AN ANALYTICAL EVOLUTION OF ROBOTICS

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Abstract— This article surveys traditional research topics in industrial robotics and mobile robotics and then expands on new trends in robotics research that focus more on the interaction between human and robot. The new trends in robotics research have been denominated service robotics because of their general goal of getting robots closer to human social needs, and this article surveys research on service robotics such as medical robotics, rehabilitation robotics, underwater robotics, field robotics, construction robotics and humanoid robotics. The aim of this article is to provide an overview of the evolution of research topics in robotics from classical motion control for industrial robots to modern intelligent control techniques and social learning paradigms, among other aspects.

Keywords— *Industrial Robotics, Medical Robotics, Rehabilitation Robotics, Underwater Robotics, Field Robotics, Construction Robotics.*

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1. INTRODUCTION

During the last 45 years, robotics research has been aimed at finding solutions to the technical necessities of applied robotics. The evolution of application fields and their sophistication have influenced research topics in the robotics community. This evolution has been dominated by human necessities. In the early 1960s, the industrial revolution put industrial robots in the factory to release the human operator from risky and harmful tasks. The later incorporation of industrial robots into other types of production processes added new requirements that called for more flexibility and intelligence in industrial robots. Currently, the creation of new needs and markets outside the traditional manufacturing robotic market (i.e., cleaning, demining, construction, shipbuilding, agriculture) and the aging world we live in is demanding field and service robots to attend to the new market and to human social needs. This article is aimed at surveying the evolution of robotics and tracing out the most representative lines of research that are strongly related to real-world robotics applications. Consequently, many research topics have been omitted for one main reason: The authors' goal of tracking the evolution of research would not have been met by presenting a catalog of every research topic in such a broad area. Therefore these authors apologize to those authors whose research topic has not been reflected in this survey. The intention is not to imply that omitted topics are less relevant, but merely that they are less broadly applied in the real robotics world. This article addresses the evolution of robotics research in three different areas: robot manipulators, mobile robots, and biologically inspired robots. Although these three areas share some research topics, they differ significantly in most research topics and in their application fields. For this reason, they have been treated separately in this survey. The section on robot manipulators includes research on industrial robots, medical robots and rehabilitation robots, and briefly surveys other service applications such as refueling, picking and palletizing. When surveying the research in mobile robots we consider terrestrial and underwater vehicles. Aerial vehicles are less widespread and for this reason have not been considered. Biologically inspired robots include mainly walking robots and humanoid robots; however, some other biologically inspired underwater systems are briefly mentioned. In spite of the differences between robot manipulators, mobile robots and biologically inspired robots, the three research areas converge in their current and future intended use: field and service robotics. With the modernization of the First World, new services are being demanded that are shifting how we think of robots from the industrial viewpoint to the social and personal viewpoint. Society demands new robots designed to assist and serve the human being, and this harks back to the first origins of the concept of the robot, as transmitted by science fiction since the early 1920s: the robot as a human servant (see Figure 1). Also, the creation of new needs and markets outside the traditional market of manufacturing robotics leads to a new concept of robot. A new sector is therefore arising from robotics, a sector with a great future giving service to the human being. Traditional industrial robots and mobile robots are being modified to address this new market. Research has evolved to find solutions to the technical necessities of each stage in the development of service robots.

2. ROBOT MANIPULATORS

A robot manipulator, also known as a robot arm, is a serial chain of rigid limbs designed to perform a task with its end effector. Early designs concentrated on industrial manipulators, to perform tasks such as welding, painting, and palletizing. The evolution of the technical necessities of society and the technological advances achieved have helped the strong growth of new applications in recent years, such as surgery assistance, rehabilitation, automatic refuelling, etc. This section surveys those areas that have received a special, concentrated research effort, namely, industrial robots, medical robots, and rehabilitation robots.

3. INDUSTRIAL ROBOTS

It was around 1960 when industrial robots were first introduced in the production process, and until the 1990s industrial robots dominated robotics research. In the beginning, the automotive industry dictated the specifications industrial robots had to meet, mainly due to the industry's market clout and clear technical necessities. These necessities determined which areas of investigation were predominant during that period.

One such area was kinematic calibration, which is a necessary process due to the inaccuracy of kinematic models based on manufacturing parameters. The calibration process is carried out in four stages. The first stage is mathematical modeling, where the Denavit Hartenberg (DH) method and the product-of-exponential (POE) formulation lead the large family of methods. A detailed discussion of the fundamentals of kinematic modeling can be found in the literature [1].

