Robotics: Emerging Technologies and Trends

Contents

1   Introduction

Robotics integrates many different component disciplines and technologies, such as computing technology, sensors, materials, actuators, control, and artificial intelligence. Advances in these component technologies have often driven robotics forward, and in return robotics has often provided the applications to motivate advances in the component technologies.

The Workshop on Emerging Technologies and Trends examined continuing and likely future advances in technology, to explore their impact on robotics, and to map the implications for future robotics research directions and funding policy. The Workshop identified 63 different technological advances which promise to impact robotics, and 35 different new applications which will be enabled by various advances. Projections were given for achievable developments in 5, 10, and 15 year time frames. This report presents the workshop's findings, grouped into the following categories:

- actuation systems

- energy and power systems

- fabrication and materials technology

- micro- and nano-technology

- human-robot interfaces

- communications and networking

- planning and control

- robustness and reliability

- machine learning

- perception

Progress in such technologies is essential for capabilities and applications envisioned for robotics, and therefore serves as a foundation for the application-oriented workshops on Manufacturing and Automation, Healthcare and Medical Robotics, and Service Robotics.

2   Strategic Findings

2.1   Actuation Systems

Advances in actuation systems are critical for progress in many applications. For many mobile robot and human-robot interaction applications we need fast, safe, low-cost, and reliable robots. This in turn requires new actuators and transmissions that have high torque-to-weight, power-to-weight, are safe interacting with people, are robust to impact, have appropriate impedance for interactive tasks, and have reasonable speed and efficiency. Current actuators can be made to

achieve good performance in a few of these metrics, but not good overall performance. This deficit has led to heavy, slow, fragile robots which are dangerous for people to work with. Just as jet engine technology is a critical strategic advantage for high performance aircraft, actuation technology will provide a competitive advantage in robotics.

Improvements in actuator technology in the coming years won't be dramatic, but steady advances and particularization to robotics will expand the capabilities of robots. The following segments of the world robot market are expected to grow rapidly if necessary actuator technologies are developed.

- *Physical assistance of humans by robots,* such as carrying a person upstairs, requires light weight actuation with appropriate impedance.

- *Micro mobile sensor nodes for security* requires miniature high performance actuators, such as for microflight.

- *Power suits and prosthetics* require high power, high torque, high efficiency actuators.

- *Domestic robots* require safe, low cost, low inertia actuators for mobility plus manipulation.

2.2   Energy and Power Systems

Two key issues, energy storage and power delivery, are both vital to many robotics domains, particularly mobile and autonomous robots. They determine payload, mission duration, and service interval. They are also vital for transportation and consumer electronics, which are much larger markets than robotics and which possess intense research programs. In fact, most progress will come from these areas.

Energy storage involves constraints arising from the fundamental chemistry, as well as numerous economic and safety-related issues. In those applications where it is practical, liquid hydrocarbons will have an energy density advantage for at least the next twenty years. In other applications batteries dominate, and are likely to improve two to three times in the same time period, but still will have ten times lower energy density than gasoline.

Other energy storage technologies have significant issues for practical usage in many applications. Hydrogen requires significant storage overhead. Monopropellants (e.g., hydrogen peroxide) have potential, but they have major safety and handling concerns. Hydrogen peroxide autodenonates at high concentrations (around 80%), but high concentrations are required to get enough energy.

Power delivery is dominated more by design than by chemistry. It is relatively unimportant in batteries for long mission durations. Improved batteries are in the commercial pipeline. There are several companies in the short-term process of commercializing new lithium battery electrode materials that can provide increases in power density and/or cycle life. However, the improved batteries in this category are unlikely to exceed the energy density of current lithium-polymer batteries with cobalt oxide electrodes. There are a group of companies working on batteries that can give 2x-3x improvement in energy density, largely in the area of metal-air batteries, such as rechargeable zinc-air batteries.

