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On autonomous robots

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1 Introduction

Autonomous robots are the intelligent agents *par excellence*. We frequently define a robot as a machine that senses, thinks and acts, i.e., an agent. They are distinguished from software agents in that robots are embodied agents, situated in the real world. As such, they are subject both to the joys and sorrows of the world. They can be touched and seen and heard (sometimes even smelled!), they have physical dimensions, and they can exert force on other objects. These objects can be like a ball in the RoboCup or Mirosot robot soccer games, they can be parts to be assembled, airplanes to be washed, carpets to be vacuumed, terrain to be traversed or cameras to be aimed. On the other hand, since robots are agents in the world they are also subject to its physical laws, they have mass and inertia, their moving parts encounter friction and hence heat, no two parts are precisely alike, measurements are corrupted by noise, and alas, parts break. Of course, robots also contain computers, and hence they are also subject to the slings and arrows of computer misfortunes, both in hardware and software. Finally, the world into which we place these robots keeps changing, it is non-stationary and unstructured, so that we cannot predict its features accurately in advance.

These, then, are the features of autonomous robots. They suffer from all the limitations of the real world, but because they are physical, they also fascinate us. They are an imitation of life, and we are drawn to watching them as they perform their tasks. It is not only the fact that they move, since many things move in the world (sometimes by gravity or sometimes by motor power), but that they move intelligently. For those of us who design and build them, this is precisely our goal.

2 A little history

During the nineteenth century there was a great deal of fascination with automata, meaning machines that move automatically in some sort of imitation of living creatures. A number of animated dogs and human figures were built. Churches and public buildings were equipped with moving figures controlled by complex mechanical clockwork. While these machines were not robots in that they did not have sensors to ascertain the state of the world, one may consider their clocks as primitive computers, which controlled the actuators and produced movement. Robots, in the sense of programmable mechanical systems, arose relatively recently. Robot manipulators were proposed by Devol in the United States in 1954; a company started by Devol and Engelberger produced the first commercial versions of these machines in 1962. Industrial robots rapidly assumed an important role in manufacturing (particularly in the automobile industry, where they are used extensively for painting, welding and assembly). In the following 20 years, the manufacture of robots gradually shifted from the US to Europe and Japan. Japan currently has the largest number of manufacturing robots of any country in the world. While the early manipulators were strictly pre-programmed mechanical arms, capable only of specific movements in highly structured environments, in recent years they have been equipped with increasing numbers of sensors (such as vision and force) which have given them some ability to adapt to changes in the environment.

However, manipulators used for manufacturing are not autonomous agents, even if they have some degree of adaptability. Another line of development led to the development of mobile robots, which could interact with the world and perform some cognitive functions. In Japan the pioneer in this line of work was Ichiro Kato from Waseda University, whose biped robot walked many kilometres, and the Wasebot piano playing humanoid were the stars of the show during the Japan Expo World's Fair of 1985. The piano playing robot was a mechanical marvel. It could read sheet music, and control its arms and ten fingers as it sat on a piano bench. The Japanese fascination with these machines and robots in general is well known (Schodt 1988). Numerous other walking machines were built in the US, Japan and Europe, with two or four or six or eight legs. Raibert's (1986) Pogo stick was a one-legged robot, which maintained its balance as it hopped in a circle at the end of a boom. It and other remarkable machines are described in his book. The foundation of behaviour-based control of mobile robots was provided by Brooks (1986), in whose laboratory many autonomous robots were designed and built. Perhaps the largest and most varied collection of mobile autonomous robots was designed and constructed by Hirose and his collaborators (Hirose, 1984, 1993).

3 Current trends and directions

3.1 Humanoids

Recently there has been a revival of interest in humanoid robots, with varying degrees of autonomy. The Honda robot, which debuted in 1996, is a biped walking machine, capable of walking up and down stairs autonomously, and adapting to changes in load. Brooks' current robot, named Cog, is a humanoid torso, with head, eye and arm movements, and some ability to hear, learn and speak (Brooks and Stein, 1994). This represents one of the current trends in autonomous robots, i.e., the incorporation of learning. Thus, the development of autonomous robots has moved from emphasis on movement to emphasis on cognition and learning. It is interesting to note that the field of synthetic agents is also concerned with the creation of agents which are "anthropomorphic", not in physical structure, but in appearance and personality.

