

# Components, Curriculum, and Community:

## Robots and Robotics in Undergraduate AI Education

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■ This editorial introduction presents an overview of the robotic resources available to AI educators and provides context for the articles in this special issue. We set the stage by addressing the trade-offs among a number of established and emerging hardware and software platforms, curricular topics, and robot contests used to motivate and teach undergraduate AI.

Robot platforms have played a fundamental role in the field of artificial intelligence (AI) for more than 30 years. Yet it is only recently that physically embodied agents have become a viable tool in the undergraduate AI classroom. Examples of the flurry of activity in this area include competitions and exhibitions, the growing options for low-cost robot hardware and software, and a number of recent workshops and symposia. This special issue of *AI Magazine* grew out of the 2004 AAAI spring symposium on Accessible, Hands-on AI and Robotics Education. In this article, we seek to showcase how robots have influenced both the curriculum and practice of teaching AI at the undergraduate level.

This survey article first overviews a number of robot platforms and presents trade-offs in choosing among them. We then highlight the variety of AI curricula supported by low-cost robotic platforms. We conclude with a summary

of the engaging and active communities that support robotic competitions and exhibitions. These robot-based components, curricula, and communities, we hope, broaden the resources available to educators, as we all invite students to share our enthusiasm for AI.

### Robot Platforms for AI Education

Stuart Russell and Peter Norvig frame their widely used AI text through a paradigm of intelligent agents (Russell and Norvig 2003). Such an approach resonates with students, all of whom have deep experience with (and as) intelligent agents. Yet nearly all of that experience is with embodied intelligent agents, and this familiarity makes robots a strong motivator of AI. This embodiment contrasts with the majority of computer science subfields, in which computers interact with the physical world very differently than we do. What's more, for AI educators, robotic hardware is not only a hook that can draw students to the field, but a fundamental facet of the AI endeavor. The challenge is to find a set of hardware and software resources that serve both as motivation and as tools to advance, not limit, the AI that students pursue in an academic course of study.

Today there exists a large and growing selection of robotic platforms suitable for conveying and investigating fundamental AI topics. Fig-

ures 1, 2, and 3 summarize some of these resources and their capabilities, with particular attention given to newer models and those widely employed at the undergraduate level.

These sensors are available from a number of retailers including HiTechnic Products and Mindsensors.com for the RCX-compatible sensors and Acroname for those sensors not specifically tailored to the RCX's Lego interface.

Before discussing the platforms listed in figure 1, it is worth mentioning a family of low-cost robotics resources we have omitted: those dedicated to teaching the electrical and mechanical engineering that underlies most contemporary robotics, such as the basic stamp microcontroller (Kuhnel and Zahnert 1997). Undergraduate AI does not ignore the impact of such design decisions but instead focuses on the computational challenges those decisions create. In the context of AI education the hardware/software interface, that is, the ease with which students can interact computationally with a robot and investigate how their algorithms behave, is a crucial criterion for evaluating robotic platforms.

### Hardware and Software

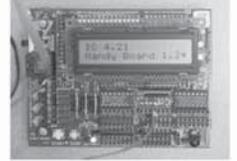
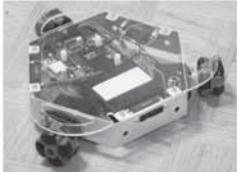
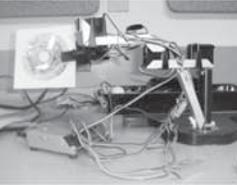
A key advantage of the two most popular platforms, Lego Mindstorms (or RCX brick) and the Handy Board, is the variety of ways in which students can program them. C-like languages and Java subsets are available for the Mindstorms through the BricxCC and LeJOS firmware upgrades. Both are open-source projects with substantial deployment. Interactive C is the default computational interface on the Handy Board. A commercial Java implementation, RoboJDE, is available for the Handy Board from RidgeSoft, LLC.<sup>1</sup> These two platforms' large user communities breed support for a wide variety of interfaces: of particular note is the Lisp interface to the Lego RCX brick described in detail later in this *AI Magazine* issue. Both Lego and Handy Board platforms provide a microcontroller to which students attach a chassis, motors, and sensors. Their flexibility enables students' hands-on investigation of the close relationship between physical agents' form and function. Fred Martin's text *Robotic Explorations: An Introduction to Engineering Through Design* (Martin 2000) is a popular and natural starting point for Handy Board-based courses. Several texts also build curricula around the RCX, such as Bagnall's *Core Lego Mindstorms Programming* (Bagnall 2002).