Power delivery is vital in fuel-based systems. Engines are already heavily optimized, with clear efficiency trade-offs. Fuel cells should see major improvement in power density, but it is not clear that they beat engines.

In the face of such modest prospects for power and energy, the main option is to explore related technologies with strong applications to robotics.

- *Harvesting.* Requirements for energy storage can be relaxed if energy can be acquired in the field.

- *Efficiency.* Requirements for energy storage can be relaxed if less energy is consumed to perform the task.

- *Miniaturization.* Most robotic systems operate on much smaller scales than transportation vehicles. Some are much smaller than consumer electronics (micro air vehicles, smart dust, etc.) New power and energy systems need to be scaled to robot-relevant sizes. Robotics can also exploit advances of hobbyists. Miniature engines and batteries are well established challenges in remote-controlled aircraft.

2.3   Fabrication and Materials Technology

Advances in fabrication and materials technology are also critical to produce the next generations of robots, by enabling novel lightweight, safe, low cost, compliant, and durable structures. *Integrated fabrication technologies* will result in compact, lightweight subsystems that are rugged and have high performance. *Miniaturization technologies* at the meso/micro/nano scale will lead to proliferation of low-cost components that are easily integrated. *Smart material technologies* will lead to compliant wearable sensors that can either form robot skin or that can be placed on humans for measurement. *New materials technologies* will yield light-weight, soft and safe robot structures. Appplications that would be enabled are:

- *Wearable robots,* e.g., prosthetics, strength assistance for the infirm, and rehabilitation

- *Servant/domestic robots* for elder and other assistance

- *Miniature robots* for safety and security, e.g., search and rescue swarms

2.4   Micro and Nano Technology

Micro and nano robotics will provide unprecedented capabilities to observe and interact with the microworld, from molecules to cells and organs. By engineering robotic systems with characteristic dimensions in the range from nanometers to millimeters, these robots will be able to interact with the environment in ways, and using physical properties, that are not possible with conventional macro-scale systems.

There are two aspects of micro and nano technology: (1) micro and nano manipulation by large robots, and (2) robots that are themselves very small. Micro and nano manipulation by large robots will improve our understanding of materials and biological structures, as well as assist in micro fabrication. The construction of very small robots will yield meso-scale untethered devices

for flight, ambulation and swimming. Artificial bacteria and cell systems are also examples of microbots. Small-sized micro- or nano-robots can act in swarms to produce enhanced capabilities.

- The overall human environment can be better observed by using swarms, in such applications as environmental monitoring and search and rescue.

- Swarms of microrobots can perform in vivo medical therapies such as micromanipulation or drug delivery.

- Artificial bacteria can be designed with sensing, manipulation and locomotion capabilities.

- Cell systems can act as miniature factories and as embedded sensors for disease detection.

2.5 Human-Robot Interfaces

Human-robot interaction is central to many of the most exciting applications of robotics, including medical robotics, assistive robotics, prosthetics, rehabilitation, transportation, human augmentation, entertainment and education. Human-robot interfaces include: voice interaction; visual interaction including gesture and inference of intent from visual monitoring; neural interfaces including physical probes, EEG (brainwaves), and surface EMG; physical interaction including exoskeletons and haptic devices; physical manipulation of the human body for transportation or rehabilitation; intelligent prosthetics; and invasive devices such as some biomonitors, surgical instruments, and neural interfaces. A review of this list shows that human-robot interfaces are central to the applications that will affect us most profoundly.

