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Book review

Robotics: State of the Art and Future Challenges, Imperial College Press, 2008.

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This document reviews the book "Robotics: State of the Art and Future Challenges". The review begins by providing a chapter by chapter summary of the book, and then concludes with a detailed review of the entire book. Robotics is a rich and exciting field of Artificial Intelligence. It has taken great strides in the last decade and a book on the state of the art and future challenges is timely. The reviewed book will assist AI researchers to keep abreast of developments in robotics—a flagship area that enjoys a high profile and profound visibility in broader society—by providing an empirically based overview of the field. The book a major outcome of a comparative robotics study and unique largely due to the fact that such field studies require a strong team of experts to invest significant time and effort, and site visits require significant funding.

The book "Robotics: State of the Art and Future Challenges" contains an extensive high level comparative review of the field of robotics across several pioneering research centers in several geographical regions by a team of scientists which included experts from NASA and US based universities. The book has seven chapters, and an appendix containing the biographies of team members. The broad field of robotics is divided into the following six research areas each of which has a single chapter devoted to it: robotic vehicles, space robotics, humanoid robots, industrial, service and personal robots, robotics in biology and medicine, and networked robots. The data for the reviews was obtained from site visits to 50 laboratories in countries such as Japan, South Korea, France, Germany, Italy, Spain, Sweden, Switzerland, and the UK. A 51st virtual site visit was conducted to Australia.

The book's findings can be summarized as follows (and are presented in the introduction chapter):

1. More private sector investment in robotics is occurring in Japan, Korea and Europe than in the US.
2. The US leads in areas such as robot navigation in outdoor environments, robot architectures, and applications to space, defense, underwater systems, and some aspect of service and personal robots.
3. Japan and Korea lead in technology for robot mobility, humanoid robots, and some aspects of service and personal robots.
4. Europe leads in mobility for structured environments (e.g. urban transportation). In Europe there are also significant programs in elder-care and home service robotics.
5. Australia leads in commercial applications of field robotics.
6. The US is lagging behind many other countries in terms of spending. A host of examples are offered.

A number of exciting and emerging areas of research are also identified, such as nanorobotic systems and robotic surgery, with the authors concluding "the age of robotics is here".

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Chapter 1—Introduction

The book begins with the authors stating their intent of assessing the "status of robotics R&D in the world", while comparing "US efforts to those of other countries". This chapter mainly discusses the scientific research methodology used—i.e. how the book's research was conducted. To assess the status of robotics R&D in the US, an invitational workshop was held in July 2004, attended by "some 100 researchers" who presented "Status Reports". Then, in October 2004, the team "traveled to Japan and South Korea, visiting 29 laboratories". In April 2005, another 21 laboratories were visited in European countries. Lastly, a "virtual site visit" (i.e. via email) was conducted with Australia. In January 2006, another two virtual site visits were conducted with Australian laboratories. The final report was published in February 2006. When conducting site visits, a set of 8 broad questions were used to guide conversation and investigation. These questions covered issues such as the history of individual laboratories, the fraction of work undertaken in the laboratory which concerns robotics, the source and adequacy of the funding for the laboratory, relationships with other institutions (labs, etc.), and each laboratory's opinions regarding the nature of research being undertaken by other researchers. A table is presented which details the specific laboratories visited by the research team, the researchers who visited each laboratory, and the date on which the visit occurred. Unusually, the last past of Chapter 1 also provides an executive summary of the major overarching findings of the survey, and the book does not contain a concluding chapter—instead the details are provided in the subsequent chapters.

Chapter 2—Robotic Vehicles

Chapter 2 discusses robotic vehicles, beginning with a discussion of what constitutes a robotic vehicle, why robotic vehicles are important, different types of robotic vehicles ("how they work"), and tasks for robotic vehicles. For example, there are three categories of tasks for robotic vehicles:

1. Robotic vehicles which "are capable of traveling where people cannot go". Thus robotic vehicles are of interest in fields such as physical exploration (e.g. space and undersea), search and rescue, and of course—war.
2. Robotic vehicles which can effectively (or more efficiently) replace direct human presence in routine tasks, such as in the fields of agriculture and mining.
3. Lastly, robotic vehicles for personal assistance, rehabilitation and entertainment, such as robotic wheelchairs and other types of robots for assisting the elderly.