Other modular robotics options have grown around off-the-shelf computational engines: the Palm Pilot robot kit (Reshko, Mason, and Nourbakhsh 2002; Avanzato 2004) and the

Nintendo Game Boy Advance's Xport Robot Controller (XRC) and related XBC (LeGrand et al. 2005). Any device with a serial port or a conversion to one can drive up to eight servo motors using Pontech's SV 203, which is a small, easily programmable controller (Bishop et al. 2004). Though less well established than the Handy Board and the Lego RCX controllers, all of these systems have been employed to teach undergraduate AI and/or robotics. They typically use a Lego or custom chassis and require some work to interface with Lego sensors. Other prebuilt controllers are also available, such as Ridgesoft's IntelliBrain, a more powerful, proprietary alternative to the Handy Board.

One perceived disadvantage of robot kits is that the resulting platforms can provide software support for only a low level of behavioral abstraction. Recent example curricula, such as Greenwald's (see his article in this issue of *AI Magazine*), mitigate these concerns: topics as computationally demanding and subtle as A\* search and Markov decision processes have run entirely on a Handy Board. Further, because it is easy to download information from each of these platforms to a PC, all of these systems can be used to collect data for off-board analysis, for example, learning the weights of a back propagation or Bayesian network (Greenwald and Artz 2004). Susan Imberman demonstrated that the results of such analysis can return to the robot for control, such as in a line-following task based on neural network parameters learned off board (Imberman 2004). On-board processing is needed only to the extent that sensed data must contribute to behavioral decisions during operation. In practice, a more important disadvantage of all of these platforms' flexibility is that they are more difficult to support with simulation software, as neither the robot morphology nor its sensor suite is known a priori.

In contrast to robot kits, preassembled platforms offer additional capabilities and convenience at a higher cost. K-Team's miniature robot, the Khepera, provides options for a huge variety of sensors and actuators including color vision and a parallel-jawed gripper. Its small form factor facilitates use in almost any space: students have watched a Khepera execute their programs from a desktop in a professor's office (Challinger 2005). The Khepera has proven itself within AI classes at a variety of schools (Harlan 2005, Kumar and Meeden 1998). K-Team's newer and slightly larger robot, the Hemission, also uses a ring of infrared (IR) sensors for proximity sensing—at a cost an order of magnitude lower than the Khepera. Not as expandable, it has also not yet received the same scrutiny in educational or research settings.

<p><b>Lego Mindstorms</b></p> <p>\$199 10x3x6 cm (w/o chassis)</p> <p><a href="http://www.legomindstorms.com">www.legomindstorms.com</a></p>	<p>Popular because it works out-of-the-box, the yellow lego RCX brick has inspired curricula and freely available software, such as is described in Klassner (2004), and Parsons and Sklar (2004). Sonar, rotation, and IR sensors can extend provided touch/light inputs.</p>	
<p><b>Xport Robot Controller</b></p> <p>\$269 8x3x1cm (w/o chassis)</p> <p><a href="http://www.charmedlabs.com">www.charmedlabs.com</a></p>	<p>The Xport leverages the computation of a handheld GameBoy (not included). KIPR offers a very capable vision-augmented system, the XBC (LeGrand et al. 2005), that provides easily configurable and very powerful region tracking.</p>	
<p><b>Handy Board Controller</b></p> <p>\$299 12x8x3 cm (w/o chassis)</p> <p><a href="http://handyboard.com">handyboard.com</a></p>	<p>Although the price does not include sensors or a typically Lego chassis, the Handy Board supports touch, light, sonar, IR, compass, and vision sensing. It is used in many AI courses (Imberman 2004, Danyluk 2004, Martin and Pantazopoulos 2004).</p>	
<p><b>Palm Pilot Robot Kit</b></p> <p>\$315 18 cm dia. x 6 cm</p> <p><a href="http://www-2.cs.cmu.edu/~pprk">www-2.cs.cmu.edu/~pprk</a></p>	<p>The Palm Pilot stand-alone kit relies on Acronames B rainStem controller, three IR ranging sensors, and a handheld computer. Designed at Carnegie Mellon University (Reshko, Mason, and Nourbakhsh 2002) the PPRK has been employed for outreach beyond AI robotics (Avanzato 2004).</p>	
<p><b>Robix/Pontech Manipulator</b></p> <p>\$550 varying dimensions</p> <p><a href="http://www.robix.com">www.robix.com</a></p>	<p>The Robix enables many manipulator forms via six servos and connective hardware. The Pontech SV203 (\$60), an 8-motor serial controller, can also control these servos (Crabbe 2004, Bishop et al. 2004, Sutherland 2000).</p>	
<p><b>Sony AIBO</b></p> <p>\$1900 10x3x6 cm (w/o chassis)</p> <p><a href="http://www.sony.net/Products/aibo">www.sony.net/Products/aibo</a></p>	<p>Used in the RoboCup legged league, the AIBO offers a microphone, vision, and touch sensing with 802.11b wireless for communications. A number of freely available software interfaces exist, as well as tested AI robotics curricula (Velooso et al. 2004).</p>	
<p><b>ActivMedia Robots</b></p> <p>\$2000+ 10x3x6 cm</p> <p><a href="http://www.activmedia.com">www.activmedia.com</a></p>	<p>The Amigobot at right is the least expensive of a large line of prebuilt robots from ActivMedia. With an RF link, sonar ring, odometry, and an interface to the ActivMedia Aria simulator, this robot spans research and educational uses (Konolige et al. 2004, Arkin 2000).</p>	
<p><b>K-Team Robots</b></p> <p>\$296-2025+ 5-12cm dia. x 5cm</p> <p><a href="http://www.k-team.com">www.k-team.com</a></p>	<p>The Khepera (\$2025+), the 5-cm platform at left, has been used in several AI robotics courses (see, for example, Harlan [2005]). It accepts a huge array of sensors at commensurate costs. The new Hemisson robot (at right) is \$296 but untested.</p>	