Advances in human robot interaction are coming rapidly and have already had an impact. The Nintendo Wii illustrates that a relatively small advance in gesture recognition can have a significant impact on the human experience. Robotic systems are already using behavior recognition to automate lab science with animal tests. Likewise teleoperated surgery has proven to be feasible and commercially successful. Neural interfaces have made striking progress in the last few years, even progressing to a first commercial system. Other applications on the horizon include:

- factory robots and military logistics robots that learn assembly and warehousing tasks by observing and assisting humans without programming;

- domestic service robots that learn specific non-repetitive tasks by observing humans, inferring how to help, and modifying their assistance through speech and gesture of the human;

- a team of search and rescue robots, working with humans, that can deploy themselves and autonomously negotiate to relay disparate information from several sites to human users such that the number of human operators is less than the number of robots;

- exoskeleton "man-amplifiers" for military and commercial use that slip over portions of the body or the entire body and intuitively enhance or replace human speed/strength/dexterity by responding to nerve impulses or other forms of human "thought".

Related technologies include speech interaction, gesture and behavior recognition, biocompatible materials, neuroscience, and bioengineering.

2.6 Communications and Networking

Communications and networking are fundamental enabling technologies for numerous high-priority applications. Communications and networking are required whenever robotic systems are distributed spatially, whenever remote data or computing resources must be accessed, or whenever human interaction is required. Advances in communications and networking will lead to more capable, more robust, and more easily deployable systems. Applications enabled by advances in communications and networking include:

- distributed mobile sensor networks, for environmental monitoring, monitoring the civil infrastructure, monitoring container shipping yards, etc.;

- autonomous passenger vehicles, which need to communicate with each other, with traffic control systems, and with offboard data and computing resources such as navigation assistance;

- domestic robotic systems, such as home security systems, home health care and assistive robotics, and home automation;

- distributed micro- or nano-systems deployed for biological instrumentation, such as intracellular scientific studies.

2.7 Planning and Control

Planning and control are the decision sciences employed to determine what actions a robot will take. They include some of the most profound challenges in robotics. Even with perfect sensing and hardware, it is clear that robotic planning and control fall well short of human performance in most tasks. With the current level of planning and control algorithms, robots often have to be employed in narrowly prescribed scenarios, following very detailed programming written laboriously by humans. In other instances, autonomy is impossible, and a human has to be integrated as part of a telerobotic system. Applications enabled by advances in planning and control will include:

- factory robots adapting to a new task without new programming;

- currently teleoperated tasks such as surgery and bomb disposal will transition to supervised autonomy;

- logistic automation will allow robots to autonomously move goods from producers through distribution network to consumers;

- autonomous control of high speed vehicles in dynamic environments will enable passenger vehicle autopilots;

- autonomous robots capable of working in novel environments without reprogramming will make domestic robotics affordable.

2.8 Robustness and Reliability

Robustness and reliability ensure that a robot will continue to do its job, even when the operating environment departs from the ideal. Failures are expensive and inconvenient, and in some applications are unacceptable. Improved robustness and reliability will enable many applications:

- When failure is unacceptable: robotic surgery, passenger vehicle autopilots, critical safety and security applications.

- When failure is expensive and inconvenient: everything else.

2.9 Perception and Machine Learning

Perception and machine learning are the techniques for using sensory information, either to recognize the state of the world around the robot (perception) or to improve its ability to do a job (machine learning). It is largely perception and machine learning that distinguish a robot from an ordinary machine. With perception and machine learning a robot can adjust its actions to the situation at hand and can improve with experience, both hallmarks of intelligent behavior. Advances in perception and machine learning enable new applications:

- Factory robots can perform a new job without re-programming, and possibly by watching a human or another robot doing the job;

- Installation of robots in all applications can be done without expensive special purpose programming, by watching humans or by being instructed by a human.

- Very challenging dynamic tasks like walking also benefit from machine learning techniques.

3 Key Challenges / Capabilities

3.1 Motivating/exemplar scenarios

Security - national, industrial, home. Security is a broad set of applications. In national security we include military operations such as combat, reconnaissance, surveillance, and logistics support, and homeland security such as border security, airport security, and other critical infrastructure installations. Robotics technology has already had a substantial impact on national security, through the use of unmanned aerial vehicles in military operations, and teleoperated bomb disposal robots. Autonomous and semi-autonomous ground vehicles are just beginning to be deployed. Video surveillance technology is also being deployed.