There are two main strategies for providing a robotic vehicle with mobility:

1. Wheels and props, e.g. traditional, engineered approaches to motion.
2. Running and flapping, or so-called biomimetics which aims to "replicate the motion of biological organisms".

The second section of Chapter 2 discusses research challenges for robotic vehicles. According to the authors, there are four major research challenges:

1. "Mechanisms and Mobility", which involves developing both principles of motion that allow artificial machines to move naturally (e.g. "dynamic" walking versus "quasi-static" walking in bipedal locomotion), and also the hardware (e.g. light and strong materials) to facilitate motion.
2. "Power and Propulsion", which involves finding ways to power and propel the robotic vehicle.
3. "Computation and Control", which involves designing embedded algorithms for controlling robotic vehicles. There are two main approaches:
   a. Hierarchical (or deliberative) control structures;
   b. Behavioral control structures.
4. "Sensors and Navigation". Sensors are used to monitor the environment, and are thus essential for the navigation of a robotic vehicle. One of the major research fields in this area is SLAM—Simultaneous Localization and Mapping (also called Cooperative Mapping and Localization). SLAM has significant outcomes, with SLAM algorithms now "commonly implemented in some form on most prototype and production vehicles, ranging from vacuum cleaners, to underwater vehicles, to planetary explorers and agricultural devices".

The third section of Chapter 2 presents an "International Survey" of research with robotic vehicles. This section is divided into three main discussion points—the US, Japan and Korea, and Europe. When discussing the US, the military receives an extensive mention, with many pictures of military vehicles presented. Robotic space vehicles also receive a mention, but these are discussed in more detail in the following chapter. Field robotics is another area in which robotic vehicles are used extensively, especially in industries such as mining and agriculture. In Japan and South Korea, there is emphasis on personal robotic vehicles (such as household robots), biomimetic mobility, and underwater robotic vehicles. Research in Europe includes the area of navigation and architectures, transportation systems for urban environments, personal and service robotics, and undersea robotics. A comparative review of each of three geographic regions is also presented, with the authors concluding:

– US leadership in robotic vehicles is dependent upon DOD and NASA spending;
– The US “lags in the identification of strategic priorities that could translate vehicle capabilities to innovation and commercial … applications”;
– Japan and Korea have “aggressive national plans” to develop robotic vehicles for health and aged care;
– The European Community has developed “strategic plans that coordinate vehicle programs and emphasize civilian and urban infrastructure”;
– Australia has made “significant contributions to both theory and implementation of these technologies”.

The final section on “key future challenges” is a little disappointing since it only contains six short points (namely, “multi-vehicle systems”, “long-term reliable deployment”, “micro- and nano-scale mobility”, “efficient and independent power”, “human–robot vehicles”, and “interactions”. A more thorough and insightful discussion could have been presented of the key future challenges.

Chapter 3—Space Robotics

This chapter begins by discussing what constitutes “space robotics”, and why space robotics is important (e.g. cost, minimization of risk to human life, etc.). Next, four key issues in space robotics are identified, namely:

1. Mobility—moving quickly and accurately without collisions or danger;
2. Manipulation—using arms, hands and tools safely and efficiently;
3. Time Delay—allowing a distant human to control the robot remotely despite the significant time delay that may occur due to the vast distances involved in space travel;
4. Extreme Environments—successful operation despite extreme heat or cold, or other extreme conditions.

Discussion of examples of space robots focus mostly on the Mars Exploration Rovers “Spirit” and “Opportunity”, with some brief discussion and pictures of the other space robots, such as Robonaut (an “astronaut-equivalent” robot), SARCOS (a dexterous hand capable of force control), and other types of rovers developed for the Moon and Mars. Discussions of Japanese and European robots follow.

Non-US efforts in space robotics are discussed in Section 3.3. Numerous examples are presented, including the Japanese ETS-VII project (a coordinate dual satellite rendezvous docking experiment), the Japanese robotic manipulator for the International Space Station, the Japanese MUSES-C asteroid sample return mission, the ROTEX experiment by the German Aerospace Center (DLR), and the robot arm on the Beagle 2 Mars Lander which was built by a collaboration of British industry and academia for sampling martian soil and rocks.