*Figure 1 A Comparison of the Price, Form Factor, Sensing, and Computational Capabilities of Eight Low-Cost Robotic Platforms Used in AI Robotics Settings.*

Product-specific URLs are on the left; references to example uses in undergraduate settings are included in the notes on each platform.

Sony's robotic quadruped, the AIBO, is supported by several freely available software development environments. Veloso and Rybski's article in this *AI Magazine* issue attests to the breadth and depth of AI topics that the AIBO can support. At approximately US\$2000, ActivMedia's Amigobot is about as expensive as an AIBO. It is a more traditional wheeled platform with a ring of sonar rangefinders providing the primary sensory input. One advantage of such a larger, stronger platform is that existing resources may be easier to integrate. For example, any robot that can support a laptop or handheld computer can support on-board vision, global positioning (GPS), and a host of other off-the-shelf inputs.

### Simulation

If robotic platforms' primary contribution to AI is their computational interaction with the world, why not abstract away the hardware completely? Simulation is an attractive option for AI educators for many reasons: the speed of students' design-test-debug cycles, the repeatability of experiments, the availability of rich visualization tools that may not be available on board a physical platform, and the (simulated) access to expensive or unavailable platforms or sensors. Gazebo, for instance, can simulate both laser range finders and autonomous helicopters.

Many robot simulators support a particular platform or controller, typically higher-end systems. The Aria simulator supports ActivMedia's line of robots; Webots grew from the Khepera robot's simulator and works equally well with the newer Hemisson. Others have evolved for and from specific tasks, for example, RoboCup soccer and rescue league simulators.

Two powerful, general-purpose simulators are the open-source projects Stage and Gazebo (Vaughan, Gerkey, and Howard 2003), which support research-level work in AI and robotics. Having grown out of the Interaction Lab at the University of Southern California, these are actively supported tools that provide access to a rich set of simulated sensing modalities: vision, laser scans, sonar, and global positioning. Figure 2 contrasts the purposes and capabilities of four robot simulators. As detailed later in this issue, the Pyro project creates an interface that eases access to these powerful tools within educational settings.

One drawback to using simulation is the loss of the physical embodiment that attracts many students to learning AI with robots. Another potential problem is the loss of the unpredictability of real-world physical interaction. Simulated vision is not vision; simulated sonar

is not sonar. Coping with this uncertainty has long been a motivation driving the field of AI Robotics. Not every simulator models sensing and actuation as noisy processes: Stage, designed for low-fidelity simulation of many agents, does not; Gazebo does.

Perhaps the ideal educational toolset comprises both a simulator and robot hardware with identical programming APIs. Player, a robot server that accompanies Stage and Gazebo, offers drivers that interface with many robots and sensors, though not typically the robotic-kit platforms. Webots allows compilation of control programs to Lego's RCX brick, the AIBO, and K-Team's robots. Pyro offers a single streamlined interface to many simulated and physical robotic platforms. Other simulators offer API support for their own hardware.