Industrial and home security will more likely be focused on surveillance. Widespread deployment in homes will be dependent on easily installed highly affordable systems

Several emerging technologies bear directly on security applications. Increased mobility and improved perception, intelligence, and communications would result in more capable military robots, especially in reconnaissance and surveillance. Sensor networks, either mobile or fixed, with improved perception and communications, would more effectively monitor security zones,

including borders, airports, marine shipping terminals, industrial security zones, and civil infrastructure facilities. All security applications benefit from advances in sensor networks, perception software, and communications networks, home security especially.

Manufacturing and distribution. Robotics and automation are well entrenched in manufacturing, most notably in automobile assembly and consumer electronics. Robotics technologies are also being deployed in the distribution chain, from fully automated shipping yards and warehouses to inventory monitoring and point of sale systems at retail outlets. The advent of more capable and more mature technologies could have a broad impact in both manufacturing and distribution. Improved technologies for power, actuation, and materials will lead to more capable and safer systems. Improvements in communications, perception, and human robot interaction will lead to more easily deployed, more affordable, and more adaptable systems. Combining all these technologies with new programming techniques, protocols, and standards will change the underlying economics, so that the technology could be adopted more broadly. Early in this scenario we would see increased adoption by large manufacturing companies, but later on we would see adoption by smaller businesses, ultimately including very small shops.

Transportation. The main focus of transportation is passenger vehicles on streets and highways. The benefits of passenger vehicle automation are enormous in cost, time, comfort, and most of all safety. Early adopters may include closed private systems such as mining or logging companies. Some of the technologies are already fairly mature, and deployed in automated shipping yards for example. Technology for urban driving in a closed environment was demonstrated in the recent DARPA Urban Challenge, making heavy use of laser ranging, radar, and GPS. Many challenges remain to produce a reliable, robust system which can safely cope with all the uncertainties of normal driving. Nonetheless, the technology will gradually shift into our vehicles. Collision warning, skid correction, navigation assistance, and adaptive cruise control are all examples of technology that is already being deployed.

Transportation is so broad that every robotics-related technology is relevant. The most obvious are perception, mobility, and navigation but advances in human robot interaction, networking and communications, actuation, power, control, and machine learning are all necessary.

Medical and health care. Medical and health care applications include surgery, rehabilitation therapy, prosthetics and orthotics, medical imaging, monitoring and therapeutic assistance. Robotics technology will impact medical and health care in many ways, providing new tools and techniques for professionals, as well as enabling individuals to monitor and cope with their own health more effectively. Robotics technology has been employed both in medical imaging and computer aided surgery for many years now, with the technology continuing to advance rapidly. New tools and techniques are being developed and demonstrated that will enable procedures that were previously impossible, or costly and dangerous. Neural prosthetics are being demonstrated in case studies, and limb prosthetics are advancing rapidly. Techniques for robotic monitoring of therapy at home are also being demonstrated. Ultimately health care technology can be embedded in our homes, and monitor our health and nutrition and behavioral anomalies. While almost every robotic technology is relevant to health care, especially relevant areas include micro and nanotechnology, power, actuation, and physical human-robot interfaces.

Domestic robotics.   Domestic robotics means use of robotics technology in the home, although some of the most important applications, security and healthcare, are covered in other applications. The most important remaining applications would be education, entertainment, cleaning, and communications. There are already notable successes in entertainment and cleaning, with a few million vacuum-cleaning robots in service. Affordability, ease of installation, and ease of use are key factors in domestic impact. Key technologies are actuators, power, human interaction, communications and networking, perception, safety, robustness and reliability.

Science and technology.   In some instances robotics technologies enable new or improved techniques in other fields of science and technology. There are many examples: micro and nanotechnology can enable superior instrumentation of biological systems, even down to the cellular level. Laboratory automation procedures enable large scale experimentation. Behavior recognition algorithms support previously impossible or expensive animal studies. Improved perception has the potential for broad impact across virtually all parts of scientific study. Several cases are already demonstrated involving lab mice studies for drug discovery, behavioral studies of insects, and even astronomical studies.

