Sentience in Robots: Applications and Challenges

The articles in this special issue on semisentient robots provide an excellent view of current research. However, we thought you might also appreciate views from other researchers and practitioners directly involved with robotics applications, to find out what they think about the applicability of this new generation of more adaptable and user-friendly robots. We also thought it would be instructive to know what the most experienced and distinguished researchers from the intelligent-robotics field think are the remaining challenges.

The first three contributions come from well-known roboticists. Paolo Dario discusses the acceptability of personal robots in human societies. He concludes that human–robot cooperation should receive particular attention, keeping in mind the different abilities of humans and robots. Robin Murphy, actively involved with using robot teams for urban search and rescue, discusses the need for various levels of semisentience in this context. Pete Bonasso, who has worked in space robotics for a long time, believes the need for sentience is a function of how closely the robot must work with humans while carrying out the task.

Since its early stages, AI has been concerned with knowledge representation, reasoning, and problem solving. These topics make up the core of what is often called *classical AI*. For various reasons, the general-purpose techniques of this longstanding AI tradition are seldom found in robots. We were, therefore, curious to know if researchers still believed that these techniques applied to robots. Bernhard Nebel, a theoretical AI researcher who leads a champion RoboCup team, thinks that such representation and reasoning techniques will eventually find their way into robots. He also discusses why this is taking so long to occur in a widespread fashion. And Nils Nilsson, three decades after building Shakey, thinks that logic-based representation and reasoning will be an essential component of sufficiently sentient robots—although different variants might be required for different kinds of tasks.

Rationality, emotions, and what else? For Rodney Brooks, the real challenge now is developing robust methods for visual object recognition, a skill that is effortless for children but very difficult for robots. He argues that this ability is essential for any reasonable understanding of the world.

—Luís Seabra Lopes & Jonathan H. Connell

Who Wants a Nosy Butler?

Paolo Dario, Scuola Superiore Sant'Anna, Pisa, Italy

For years, AI research has focused on developing entities with intelligence comparable to that of humans—that is, with the capability of reasoning and managing knowledge. The Turing test demonstrates how researchers have pursued machine intelligence. Recently, AI research has changed its focus. Recognizing (as Rodney Brooks at MIT first proposed) that interaction with the physical world is critical to developing intelligence, many research groups have tried to develop humanoid "bodies." According to this approach, human-like intelligence relates not only to reasoning but also to learning, perceiving, and interpreting the physical world and to interacting with the world and humans.

These goals are much more difficult to implement in machines than pure reasoning. As Tommaso Poggio pointed out, humans have developed reasoning rules only in the last few millennia; perception seems so natural to us because nature has refined it over millions of years. In fact, we've accomplished what was AI's biggest challenge for decades—defeating a human champion in the game of chess. AI's new, much more challenging goal is to develop humanoid robots that can play, and possibly win, against a human soccer team.

Even when AI is connected to robotics—which provides a physical body for machines—its goals are still to develop entities that can autonomously perceive, reason, learn, and act, thus exhibiting human-like aspects of intelligence. But should these entities really be autonomous? Real-world applications of robotics implies using robots in close interaction with humans. In this nonabstract context, intelligence means interacting with humans and their environment safely, effectively, and pleasantly. In most cases, this interaction requires cooperation between the robot and human, rather than autonomous behavior.

Researchers in rehabilitation robotics have analyzed in depth the need for semiautonomous robots and human–robot cooperation in real-world applications. My group has obtained experimental evidence that the acceptability of personal robots (robots that assist humans) is lower when the system is autonomous, especially in everyday tasks at

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home. Who feels confident with—or likes—an autonomous machine that moves around the house and makes decisions? Furthermore, why should we let a robot waste effort trying to recognize our favorite drink when we could help it (and our safety) by simply confirming that the object it is painfully trying to identify is really a bottle?

If the goal is to develop robots that can participate in human society and move and act in domains as complex as human environments, these robots should be able to communicate with humans using human-friendly modalities. They should possess some form of reasoning capabilities and be able to learn their user's preferences and adapt to the changing environment. This means research must consider the differences between natural and artificial intelligence and develop machines that can synergistically exploit such complementarity in their interaction with humans.