Such tandem systems allow educators to provide access to robotic experiments without stocking a large lab full of platforms. Students develop and test software in simulation before transferring their code for trial runs on one or a small number of physical robots. Though breakdowns and scheduling conflicts are potential concerns with fewer robots, ease of maintenance and a natural reinforcement of the software design and testing process are certainly pluses. Hardware slows down students' code-test-debug loops dramatically. Depending on the extent to which realistic sensor noise and other sources of uncertainty are modeled in simulation, students' programs may require substantial rewriting in order to succeed on physical hardware. Such experiences, though frustrating, also offer the opportunity for deeper insight into the difficulty of computational interaction with the physical environment.

Spending a fixed budget on fewer platforms may also better serve undergraduate research projects by providing a richer sensor suite than a large number of lower-cost kits can. Simulators can then expand the reach of a few (or no) hardware resources to a much larger class of students.

### Sensing and Computation

The sensor suite available is likely to have the greatest curricular—and financial—impact on an undergraduate's experience with AI robotics. To a large degree, it is the richness and reach of a platform's sensors that drive both its cost and its capabilities. Student projects with inexpensive robot kits tend to focus on local sensing: contact sensors that detect collisions, photoresistors for determining ambient light strength, and short-range infrared distance sensors. Reactive architectures are natural for these platforms, localization and navigation much

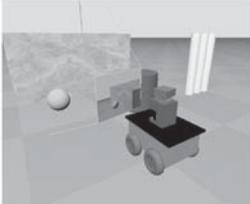
<b>Stage/Gazebo</b>	<p>Stage offers multiagent 2D simulation; Gazebo provides more fidelity in 3D simulation of a few robots (Vaughan, Gerkey, and Howard 2003). This image shows simulated vision on a Pioneer. The Player system connects Stage/Gazebo to many physical robots.</p>	
<b>Robocup Soccer Simulator</b>	<p>The RoboCup simulation league runs competitions atop the original 2D simulator (this image is a Pyro client), a newer 3D version, and for contributions to its codebase. It is the backdrop of several AI courses (Stone 2004, Coradeschi and Malec 2000).</p>	
<b>Robocup Rescue Simulator</b>	<p>The RoboCup rescue competition began in 2001 and includes physical-robot and simulated leagues. This simulator models intact/collapsed structures, cars/traffic flow, fire progress, civilians, and emergency crews in 2D and 3D (Kleiner 2004)</p>	
<b>Cyberbotics Webots</b>	<p>Like Stage/Gazebo, this physics-based simulator offers drivers for physical platforms common to undergraduate education: Aibo, RCX, and K-Team robots. In contrast to those systems, Webots is also supported on Windows systems (Michel 2004).</p>	

Figure 2. An Overview of the Capabilities and Costs of Four Robot Simulators.

less so. However, as illustrated in figure 3, sonar, IR rangefinders, and color vision are available as extras for the Lego RCX and Handy Board platforms (though the Lego Vision Command system camera is tethered to a personal computer). Relatively recently, the Kiss Institute for Practical Robotics<sup>2</sup> has offered the XBC, a powerful controller for Lego platforms (LeGrand et al. 2005). The XBC can support an extensive sensor suite, and its support for vision is particularly strong: an integrated camera, the capability for multiple-region tracking, and the very accessible configuration of its image processing. Like Charmed Labs' XPort Robot Controller on which the XBC is based, these emerging resources leverage the powerful processor and color screen available in the ubiquitous handheld Game Boy Advance.

Shaft encoders, which allow the measurement of position and velocity, and a ring of range sensors (sonar in the case of the Pioneers, IR for the Khepera and HemiSson) offer student

access to spatial reasoning algorithms from basic wall following to topological mapping. Encoders are available, too, for the Handy Board, RCX, XBC, and the Intellibrain. The XBC further computes position and velocity by measuring the motors' back-emf, obviating the need for encoders. All of these smaller controllers also support a sonar or IR sensor mounted on a rotating servomotor turret as a less expensive alternative to a ring of range sensors. Vision facilitates landmark detection and identification, along with the classification and deliberative tasks that can build on those capabilities. Although even simple platforms can motivate research-level AI robotics projects (Huang and Beevers 2004), it is primarily the sensing available that provides options to students, educators, and researchers alike.