Another interesting trend arises from a fundamental connection between biology and robotics. Both fields address the problems faced by an agent which survives and achieves some behavioral goals in the real world. In robotics, the application of biological observations to the design of robots is called biomimetics. There is also some flow of ideas and techniques from robotics to biology.

3.2   Capabilities Roadmap

3.2.1   Actuation Systems

The impact of actuation system developments is sketched for two robotics systems. *Ornithopters* are flapping-wing robots, for example, bird-like (50 cm) or insect-like (5 cm). The capabilities envisioned are full roll/pitch/yaw/thrust/lift control authority, and a 30-minute mission duration.

5 years: 50 cm ornithopter - cargo capacity equal to actuator system mass.

  5 cm ornithopter - cargo capacity equal to 1/10 actuator system mass

10 years: 50 cm ornithopter - cargo capacity equal to 10X actuator system mass.

  5 cm ornithopter - cargo capacity equal to actuator system mass

15 years: 50 cm ornithopter - cargo capacity equal to actuator system mass, 30 day mission duration.

  5 cm ornithopter - cargo capacity equal to 10X actuator system mass.

Powered exoskeletons for motion assistance are envisioned with an 8 hour mission duration (work shift). A key development are actuators with passive and/or variable impedance.

5 years: Cargo capacity equal to exoskeleton mass.

10 years: Cargo capacity equal to 10X exoskeleton mass.

15 years: Cargo capacity equal to 10X exoskeleton mass, load carried in arms.

3.2.2 Energy and Power Systems

Harvesting. There are two issues in harvesting: mechanisms for energy location and acquisition; and algorithms for power management and energy-seeking behaviors. Harvesting must be well-matched to consumption: it is pointless to harvest milliwatts of vibration energy in a robot that consumes several watts.

Efficiency. Efficiency is mostly a mechanism problem: improved actuators and valves, energy recovery (elastic and/or regenerative), and algorithms for power management. Improvements here also have application to industrial automation, a larger market.

Miniaturization. Miniaturization is often simply an issue of repackaging, but sometimes scaling laws dominate.

3.2.3 Nano and Micro Technology

5 years: Sub-mm untethered devices capable of in vivo targeted delivery and sensing demonstrated in animal models.

Robotic nanomanipulation of sub-100nm non-spherical objects with precise 5DOF control in fluid, including force servoed nanomanipulation of high molecular weight molecules.

High throughput cell assays with relevant industrial applications.

Wired instrumented cell systems, i.e., networks of nanosensors acquiring and processing in real time data in multiple modalities and multiple temporal and spatial scales, for biological investigations ("understanding biology")

Sub-cm untethered devices capable of flight, ambulation or swimming in outdoor environments.

10 years: Increasingly complex in vivo sensing and manipulation therapies by sub-mm micro-robots.

Tracking and precise control of sub-100nm non-spherical objects in vivo.

Intracellular nanorobots for biological investigation.

Artificial bacteria: sensing and locomotion.

Molecular assays based on robotic nanomanipulation, including investigation of Force-structure-function relationships in proteins using manipulation.

Instrumented cell systems, but wireless and embedded in tissue (possibly explants), for applications also in disease detection.

Artificial bacteria-like robots powered from external fields.

Sub-cm untethered devices capable of all-terrain mobility, and working in coordinated swarms for tasks such as disaster search and rescue.

15 years: In vivo self-assembling microrobots. Standardized microrobot platform for delivering a variety of in vivo medical therapies.

Artificial bacteria: sensing, manipulation, and locomotion.

Experimental platform for drug development based on nanomanipulation of molecules.

Instrumented cell systems, but having actuator capabilities (e.g to move around, to release drugs, or to mechanically interact with cells) and in vivo.

