigation systems are designed and enabled a new generation of solutions. Nonetheless, localization and planning in GPS-denied environments which are quite common remains a very important research area. In addition there has been tremendous progress on image recognition with scaling to large databases. In the future a large number of robots will rely on sensory feedback for their operation and the application domain will go beyond prior modeled settings. There is therefore a need for reliance on multiple sensors and fusion of sensory information to provide robustness. It is expected that the use of image-based information in particular will play a major role. Vision will play a crucial role in new mapping methods, in facilitating the grasping of novel objects, in the categorization of objects and places beyond instance based recognition, and in the design of flexible user interfaces.

Robust, High-fidelity Sensors

Advances in microelectronics and packaging have resulted in a revolution in sensory systems over the last decade. Image sensors have moved beyond broadcast quality to provide mega-pixel images. MEMS technology has enabled a new generation of inertial sensor packages and RFID has enabled more efficient tracking of packages and people. Sensors have enabled solid progress in domains with good signal quality. As the domains of operation are widened there will be the need for new types of sensors that allow robust operation. This requires both new methods in robust control, but more importantly sensors that provide robust data in the presence of significant dynamic variations and a domain with poor data resolution. New methods in silicon manufacturing and MEMS open opportunities for a new generation of sensors that will be a key aspect of future progress in robotics.

Novel Mechanisms and High-Performance Actuators

There is an intricate interplay between progress in mechanical devices and actuation and the algorithmic complexity required to use them in accordance with their function. Some algorithmic problems can be solved or their solution greatly facilitated by intelligent mechanical design. Advances in mechanism design and high-performance actuators could therefore critically enable ground-breaking innovations in other basic research areas as well as enable several of the capabilities listed in the roadmap. Important research areas include the design and development of mechanisms with compliance and variable compliance, highly dexterous hands, inherently compliant hands, energy-efficient, safe, high-performance actuators, energy-efficient dynamic walkers, and many more. Of particular interest are “intelligent” mechanical designs that can subsume—through their design—a function that otherwise had to be accomplished through explicit control. Examples include self-stabilizing mechanisms or hands with special provisions to achieve form closure without explicit control.

Learning and Adaptation

Many of the basic research areas described in this section can benefit from advances in and application of learning and adaptation. Service robots occupy complex environment and live in high-dimensional state

spaces. Knowledge of the environment and of the robot's state is inherently uncertain. The robot's actions most often are stochastic in nature and their result can best be described by a distribution. Many of the phenomena that determine the outcome of an action are difficult or even impossible to model. Techniques from machine learning provide a promising tool to address these aforementioned difficulties. These techniques can be useful for learning models of robots, task or environments; learning deep hierarchies or levels of representations from sensor and motor representations to task abstractions; learning of plans and control policies by imitation and reinforcement learning; integrating learning with control architectures; methods for probabilistic inference from multi-modal sensory information (e.g., proprioceptive, tactile, vision); structured spatio-temporal representations designed for robot learning such as low-dimensional embedding of movements.

Physical Human-Robot Interaction

Gradually the safety barriers that have been common in industrial robotics are removed and robots will to a larger degree engage with people for cooperative task execution and for programming by demonstration. As part of this, robots will have direct physical contact with the user. This requires first of all careful consideration of safety aspects. In addition there is a need to consider how these robots can be designed to provide interaction patterns that are perceived as natural by users. This spans all aspects of interaction from physical motion of the robot to direct physical interaction with a perception of minimum inertia and fluid control. In addition there is a need here to consider the interaction between design and control to optimize functionality.

Socially Interactive Robots

As robots engage with people there is a need to endow the systems with facilities for cooperative interaction with humans. This interaction is needed for tasking of a system, for teaching of new skills and tasks and for cooperative task execution. The current models for social interaction include gestures, speech/sound, body motion/pose, and physical position. There is here a need to integrate skill and task models with interpretation of human intent to enable interpretation of new and existing activities. In service robotics there is a broad need for social interaction from encounters with novice users to cooperative tasking with an expert operator. The full span of capabilities is required to provide engaging and long-term adoption of robotics.

5. Contributors

This report documents the result of brainstorming session that took place 7-8 August 2008 in San Francisco, CA. The report is part of the CCC study on Robotics. The Computing Community Consortium (CCC) is a project managed by the Computing Research Association (CRA) and is sponsored by the National Science Foundation (NSF). The present report has been authored by the workshop organizers and does not reflect the opinion of CRA, CCC or NSF. The responsibility of the report lies entirely with the authors.

The CCC workshop on service robotics was organized by Oliver Brock, University of Massachusetts, Bill Thomasmeyer, The Technology Collaborative, Inc, and Henrik I Christensen, Georgia Institute of Technology. The workshop was attended by the following people from academia and industry:

Chad Jenkins	Brown
Nicholas Roy	MIT
Aaron Dollar	MIT
Stefano Carpin	UC Merced
Jana Kosecka	George Mason
Andrew Ng	Stanford
Andrea Thomaz	Georgia Tech
Jing Xiao	UNC Charlotte
Charles Rich	WPI
Candace Sidner	WPI
Stewart Tansley	Microsoft Research
Joshua Smith	Intel
Eric Berger	Willow Garage
Martin Buehler	iRobot
Paolo Pirjanian	Evolution Robotics
Bill Townsend	Barrett Technology
Scott Thayer	Red Zone
Chris Urmson	CMU / GM
Cynthia Breazeal	MIT
Michael O'Connor	Novariant
Paul James	Adept
Eric Whinnem	Boeing - Mfr Tech
Charlie Kemp	Georgia Tech
Trevor Blackwell	Anybots
Dan Miller	Anybots
Brian Carlisle	Precise Automation
Parag Batavia	Foster-Miller
Andreas Hoffman	Vecna
James Kuffner	CMU
Alex Foessel	Deere
Oliver Brock	UMass Amherst
Bill Thomasmeyer	Tech Collaborative
Henrik Christensen	Georgia Tech
Jake Huckaby	Georgia Tech