Figure 1. ASIMO. Photograph courtesy of American Honda Motor Co

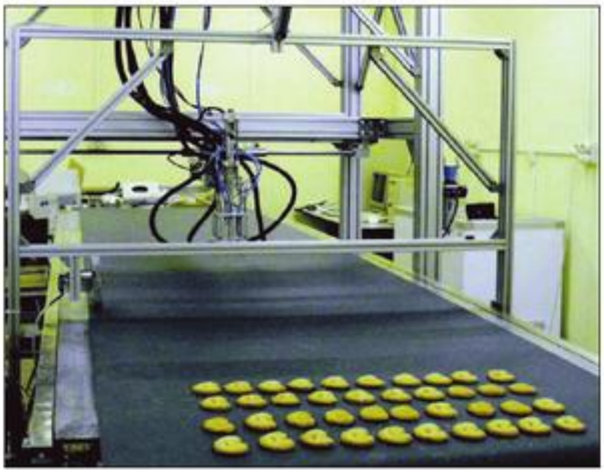

Figure 2. Robots in the food industry

The gap between the theoretical model and the real model is found in the second stage by direct measurement through sensors. Thus, the true position of the robot's end effector is determined, and by means of optimization techniques, the parameters that vary from their nominal values are identified in the third stage. Last, implementation in the robot is the process of incorporating the improved kinematic model. This process will depend on the complexity of the machine, and iterative methods will have to be employed in the most complex cases. Research in robot calibration remains an open issue, and new methods that reduce the computational complexity of the calibration process are still being proposed [2], [3]. Another important research topic is motion planning, wherein sub goals are calculated to control the completion of the robot's task. In the literature there are two types of algorithms, implicit methods and explicit methods. Implicit methods specify the desired dynamic behavior of the robot. One implicit scheme that is attractive from the computational point of view is the potential field algorithm [4]. One disadvantage of this approach is that local minima of the potential field function can trap the robot far from its goal. Explicit methods provide the trajectory of the robot between the initial and final goal. Discrete explicit methods focus on finding discrete collision-free configurations between the start and goal configurations. These methods consist mainly of two classes of algorithms, the family of road-map methods that include the visibility graph, the Voronoi diagram, the free-way method and the Roadmap algorithm [5], and the cell-decomposition methods [6]. Continuous explicit methods, on the other hand, consist in basically open-loop control laws. One important family of methods is based on optimal-control strategies [7], whose main disadvantages are their computational cost and dependence on the accuracy of the robot's dynamic model. Besides planning robot motion, control laws that assure the execution of the plan are required in order to accomplish the robot's task. Thus, one fundamental research topic focuses on control techniques. A robot manipulator is a nonlinear, multi-variable system and a wide spectrum of control techniques can be experimented here, ranging from the simpler proportional derivative (PD) and proportional integral derivative (PID) control to the computed-torque method [8], and the more sophisticated adaptive control [9] whose details are out of the scope of this survey. Typical industrial robots are designed to manipulate objects and interact with their environment, mainly during tasks such as polishing, milling, assembling, etc. In the control of the interaction between manipulator and environment, the contact force at the manipulator's end effector is regulated. There are diverse schemes of active force control, such as stiffness control, compliant control, impedance control, explicit force control and hybrid force/position control. The first three schemes belong to the category of indirect force control, which achieves force control via motion control, while the last two methods perform direct force control by means of explicit closure of the force-feedback loop. Readers who wish to study this subject in detail will find an interesting account in [10]. An attractive alternative for implementing force-control laws is the use of passive mechanical devices so that the trajectory of the robot is modified by interaction forces due to the robot's own accomodation. An important example of passive force control is the remote center of compliance (RCC) system patented by Watson in 1978 [11] for peg-in-hole assembly. Passive force control is simpler than active force control laws but has disadvantages, such as lacking flexibility and being unable to avoid the appearance of high contact forces. As 1990 began, new application areas for industrial robots arose that imposed new specifications, with flexibility as the principal characteristic. The new industries that introduced industrial robots in their productive process were the food and pharmacy industries (see Figure 2). Postal services too looked for robotic systems to automate their logistics. The main requirement was the capacity to accommodate variations in product, size, shape, rigidity (in the case of foods), etc. The ability to self-adapt to the product and the environment became the issue in the following lines of investigation in the area of industrial robotics. The main line of research now is aimed at equipping the control system with sufficient intelligence and problem-solving capability. This is obtained by resorting to artificial-intelligence techniques.