Artificial autonomous bacteria.

Swarms of untethered sub-cm devices capable of large area environmental monitoring and control such as crop pollination, health monitoring, and pest protection.

3.2.4 Human-Robot Interfaces

5 years: Robust control of exoskeletons using surface electromyography embedded in links.

Reliable gesture/voice command of service robots based on limited taxonomies with few-to-no training iterations.

Shared control of surgical procedures using real-time sensory feedback and imaging.

Commercially available, low cost (video game-ish), PHANToM-like haptic device.

Adaptable standards and practices for intuitive telepresence interfaces for one-to-one control.

10 years: Neurological control of exoskeletons using neuro-prosthetics and advanced surface EMG.

Inference of complex intention from natural gesture/voice interaction with humans.

Remote control of surgical procedures over limited networks using real-time sensory feedback and imaging with predictive correction and pacing of the procedures.

Adaptable standards and practices for intuitive telepresence interfaces for 1:N (human:robot) control of remote robots.

Adaptable standards and practices for safe interaction of humans with robots based on task and sensory feedback.

15 years: Neurological control of exoskeletons using brainwaves (EEG).

Invasive neurological control that is widely acceptable to potential users.

Seamless cooperation interfaces using gesture, voice, and communication-through-the-task.

Adaptable standards and practices for intuitive, self-arbitrating interfaces for many humans controlling many remote robots.

3.2.5 Communications

5 years: Protocols for sparse, highly volatile multi-hop, ad-hoc networks with high bandwidth and low latency.

Improvements in localization in UWB networks and better spectrum utilization.

Integration of wide-area, local-area, and personal-area networks for more seamless local-to-global coverage (heterogeneity).

Cooperative communication clusters in ad-hoc networks for better connectivity, power utilization, etc.

Integration of the cellular and satellite phone networks to augment other networks.

10 years: Cognitive Radio - extension of theory and development of deployable systems.

Improvements in meta-level methods and protocols (middleware) for heterogeneous agents for task allocation, resource sharing, etc.

General methods and theories encompassing non-traditional communication (biological forms as opposed to RF).

Communication through the task.

Local collaboration strategies that better deal with poor network connectivity in volatile environments (all environments).

15 years: Expanded use of commercial multimedia standards (video object layer, content keying, etc).

Incorporation of cognitive radio standards with multi-agent collaboration/cooperation strategies.

Robust middleware approaches for generic task allocation, resource distribution and data sharing across multiple network modalities with frequent outages.

4 Research/Technologies

4.1 Actuation Systems

The following are projections for actuation developments in 5, 10, and 15 year time frames.

5 years: higher torque and power to weight than muscle (> 20 Nm/kg and > 50 W/kg) with appropriate impedance in 1 gram to 1 kg size-scale.

10 years: 5X improvement in torque and power to weight with appropriate impedance, in milligram to kg size-scale, sufficient bandwidth, power plant efficiency $> 40\%$, minimal holding power, low complexity control.

15 years: high performance actuators for light weight/safe mobile manipulation hierarchical for precision/power tradeoff and fault tolerance alternate power sources (food rather than batteries?)

4.2 Energy and Power Systems

The following are projections for energy and power developments in the 5, 10, and 15 year time frames.

5 years: Harvesting. Develop a 10 kg mobile robot capable of fully autonomous recharging in an office environment.

Efficiency. Construct a robust legged locomotion system that consumes 2x power compared to a similar biological system.

Miniaturization. Fabricate a 100 mg battery exceeding 500 kJ/kg and 1 kW/kg energy storage and power delivery capability.

10 years: Harvesting. Develop a 10 kg mobile robot capable of fully autonomous recharging and power management outdoors ($> 25\%$ duty cycle). Develop a 1 gram UAV capable of operation at a 5% duty cycle while harvesting in an indoor/office environment.

Efficiency. Improve the legged locomotion system to equal power to biological model.