Semisentience Doesn't Mean Being a Team Member

Robin Murphy, University of South Florida

Our work with rescue workers has led to a surprising discovery about intelligent robots for urban search and rescue. Although USAR robots need intelligence to operate in the complex, wireless-hostile environment of a collapsed building, it's not clear that the rescuers need robots to be recognizably semisentient.

One approach to USAR robotics concentrates on giving the robot the ability to work in the existing technical-rescue-team structure. In this approach, the robot's relationship with humans is similar to that of a rescue dog—only one or two humans who have bonded with the robot care for and handle it. Such a relationship presumes recognizable semisentience—humans treat the robot as an intelligent entity or near peer.

However, one motivation for USAR robots is that there aren't enough confined-space rescue workers certified for entry into a collapsed structure to respond to a major disaster. Robots that less-specialized rescue workers can operate could alleviate the manpower problem. The catch with the robots-as-a-tool scenario is that a fire rescue worker might receive only 30 minutes' training every few months on a particular rescue tool. So, the rescue worker treats the robot as a generic tool, not a near peer, and up to 10 different workers might use a robot in a day. Likewise, the workers are unlikely to use the same robot each shift. There's no advantage in having a social bond, such as is induced when a human recognizes a robot as semisentient.

Clearly, we need semisentience for both the robot-as-a-peer and robot-as-a-tool to perform their task competently. It is the human's perception of the robot's sentience that is different. To be treated as a team member, a robot must be able to communicate naturally, explain itself, and adapt to humans—but precisely because the robot is semisentient, it can also take advantage of humans willing to adapt to it. To be a useful tool, a robot must be able to accomplish the same tasks but with a wider range of users, who have less motivation and time to coadapt to a peer.

In the end, robots may have to be much smarter to appear comfortably dumb.

> **Perhaps someday we'll show that emotional biasing of robot behaviors is the most efficient control paradigm. Until then, the only real value of sentient robots is to communicate better with humans.**

Natural Language Beats Programming

Pete Bonasso, Johnson Space Center, NASA

Sentient robots (those capable of not only perception but also feelings) are useful only when they work in close proximity with humans. Perhaps someday we'll show that emotional biasing of robot behaviors is the most efficient control paradigm. Until then, the only real value of sentient robots is to communicate better with humans. Humans understand each other more completely by using communications channels beyond language—such as speech prosody, facial expressions, and body language. So, it seems only reasonable to endow robots with more than just the ability to interact through menus or simple spoken commands. Given that the emotional model and its subsequent output accurately reflect the robot's state and its understanding of the world, human–robot team efforts should prove more efficient. For space applications, examples of such robots might be the control computers on the space station (the present-day incarnation of the HAL 9000) or human–rover teams exploring and mapping planetary surfaces (the year 2015 version of *Star Wars*' C3PO).

However, the usefulness of a robot's emotional aspects decreases as some function of its distance from the human or, more accurately, as a function of the increasing cycle time of communications response. This point is obvious for deep-space probes, whose communications with humans are more akin to sending surface-mail letters than to having a conversation. When the robot works autonomously for long periods of time—such as an intelligent satellite monitoring sunspot activity—there is little need for sentience or anything more than a graphical display and a command menu.

Let me issue a caveat about my comments regarding language ability. One normally identified practical motivation for endowing robots with a natural language capability is that in many human–robot tasks, the human can't easily access a keyboard or a graphical interface. A singular exemplar for this is the suited astronaut on Mars working with an intelligent rover. Yet there is another good reason to develop natural language interaction with robots: to obviate the need for the human to learn a new interface with every robot or computer-controlled machine he or she encounters.

In my work with long-running autonomous life support systems, for example, I've seen many instances where the human supervisors wish to make special queries, temporarily override restrictions, or otherwise modify the system behavior on an ad hoc basis. Without a language capability tied to the control system, either the programmer must be on hand to temporarily change the code or to code a new piece of interactive graphics, or we must add new selections to existing menus—often for rarely performed tasks. It is often cheaper to have the programmer manually obtain the information or perform the task at the time it is needed than to build and test new code and place it under configuration control.