4. MEDICAL ROBOTS

In recent years, the field of medicine has been also invaded by robots, not to replace qualified personnel such as doctors and nurses, but to assist them in routine work and precision tasks. Medical robotics is a promising field that really took off in the 1990s. Since then, a wide variety of medical applications have emerged: laboratory robots, telesurgery, surgical training, remote surgery, telemedicine and teleconsultation, rehabilitation, help for the deaf and the blind, and hospital robots. Medical robots assist in operations on heart-attack victims and make possible the millimeter-fine adjustment of prostheses. There are, however, many challenges in the widespread implementation of robotics in the medical field, mainly due to issues such as safety, precision, cost and reluctance to accept this technology Medical robots may be classified in many ways: by manipulator design (e.g., kinematics, actuation); by level of autonomy (e.g., preprogrammed versus teleoperation versus constrained cooperative control); by targeted anatomy or technique (e.g., cardiac, intravascular, percutaneous, laparoscopic, micro-surgical); by intended operating environment [e.g., in-scanner, conventional operating room (OR)], etc. Research remains open in the field of surgical robotics, where extensive effort has been invested and results are impressive. Some of the key technical barriers include safety [16], where some of the basic principles at issue are redundancy, avoiding unnecessary speed or power in actuators, rigorous design analysis and multiple emergency stop and checkpoint/restart facilities. Medical human-machine interfaces are another key issue that draws upon essentially the same technologies as other application domains. Surgeons rely on vision as their dominant source of feedback; however, due to the limited resolution of current generation video cameras, there is interest in optical overlay methods, in which graphic information is superimposed on the surgeon's field of view to improve the information provided [17]. As surgeons frequently have their hands busy, there has been also interest in using voice as an interface. Force and haptic feedback is another powerful interface for telesurgery applications [18]. Much of the past and present work on telesurgery involves the use of master-slave manipulator systems [19], [20]. These systems have the ability to feed forces back to the surgeon through the master manipulator, although slaves' limitations in sensing tool-to-tissue forces can some-what reduce this ability. The field of medical robotics is expanding rapidly and results are impressive as a large number of commercial devices are being used in hospitals. However, societal barriers have to be overcome and significant engineering research effort is required before medical robots have wide- spread impact on health care.

5. REHABILITATION ROBOTS

Activity in the field of rehabilitation robotics began in the 1960s [21] and has slowly evolved through the years to a point where the first commercially successful products are now available. Today, the concept of "rehabilitation robot" may include a wide array of mechatronic devices ranging from artificial limbs to robots for supporting rehabilitation therapy or for providing personal assistance in hospital and residential sites. Examples include robots for neuro-rehabilitation [22], power-augmentation orthosis [23], rehabilitative orthosis, etc. The field of rehabilitation robotics is less developed than that of industrial robotics. Many assistive robotic systems have featured an industrial robot arm for reasons of economy and availability [24]. However, the specifications for robots in these two application areas are very different. The differences arise from the involvement of the user in rehabilitation applications. Industrial robots are typically powerful and rigid to provide speed and accuracy. They operate autonomously and, for reasons of safety, no human interaction is permitted. Rehabilitation robots must operate more slowly and be more compliant to facilitate safe user interaction. Thus, rehabilitation robotics is more akin to service robotics, which integrates humans and robots in the same task. It requires safety and special attention must be paid to human-machine interfaces that have to be adapted for disabled or non skilled people operating a specific programming device. It is also recognized that there is a need for research and development in robotics to focus on developing more flexible systems for use in unstructured environments. The leading developments of this type in rehabilitation robotics concern, among other topics, mechanical design (including mobility and end-effectors), programming, control and man machine interfaces [25]. Subsection "Humanoid Robots" of this article expands on new research into human-robot interaction.

6. ROBOTIC MAPPING

Because map-based robot localization and robotic mapping are interdependent, research since 1990 has focused on solving both problems simultaneously. However, before then, the field of mapping was divided into metric and topological approaches. Metric maps capture the geometric properties of the environment [30], while topological maps describe the connectivity of different places by means of nodes-and-arcs graphs [31]. In practice, metric maps are finer grained than topological maps, but higher resolution comes at a computational burden. Metric maps can be discretized based on the probability of space occupation. The resulting mapping approaches are known as occupancy-grid mapping. In contrast, the metric maps of geometric elements retain positions and properties of objects with specific geometric features Since 1990, robotic mapping has commonly been referred to as simultaneous localization and mapping (SLAM). Some methods are incremental and allow real-time implementation, whereas others require several passes through the whole of the perceived data. A broad family of incremental methods employ Kalman filters to estimate the map and the robot location and generate maps that describe the position of land marks, beacons or certain objects in the environment. Extensions of the algorithms based on the Kalman filter include the FastSLAM, the Lu/Milios algorithm and very recently, the sparse extended information filter, based on the inverse of the extended Kalman filter (EKF). An alternative family of methods is based on Dempster's Expectation Maximization algorithm, which tries to find the most probable map by means of a recursive algorithm. These approaches solve the correspondence problem between sensorial measurement and objects in the real world. Recently researchers have been working on mapping dynamic environments. This is a considerable problem, since many realistic applications for robots are in non-static environments. Although Kalman-filter methods can be adapted for mapping dynamic environments by supposing landmarks that move slowly over time, and, similarly, occupancy-grid maps may consider some motion by reducing the occupancy over time, map generation in dynamic environments has been poorly explored. There are a few algorithms based on the dynamism of the environment. Many questions, however, remain open, such as how to differentiate between the static and dynamic parts of the environment and how to represent such information on the map. A complete survey of mapping methods can be found in Mobile robots are traveling from laboratory prototypes to real-world applications. Direct service applications of mobile robots include cleaning and housekeeping, where autonomous vacuum cleaners and lawn mowers take advantage of all the research in mobile navigation to help at home. Mobile robots also show potential for use as tour guides at museums and as assistants in offices, hospitals and other public venues. Such robots address key problems of intelligent navigation, such as navigation in dynamic environments, navigation in unmodified environments, short-term human-robot interaction and virtual telepresence. Surveillance is another potential application of mobile-robot technology and private security companies are becoming interested in incorporating guard robots.