Sony's AIBO robotic dog stands out in a number of ways among the platforms in figure 1—it is the only legged robot and it offers an array of sensors and computational facilities rich

enough to support deliberative, cooperative tasks like soccer. The AIBO user community, represented in this issue by Manuela Veloso and Paul Rybski's article, has created a set of software resources that make the robot a promising one for AI education. Their abstractions of low-level behaviors and raw sensor input make the AIBO particularly suitable for investigating task-directed decision making in the face of uncertainty.

The computational resources among the platforms in figure 1 vary widely, and they can affect the sophistication of the algorithms available on board. Although the Lego RCX's Hitachi H8 microcontroller lists at 16 megahertz and 32 kilobytes of memory, the overhead of the firmware and interpreter yield about 10 kilobytes and 500 hertz throughput for a typical user—slightly better with alternative versions of the firmware (Gockley 2003). The Handy Board's Motorola 2 megahertz 68HC11 is not too different, though its Interactive C interface additionally provides for up to 4 threads. The Game Boy's 32-bit 16 megahertz ARM processor, however, does sport noticeably deeper computational pockets: 256 kilobytes of memory, 92 kilobytes of video random-access memory, and up to 32 threads. The AIBO's current 576-megahertz 64-bit RISC chip pushes performance to yet another level—particularly important because vision is its primary sensor. Although additional capabilities certainly ease students' investigation of a wide variety of algorithms, the limitations of an RCX or Handy Board can also serve to motivate research issues, for example, in sensor-limited robotics and resource-bounded reasoning.

### Onward

The available resources for incorporating robots into AI education are considerable, yet they may only hint at the opportunities on the horizon. One emerging possibility is that some educational robots will blur away from the status quo of "complete systems" into peripheral form factors that use existing cameras, laptop computers, and networking capabilities. By relying on mobile computational devices such as game consoles and handheld computers, the Palm Pilot robot kit (PPRK), XPort Robot Controller, and XBC have begun this process, as have trial laptop-based systems like the Evolution ER1. Leveraging existing infrastructure offers an opportunity for producing physical agents with high-end capabilities at a lower cost than today's kit-based systems. Most visibly represented by iRobot's vacuum cleaners,<sup>3</sup> the nascent home robot industry similarly promises to make autonomous mobile compu-

tation ubiquitous. As of October 2005, the Roomba offers a serial interface to interested roboticists.<sup>4</sup> The extent to which communities will develop to support these emerging platforms with software, sensors, and curricula still remains an open question.

In addition, the impact, marketing power, and economies of scale in the toy and entertainment industry will continue to play important roles in creating inexpensive robotics resources. The use of the AIBO for research and education has followed its introduction as a sophisticated Tamagotchi. In fact, academic interest has helped guide Sony's own choice of next-generation AIBO features and software support. As for two-legged platforms, the University of Freiburg has already prototyped a soccer team of Robosapiens running from handheld computers.<sup>5</sup>

Similarly, the software that supports AI robotics education will continue to mature. Improvements and software resources come from at least three directions. First, commercial third-party products such as the multiplatform Webots simulator and the RoboJDE development environment (Michel 2004) offer turnkey interfacing and development capabilities. A second source of software is the research community: the Stage and Gazebo simulators demonstrate the benefits of developing a research-inspired codebase into a more general-purpose tool. Finally, enthusiasts of all stripes donate time and effort to make the materials they have developed available to the community. Each of the articles in this *AI Magazine* special issue contributes to this effort by encouraging educational access to software and hardware that AI researchers use as a matter of course.

Figures 1, 2, and 3 list a number of factors that inform whether and how physical agents fit into an AI course or sequence. Yet the figures do not address the most important pedagogical factor in choosing a platform: the AI topics supported or enhanced by each resource. The next section outlines the variety of options and approaches available for undergraduate curricula in AI robotics.

## AI Robotics Curricula

Robot platforms can be introduced into AI education in a variety of ways, ranging from adding a single robot assignment to an AI course to designing a complete AI robotics course to adding AI material to an integrated robot engineering course. The early adopters of low-cost robotics in AI education began by using robot platforms to teach behavior-based or