3.2 Hospital and medical applications

This is likely to be one of the major emerging applications of autonomous robots. The Helpmate (manufactured in the US) is a hospital service robot, which carries food trays along hospital corridors while avoiding obstacles. It is equipped with a map of the hospital which enables it to locate a destination room and to use the elevator when necessary. Other robots being developed in Europe and Japan will be capable of assisting persons with disabilities or the feeble elderly in a number of tasks, from fetching objects to feeding or assisting with personal hygiene. In all industrialized countries which have an increasing percentage of older people, the need for providing them with some independence will continue to grow. They will have to work in close proximity to people, perhaps placing food in the person's mouth or assisting with movement from bed to wheelchair. The autonomous robots needed for such applications will require a large number of sensors, ability to learn and adapt to the needs of different patients and extremely high levels of safety and reliability. Even more, the robotic agent should be perceived as "friendly" rather than potentially dangerous. I believe that the issue of perceived friendliness in these agents will be increasingly important in the future. It should be noted that the Sony robot "pets" (which were exhibited at the conference) were frequently described by such terms as "charming", "lovable", "cute" or "friendly". This is quite a compliment for an inanimate agent.

3.3 Human service and cooperation

In addition to the medical and hospital applications cited above, I believe that more and more robots will be used to assist people in a variety of tasks. Such jobs may include street cleaning, gasoline pumping, vacuuming large carpets, washing aircraft, or inspecting pipelines from the inside. Prototype robots for such tasks have already been built. Some degree of autonomy will be completely essential for such robots. One of the distinguishing features of human service robotics (as with the medical robots described above) is the fact that the machines will be working in close proximity to and in cooperation with humans. This is drastically different from the early days of industrial robotics, where great care was taken to insure that humans and robots were well separated to minimize the risk of injury. Such human-robot interaction will require that the agents relate to humans in novel ways, in order to be able to respond to commands, motivations and goals. The agents may be required not only to understand spoken commands, but also to "read" the tone of voice, facial expressions, and gestures of their human coworkers.

3.4 Agriculture, construction and transportation

The Robotic Engineering Center at Carnegie Mellon University has been developing an autonomous robot tractor (named Demeter). The machine has already demonstrated the ability to operate in large fields and to perform harvesting operations. Autonomous road building machinery is being tested in such applications as excavation, pipe laying, and paving. Construction robots in Japan are being used to assemble steel beam structures and to spray asbestos for fireproofing. In the area of transportation, projects at CMU and in Germany have demonstrated the ability of autonomous passenger automobiles to travel on highways for long distances at normal traffic speeds. Clearly, all these are applications for agents.

3.5 Groups of robotic agents

The above examples have featured applications of individual robots to specific tasks. Another major trend is the increasing development of computational models and tools to created behaviour-based colonies of agents. Work at MIT and Brandeis by Mataric, Georgia Tech by Arkin, and Nagoya by Fukuda are only a few examples of a major and growing trend. Our own laboratory at USC is working on a colony of agents (involving both ground-based and flying vehicles) to perform reconnaissance and other tasks, with a minimum of inter-agent communication and outside supervision. Such tasks typically involve the ability of a colony to reach global goals when each agent has only local information. A number of papers in this field were published in a recent issue of the journal *Autonomous Robots* (Arkin and Bekey, 1997).

4 Papers at this conference

The papers presented at the *First International Conference on Autonomous Agents* were concerned with a number of the areas described above, as well as other basic issues. A number of the papers concerned sensing and perception, not just in novel approaches to the traditional areas (like vision) but also in representation of the attentional state of a robotic agent. As indicated above, learning was a major theme, and several papers described novel architectures which facilitated learning. Behaviour-based architectures were very much in evidence, in these and other papers. As indicated in our overview of trends, multiple robotic agents were in evidence in a number of papers. Groups of cooperating robots were used to explore and map unknown interior environments. Teams of robots playing a version of soccer were described in connection with the RoboCup initiative. Control of multiple ground vehicles provided insight into the relationship of robotic agents and planning agents. The development of robot architectures which provide new ways of relating high level planning to execution was another theme. It is clear that in the future multiple robots will be engaged in more complex and challenging endeavours than gathering of simple objects or herding. The development of increasingly life-like robots was mentioned above as a current trend. While there were no papers dealing with humanoid robots, there was a paper and a demonstration of the Sony robot "dogs". These charming little quadruped robots displayed a wide variety of unpredictable behaviours, and opened a serious discussion of open architectures for mobile, entertainment-oriented robots.

5 Conclusion

In summary, we see robotic agents in the future incorporating the following features:

(1) Some form of machine learning, applicable to behaviour in the real world.
(2) Human-robot interaction, including the ability of the agents to respond to a large variety of commands and cues from humans.
(3) Multi-agent behaviour, involving cooperative actions and cooperative problem solving among many robots.
(4) Humanoid robots, which resemble humans both in physical appearance, behaviour and some aspects of cognition.
(5) The incorporation of emotional components into robot behaviour.

It is interesting that many of these features, such as human-agent interaction, multi-agent systems and emotions, also characterize developments in software agents. We expect that in the future the boundary between softbots and robots may become increasingly fuzzy, as the software and hardware agents we build become more intelligent, have greater ability to learn from experience, and to interact with each other and with us in new and unexpected ways.

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