The current state-of-the-art in space robotics “is defined by MER, the Canadian Shuttle and Station arms, the German DLR experiment Rotex, … and the Japanese experiment ETS-VII”. No doubt much of the information about the robotic technology used in these projects is commercial and in confidence however it would have been valuable to have some kind of explanation as to why these particular projects represent the state-of-the-art, or why they are superior to other projects.

However, despite the recent launch of the external robot on the space station spending on space robotics has declined recently. The authors state that “There are no clearly identified, funded or soon-to-be-funded missions for robotics expected for the current manipulation systems for the Space Station, the planned US and European Mars rovers, and a possible Japanese lunar rover”. In the US space robotics projects have been shelved with renewed high level interest in missions that will return man to the Moon.

Future work is expected to lead to planetary robots that operate autonomously for days on end, and robots that can construct and assemble other space hardware and equipment in space.

Chapter 4—Humanoids

This chapter begins by discussing the influence of science fiction on mainstream perceptions of humanoid robots, presenting pictures from movies such as “I, Robot”, “Star Wars Episode II” and “Star Wars Episode III”. Next, a definition of a humanoid robot is offered—“humanoids are machines that have the form of function of humans”. The authors report however, that in terms of physical robot construction, not all humanoids have human form (i.e. 2 legs, 2 arms, 2 eyes etc), as some research laboratories may specialize on a single subsystem of a humanoid robot, such as eye–hand coordination or bipedal locomotion. For example, some “humanoid” robots may not have legs—instead they may have wheels.

A number of challenges in humanoid robotics are carefully identified. These include:

– Design, packaging and power—how is a humanoid robot physically constructed? There is a high cost of entry in the humanoid research domain, with the vast majority of humanoid robots used by research laboratories constructed by the research laboratory itself (rather than being purchased commercially).

– Bipedal walking. Bipedal walking is one of the main motion challenges for humanoid robots. Most humanoid systems use the Zero Moment Point algorithm, which involves managing the "tipping point" of the system. However, this approach results in "crouched gait" walking, and new algorithms are being developed which use the upper body to manage the robot's center of gravity, with the aim of creating "straight leg walking".
– "Wheeled Lower Bodies" is presented as a research challenge, however, it is not explained exactly how having wheeled humanoid robots is a research challenge.
– Dexterous limbs. Humanoid robots require dexterous limbs, and there is research being undertaken to create dexterous hands. "Key advances in dexterous hands include tactile skins, finger tip load sensing, tendon drive trains, miniature gearing, embedded avionics, and very recent work in low-pressure fluid power systems". However, arms are expensive, and there are few options for the budding researcher. "The best arms in the field have integrated torque sensing, and terminal force-torque sensors that allow for smooth and fine force control. The arms have 7+ DOF, and are able to handle payloads on the order of 5 kg or higher. They have embedded avionics allowing for dense packaging and modular application".
– Mobile manipulation. Mobile manipulation involves using the lower-body (e.g. legs or wheels) to move the robot to a position of interest, and then using the upper body (e.g. arms) to perform "value-added work".
– Human–Robot Interaction, which involves understanding the social and psychological which will facilitate people's acceptance and interaction with humanoid robots.

Research challenges for humanoid robots are briefly discussed. These include:

– Designing the best leg, spine and upper limb arrangements (both sensory and mechanical) to enable energy efficient walking.
– How to represent and manage knowledge about the environment?
– How can people interact with humanoids to form effective and safe teams?
– The killer app.... What is it? There is no clear business plan for humanoid robotics.

The second half of this chapter is focused on a regional, comparative assessment of humanoid robotics. Japan is the world leader in humanoid robotics, with Korea having the "best first derivative". The chapter concludes by arguing humanoid robotics lacks a clear business plan, but that the lack of business model is not stopping research. The authors argue this is due to two main reasons: first, the "emotional and cultural drive towards building machines that look and work like humans"; and second, human-like robots will be able to seamlessly integrate into human society.

Chapter 5—Industrial, Personal and Service Robots

Chapter 5 focuses on an eclectic mix of robots—from entertainment robots such as the Sony AIBO to factory automatons. The chapter begins by discussing robot classifications. An "*industrial robot* is an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes which may be either fixed in place or mobile for use in industrial automation applications". A "*service robot* is a robot which operates semi or fully autonomously to perform services useful to the well being of humans and equipment, excluding manufacturing operations", while "*personal robots* are service robots that educate, assist or entertain at home". A textbook-like paragraph then discusses where robotic applications (in general) are applied—the so-called "4-D tasks"—tasks that are "dangerous, dull, dirty or dumb".