So, we are developing a language discourse ability for our intelligent control systems that will let the human perform such ad hoc actions more naturally without programmer intervention.

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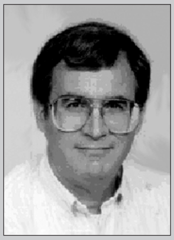

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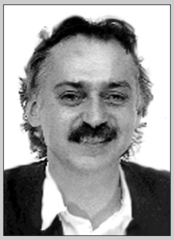
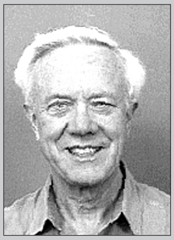


Bernhard Nebel is a professor at Albert-Ludwigs-Universität Freiburg and is head of the Artificial Intelligence research group. He is generally interested in knowledge representation and reasoning and, in particular, description logics, temporal and spatial reasoning, constraint-based reasoning, planning, and belief revision. One of his current favorite application areas is robotic soccer. He received a diploma in Computer Science from the University of Hamburg and his PhD from the University of Saarland. He is a member of AAAI and ACM, has been a program chair of a number of conferences, including IJCAI-01, and is on the editorial board of a number of journals, including *Artificial Intelligence*. Contact him at nebel@informatik.uni-freiburg.de.



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Do Intelligent Robots Need Knowledge Representation and Reasoning?

Bernhard Nebel, Albert-Ludwigs-Universität, Freiburg, Germany

Knowledge representation and reasoning covers much of AI's theoretical aspects and offers methods to represent knowledge and reason with it. In other words, this technology could support the specification of abstract, high-level controllers for robots. However, for three reasons, previous robot systems have not had much of this technology. First, research was needed to make basic robot capabilities (such as self-localization, navigation, and mapping) more robust. So, high-level control might not have had the highest priority in most robotic projects. Second, because of these problems, a typical robot's action repertoire was very limited. Thus, there was little need to deliberate about what to do next. Third, reasoning and action planning approaches proved slow and inefficient and thus didn't seem mature enough to be incorporated in a robotic control system.

However, this situation seems to be changing. Several researchers have investigated *cognitive robotics* or high-level control. Indeed, the time seems ripe for such approaches. Although the basic capabilities are far from perfect, mobile robots can easily act for an extended period of time without getting lost or stuck. Also, in some applications, the size of the robot's action repertoire has become larger than we can manage using pencil and paper. So we clearly need to coordinate different possible actions. For instance, our robotic soccer team, CS Freiburg, has over a dozen different actions, parameterized by the situation.[1] It has become a nontrivial problem to select the right action and switch between different actions. Finally, current action planning methods and decision-theoretic action selection methods scale well enough to cope with realistic problems in robotic domains. For example, current planners can easily generate plans with 100 steps, whereas planners five years ago failed on 10-step plans. In addition, to reduce the combinatorics inherent in planning, we can use agent-programming languages as an alternative to deliberation. One famous agent-programming language is Golog, a logical specification language that has even been extended to incorporate decision-theoretic notions.[2]

In general, more techniques and methods from knowledge representation and reasoning and AI will find their way into robots.

1. T. Weigel et al., "CS Freiburg: Doing the Right Thing in a Group," *RoboCup 2000: Robot Soccer World Cup IV*, P. Stone, G. Kraetzschmar, and T. Balch, eds., Springer-Verlag, New York, 2001.

2. C. Boutilier et al., "Decision-Theoretic, High-Level Agent Programming in the Situation Calculus," *Proc. 17th Nat'l Conf. Artificial Intelligence* (AAAI 2000), AAAI Press, Menlo Park, Calif., 2000, pp. 355–362.

Logic, but Which Variants?

Nils Nilsson, Robotics Laboratory, Stanford University

Robots that are sufficiently sentient need to be able to represent their environment and reason about it. Many robot actions will be "automatically" evoked by particular combinations of perceptual inputs. And some will be calculated by path-planning algorithms using, perhaps, some kind of configuration-space representation. But robots that can receive, represent, and utilize declarative information, such as "deliveries are not to be made to rooms on the second floor on Tuesdays," would be much more flexible (or sentient?) than ones that merely react to specified perceptual cues.