Miniaturization. Produce a fuel-based power source with converter mass < 50 mg, power > 100 W/kg, and efficiency $> 10\%$.

15 years: Harvesting. Develop a 1 gram UAV capable of operation at a 25% duty cycle while harvesting outdoors.

Efficiency. Improve the legged locomotion system to 50% power of the biological model.

Miniaturization. Produce a fuel-based power source with converter mass < 50 mg, power > 1 kW/kg, and efficiency $> 10\%$.

4.3 Fabrication and Materials Technology

Roadmaps are organized by four areas, addressing several key issues: cost; throughput; heterogeneous integration; complexity (2d or 3d); compliance; strength-to-weight; time-to-market; biodegradable/recyclable/green; modularity;

1. Integrated fabrication roadmap. Enabled technologies include low cost, consumer robots, high performance (high power and low weight), high reliability, and protection of US intellectual properties.

5 years: integrated sensing, mechanics, actuation, wiring, packaging (encapsulating key components)

10 years: a unified programmable fabrication process (e.g. printing, deposition, etc.) of heterogeneous components with no manual assembly

15 years: Y10 + high throughput

2. Miniaturization roadmap. Enabled technologies include security, healthcare, and mobile sensor networks for search and rescue.

5 years: miniaturized integrated sensing, mechanics, actuation, wiring, comm, packaging (encapsulating key components); Combined meso/micro/nano components and systems.

10 years: high throughput

15 years: Y10 + low cost + use of micro- and nano-technology based intelligent materials

3. Smart material roadmap. Enabled technologies include power suits and prosthetics.

5 years: compliant wearable sensor skin

10 years: compliant wearable sensor and actuator skin customized to fit the individual wearer's skeletal structure

15 years: compliant wearable sensor and actuator skin with integrated power/energy; modular, mass-produceable smart-material actuators co-fabricated with the skin structure

4. Materials roadmap. Enabled technologies include higher performance, safer, more agile robots.

5 years: light-weight, soft and safe robot structures (e.g. humanoid with mass of 20 kg for light duty household tasks); new materials with controllable adhesion/friction properties for agile and high efficiency mobility and fragile part manipulation.

10 years: embedded sensors and actuators in soft materials for robot limbs and bodies; controllable softness; highly maneuverable flapping wing based centimeter scale flying robots.

15 years: both low-cost mass production and customizable fabrication of soft robots, from meso to nanoscale, with recyclable materials.

4.4   Planning and Control

5 Years: A new generation of filtering algorithms that exploit task constraints to minimize sensing, computation, and estimation.

Robust, publicly available libraries to compute optimal feedback plans in several (3 to 6) dimensions.

Rapid replanning approaches based on precomputation and low-cost memory, providing an alternative to explicitly stored feedback plans.

Development of mathematical criteria for predicting the quality of motion primitives or behaviors in planning algorithms.

10 Years: Sensor-centric planning and control algorithms that operate directly in the reduced information spaces resulting from minimalist filters.

Development of sampling-based techniques that compute feasible feedback plans or control laws in high-dimensional spaces.

Unified the notions of real-time replanning and feedback control, including mathematical analysis of convergence properties.

Automatic synthesis of motion primitives based on optimizing newly introduced criteria.

15 Years: Optimal feedback motion planning for nonlinear systems with obstacles in ten or more dimensions.

Unified theory and techniques for reducing the topological, combinatorial, and dimensional complexities of information spaces.

Algorithms that eliminate the artificial boundaries between sensing, planning, control, and learning.

Dramatic performance improvements in applications that use planning and control due to automatically synthesized primitives.

5 Contributors

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The CCC Workshop on Emerging Technologies and Trends was organized by John M. Hollerbach, University of Utah, Matthew T. Mason, Carnegie Mellon University, and Henrik I. Christensen, Georgia Institute of Technology. The workshop was attended by the following people from academia and industry:

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