A short market analysis of robotics is conducted, with industrial robots in 2004 accounting for $4 billion market, with a growth rate of 4%. There are apparently over 20,000 professional service robots in use today, with a value of $2.4 billion. Next, a review of the state-of-the-art is conducted. As industrial robots have a long history (with the first being installed by General Motors in 1961), today they represent a "mature technology". Most industrial robots are manufactured in Japan and Europe (though they are used all over the world). Industrial robots today feature vision-guided fixturing and grasping, force feedback, collision detection, compliance control, and payload identification. However, "industrial robots still do not have the sensing, control and decision making capability that is required to operate in unstructured, 3-D environments". Service robots use simple algorithms to localize in a two-dimensional map of the world (e.g. vacuum cleaning robots). The challenges for service robots include those of industrial robots—dexterous manipulation of objects, vision-based sensing of the world—but also, in addition, include issues related to mobility.

An international assessment and comparison is presented. The leading manufacturer of industrial robots is Japan. Europe also has some major manufacturers. Qualitatively, the authors argue that only Japan and Korea have large, national concerted efforts which emphasize collaboration between government, academia and industry. Lastly, future challenges are discussed. These include:

– Manipulation and physical interaction with the real world;
– Perception for unstructured environments;
– Safety for operation near humans;
– Human robot interaction;
– Networks of robots, sensors, and users.

Chapter 6—Robotics for Biological and Medical Applications

This chapter discusses robots built for medical and biological applications. The chapter begins by examining the need robotics in biology and medicine. The main use of robotics in biology is to improve productivity in research experiments. Typically these experiments involve the "delivery and dispensation of biological samples/solutions in large numbers each with very small volumes". Applications include DNA sequencing, compound screening for drug development, and bio-solution mixing. Another purpose for robotics in biological applications is for the "effective handling and exploration of molecular and cell biology". In medical applications, robots are finding uses in surgery where the precision and repeatability of a robot surpasses that of the human hand. Moreover, robots can work *inside* the human body. Robots are also being used for diagnosis (e.g. there are robotic capsular endoscopes) and for physical enablement (e.g. prosthesis, autonomous wheelchairs, etc.). The rest of this section (Even though it does not seem consistent with the Section title) considers "Robotic Tools, Devices and Systems" (such as robot manipulators and software), "key technologies", and "fundamental research challenges".

Key Technologies include:

- Microelectromechanical systems (MEMS)—used to fabricate biosensors;
- Robotic surgeons. "The challenge is to program motion of robots efficiently based on patient-specific modeling and analysis";
- More efficient and straightforward integration (delivery?) of robotic systems for specific operations/tasks;
- "Engineering modeling of biological systems";
- "Solid understanding of life science".

Fundamental research challenges for biological applications include automating:

- Cell handling;
- Protein characterization;
- Protein crystallography;
- DNA sequencing;
- DNA and protein chip production and analysis.

Fundamental research challenges for medical applications revolve around the following areas:

- Modeling and analysis;
- Interface technologies;
- "Systems"—developing architectures, analysis and design techniques to allow rapid development.

The second half of the chapter focuses on a regional assessment. At the US workshop, three presentations were presented by three different American-based researchers. Apparently, a total of more than 30 American organizations were mentioned in the three presentations. In terms of commercial applications, "the US has a very successful system called *Da Vinci*". Da Vinci assists surgeons with complicated medical operations. In Japan, researchers attending a number of organizations, with Nagoya being mentioned for its work on "non-contact cell manipulations using lasers, and intravascular surgery based on 3D-reconstructed cerebral arterial model using CT images". Waseda University is well-known for research in legged locomotion. European research receives the lengthiest mention. Numerous projects are mentioned, including the evolution of artificial cells whose purpose is to mimic biological growth, haptic control mechanisms for human arms and eyes, and implantable microdevices which can detect neuron signals to allow control of robotic devices.

Chapter 7—Networked Robots

"Network Robots refers to multiple robots operating together in coordination or cooperatively with sensors, embedded computers, and human users".

The first section of this chapter focuses on the benefits that networked robots can offer.