Given that representing and reasoning with declarative information is important, what is the best form for such representations? There is less to that question than meets the eye. Most of the efficient representational forms, such as structured ones like semantic networks, turn out to be variants of relational calculi. They are efficient because certain frequently used inferences, such as those involving taxonomic and inheritance information, are precoded in their structures. The main question is thus not whether to use some language such as the first-order predicate calculus (FOPC), but rather which structural variants are most appropriate for the kinds of reasoning to be performed in the particular tasks at hand.

Some promising work has already been done on robot architectures that combine low-level reactive capabilities with high-level, logic-based declarative reasoning—in particular, research on logic-based subsumption architecture.[3]

3. E. Amir and P. Maynard-Reid II, "Logic-Based Subsumption Architecture," *Proc. 16th Int'l Joint Conf. Artificial Intelligence* (IJCAI 99), Morgan Kaufmann, San Francisco,1999, pp. 147–152.

Toward Better Semisentient Robots

Rodney A. Brooks, MIT AI Lab

Over the last few years, both the academic and commercial world have made tremendous progress toward making sentient and semisentient robots a reality. The world of mobile robots in 2001 is almost unrecognizable by 1996 standards.

Building 2D metric maps indoors using sonars or laser scanners is now routine, as is collision avoidance and corridor following based on sonar or vision. Such systems provide the basis for commercial remote-presence robots, built on top of the Internet infrastructure. Such a remote robot with local perception and intelligence can perform useful work in a harsh or hard-to-reach location if a person can provide long-latency supervisory commands.

On the research front, many systems are available for tracking moving objects visually from a (temporarily) static camera, as are commercial systems for real-time stereo depth maps. Active vision systems with saccades, smooth pursuit, and vestibular ocular reflexes abound. Finding people on the basis of skin color or face detection is common. Despite our intuition that every face is different, so much commonality exists that there are many robust techniques for finding faces, determining facial features, and detecting gaze direction. Facial recognition has received intense research attention, and there is a real payoff with practical recognition now a reality in many applications. Recent work combining voice prosody understanding, facial detection, and gesture and expression understanding has lead to the first few robots that can engage in genuine social interactions with robot-naive people. And finally, the first steps have been made toward robots developing a practical understanding of human intent, attention, and knowledge, a set of capabilities that autistics never develop.

With all this positive news, what stumbling blocks might impede the future development of sentient robots? Some might argue that we still have not determined how to organize the higher-level control systems and find the right mix between cognitive, reflexive, and homeostatic arbitration. And some might argue that we are missing a fundamental understanding of some sort of key ingredient of all living systems, which is holding back our development of robust comprehensive artificial creatures. However, there is a more fundamental problem that we all know but have pushed to the back of our consciousness and out of our active research agendas. Fundamentally, all our robots are limited by their inability to recognize objects visually. This skill is effortless for small children and primates, but our robots perform it pathetically. It is a skill that we do not even discuss and for which obtaining research funding is difficult—we have relegated this to the "not likely any time soon" category. We do not even know whether object recognition should be built as a front-end perceptual system that delivers descriptions of the world, or whether it is something that emerges from the interaction of more primitive visual capabilities, higher-level knowledge of the world, and embodied active motion and manipulation of the world.

Our current robots live in a sea of the immediate, perhaps with a 2D map of where undifferentiated stuff exists. Everything else is transient—a face here, a colorful object there—appearing and disappearing from a background of largely misunderstood features. None of our robots can reliably differentiate a cell phone, a stack of business cards, or a wallet, let alone pick out the chairs, tables, televisions, couches, desks, VCRs, file cabinets, or a thousand other object categories that we can all effortlessly perceive and name.

Without this capability, our robots cannot have any reasonable understanding of the world for carrying out complex tasks. Furthermore, they cannot begin to do even the rudimentary nondextrous manipulation of the world that a one-year-old child can achieve.

We need some good ideas and innovative research that will lead to the beginnings of real object recognition under general viewpoint and lighting conditions. It might need to rely on interaction with the world, or it might turn out to be solvable passively. Until some bright researchers make a dent in this, our robots and their sentience are going to remain limited.

Coming Next:

Human Language Technology in Knowledge Management