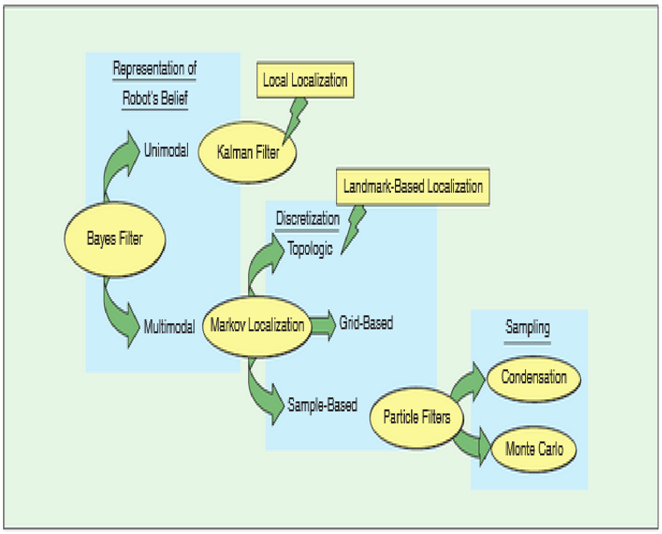

Figure 3. A classification of localization algorithms

CONCLUSION

Since the introduction of industrial robots in the automotive industry, robotics research has evolved over time towards the development of robotic systems to help the human in dangerous, risky or unpleasant tasks. As the complexity of tasks has increased, flexibility has been demanded in industrial robots, and robotics research has veered towards adaptive and intelligent systems. Since 1995, robotics research has entered the field- and service-robotics world, where we can find manipulators, mobile robots and animal-like robots with great perspectives of development and increasing research interest. Surgical robots have been the first successes, and recently different areas in medical and rehabilitation-robotics applications have arisen. Other examples can be found in the fields of home cleaning, refueling and museum exhibitions, to name just a few areas. Service-robotics research is also aimed at providing a comfortable, easy life for the human being in an aging world. The United Nations Economic Commission for Europe (UNECE) forecasts strong growth of professional robots in application areas such as humanoid robots, field robots, underwater systems and mobile robot platforms for multiple use in the period of 2005–2008. The UNECE also forecasts a tremendous rise in personal robots in the next few years. Robotics research has to make a great effort to solve in very few years the challenges of this new field of research, which will be largely determined by interaction between humans and robots. Figure 10 summarizes the evolution of robotics research over the last 50 years. it is a fact that, during the last decade, the activity in conferences and expositions all over the world has reflected low activity in industrial manipulators and huge activity in other areas related with manipulation in unstructured environments and mobility, including wheeled, flying, underwater, legged and humanoid robots. Maybe the key is that new challenges in manipulation in factories require less research now because factory needs lie in the field of traditional engineering. With these premises we can conclude: Yes, definitely robotics research is moving from industrial to field and service applications, and most robotics researchers are enthusiastic about this broad, exciting field. One development that is very representative of the way the field is evolving is the controversy set off by Prof. Engelberger, the creator of the first robotics company, at the 2005 International Robot Exhibition in Tokyo, Japan, when he commented on the needless research by both Japanese companies and scientific institutions for developing toy-like animal and humanoid robots for very doubtful use. Engelberger thus gained many detractors, who have rapidly argued back that these kinds of robots are a necessary step in the evolution towards real robots capable of helping disabled persons, performing dangerous work and moving in hazardous places Other defenders of the development of human-like personal robots advocate the importance of aiming at such challenging tasks because of the technology that can be developed, which would prove very important from the commercial point of view in other industrial activities. Maybe behind all the arguments there still lies the human dream of the universal robot—a single device that can perform any task. Nothing better for that than a device resembling—what else?—a human being. So, let our imagination fly into the world of service robotics, but, please, do not forget to keep an eye on traditional industrial manipulators.

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