- "Networked robots allow multiple robots and auxiliary entities to perform *tasks that are well beyond the abilities of a single robot*".
- "Tasks like searching or mapping, in principle, are performed faster with an increase in the number of robots".
- "Perhaps the biggest advantage of using the network to connect robots is the ability to connect and *harness physically-removed assets*". For example, "mobile robots can react to information sensed by other mobile robots in the next room".
- "The ability to network robots also enables fault-tolerance in design".

The Introduction then considers two applications for networked robots. Firstly, US military uses of networked unmanned vehicles. Second, the deployment of satellites using the shuttle robot arm requires coordination of the space shuttle, human operators on earth, the astronaut, and the shuttle arm.

The second section is titled "Significance and Potential", in it the authors argue there is significant/enormous potential for networked robots, from sensor networks, health care such as "tele-medicine", and the manufacturing industry. To argue for the significance of networked robots, "nature provides the proof-of-concept of what is possible", with many animals using simple behaviors and only sensing nearest neighbors, yet complex behaviors can emerge.

The third section is titled "State of the art in theory and practice". This section discusses numerous examples of networked robots. The first paragraph discusses automated guided vehicles in the manufacturing industry, but does not cite a specific example. The US military project "Future Combat Systems" is discussed, which is an initiative to develop network-centric approaches to deploying autonomous vehicles. Mobile sensor networks are also being utilized in environmental studies to measure environmental conditions. The European Union has several "swarm" related projects, while the COMET project integrated multiple unmanned vehicles for applications like terrain mapping and fire-fighting.

The fourth section is titled "Scientific and Technical Challenges". Three challenges are identified:

- How to coordinate multiple robots.
- Devising an effective way "for multiple humans to be embedded in the network and command/control/monitor the network without worrying about the specificity of individual robots in the network".
- Finding ways to predict the performance of a dynamic robot network.

The fifth section is titled "International Comparisons". There are several national Japanese research projects in this area. There are many "mature efforts in Japan and Europe to develop better sensors and robot hardware to facilitate the development of robot networks". Apparently Japan has a bigger investment in networked robots than the US, but there are "impressive embodiments and imaginative applications of networked robots" in the US.

The chapter concludes with "Future Challenges". The main challenges are:

- "Technical challenges to scalability"—there are no methodologies for creating robust, self-organizing robots networks.
- Performing "physical tasks" in the real world—currently networked robots do mostly sensing, rather than acting.
- Human interaction for network-centric control and monitoring.
- Creating *pro-active* robot networks.

Overall

The book's title "Robotics: State of the Art and Future Challenges" might suggest a detailed look into the technical world of robotics, however its focus is on the comparison of robotics R&D programs in Europe, Japan, Korea, and Australia with the US effort, rather than a technical evaluation of where the field of robotics is up to from a technical perspective, what the next technical challenges are and suggestions for how we can take the next exciting steps. A large part of the book focuses on comparing US research with Europe, Japan and Korea, and to a lesser extent Australia (perhaps almost half of the book is devoted to regional assessment and comparison—in 6 of the 7 chapters there is a lengthy section on this topic). The book presents the findings of an international study report from the World Technology Evaluation Center (http://wtec.org/robotics), which was funded by the US National Science Foundation, NASA, and the US National Institute of Biomedical Imaging and Bioengineering (NIBIB).

In conclusion, the book provides a solid, high level assessment of the current state of robotics research and some of its future challenges by a team of robotics experts. This book is best suited for those wanting to gain an overview of the field of robotics in terms of regional activities and priorities (though there are many countries which are not investigated or discussed in this book). It provides a comprehensive regional assessment of "who is doing what", while avoiding technical details of *how* and why the research is being pursued. The book is also well suited to those who wish to gain an overview of robotics, as at the beginning of each chapter there is an introductory section describing the class of robotic applications being discussed (e.g. "what is a robotic vehicle?"). Discussion of future challenges is not particularly detailed and definitely non-technical (in some chapters, the "future challenges" section consists of a few sentences in point form). The book could be strengthened by a final, concluding chapter in which future challenges are discussed more extensively, where lessons learned from the previous chapters could be insightfully consolidated. However, the coverage of different areas of robotics research is extensive and thorough, with the book providing a comprehensive overview of the state of the art of robotics in the US, Europe, Japan and Korea.