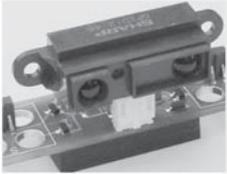
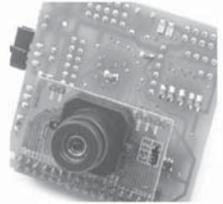
<b>IR sensors</b>	There are two fundamentally different IR sensors: detectors that report a bit indicating the presence or absence of an object, and rangers that return a value proportional to the object's distance. Ranges from 4 cm to 30 cm or 10 cm to 80 cm are widely available.	
\$10-40		
Sensor range: 4 - 80 cm		
<b>Sonar sensors</b>	Sonar sensors convert the time-of-flight of an ultrasonic ping into range. Sonar and IR sensors enable the building of evidence-grid representations of the environment when encoders/rotation sensors are available (Martin and Moravec 1996).	
\$34-60		
Sensor range: 4 - 1000 cm		
<b>Cameras</b>	The CMUCam2, and to a lesser extent the original CMUcam, can provide raw images and, more usefully, statistics about sequence-tracked regions of uniform color. They do not interface with the RCX, however (Rowe et al. 2002).	
\$109-200		
Sensor resolution: 176 x 255 pixels		

Figure 3. Three of the Most Commonly Used Sensors beyond Basic Light and Touch Feedback for Lego Mindstorms, the Handy Board, Xport, or PPRK Controllers.

reactive architectures (Martin 1996). This was driven in large part by the perceived limitations of the processing capabilities of the platforms (for example, Murphy 2000). Work on using these platforms that goes beyond reactive control structures has flourished since then. Though necessarily incomplete, table 1 shows a sampling of the wide range of AI topics that have been successfully implemented on low-cost robot platforms, along with the platforms used and links to accompanying curricular material.

Table 1 omits an important consideration for AI educators contemplating the use of robots: how well they fit into the overall syllabus of course topics. One approach presents AI robotics as a separate topic, as in Russell and Norvig (2003). In his article in this issue, Frederic Crabbe offers an alternative view that deeply integrates AI and robotics as a process of abstraction and interpretation. This framework consists of layers of abstraction ranging from signal processing to long-term behaviors. Crabbe shows how different approaches to teaching robotics, including teaching AI using robotics, can be formulated using this framework. This framework describes subfields using varying levels of data abstraction and interpretation. At the level of behavior-based robotics, data is interpreted as the presence or absence of

a situation through trigger events. The next level builds representations such as maps for navigation. A subsequent tier interprets information at the knowledge level for reasoning and planning. This view can provide a natural approach for incorporating robotics within the various subfields of AI. Alternatively this view can provide a means of exploring a progression of AI topics by first beginning with developing a deliberative robotic system to navigate and solve a task, then progressing to behavior-based control, and finally developing hybrid approaches that lead to complete solutions.

The choice of platform directly affects the construction of an AI curriculum using physically embodied agents. Robot kits such as the Lego RCX, Handy Board, or Xport use Lego building blocks and gears to provide an easy means for students to build mechanical structures. While students tend to be drawn to the creative and experimental nature of building their own robot, the use of such platforms must be weighed against the time students spend building and rebuilding. Alternatives approaches provide prebuilt platforms (for example, Bruder and Wedeward [2003]) or plans for and examples of platforms to aid student construction. These choices affect the student's experience. For example an ordinary differential drive (a motor driving one wheel on each side)

will undergo significant rotational drift due to natural differences in motors. In contrast, a drive using a differential or dual differential, in which a single motor drives both wheels while a second motor provides turning, will provide more accurate straight-line motion and turning (Mayer 2004).

Are robots worth the effort required to incorporate them in an undergraduate AI curriculum? Existing resources have a major impact on effort and educational effectiveness. For some platforms, user communities and interest groups provide ready-made educational resources via books (such as Martin [2000]), discussion boards and software (for example, the Lego User's Group),<sup>6</sup> and commercial sites (such as HiTechnic Products).<sup>7</sup> Table 1 offers pointers to some of these resources—particularly those of use to educators designing undergraduate AI curricula.

Curriculum, however, is only part of the story. Robots have also spawned vibrant communities of educators and researchers who share their work at competitions and exhibitions. The next section looks at the impact of some of these forums.

## Robot Contests

Robot contests provide a forum in which students design and build robots to solve a specific engineering problem. Competitions represent the integration of many facets of engineering and science—from mechanical construction to computer programming. They are excellent opportunities to reinforce the relationship math and science have on tangible real-world applications. Pedagogically, competitions can be useful in motivating and developing the social aspects of teamwork and collaboration, and they can be effective in bridging the gap between cursory and deep mastery of subject matter.

A number of robot contest traditions, such as RoboCup and the AAI Robot Competition, have emerged as natural motivators to students and researchers alike. These opportunities can excite students about engineering and science. Even so, special care must be taken to link the experience with a mathematics and science foundation. If not, robotics competitions become a tool only to encourage, but not to teach, leaving a formidable gap between entertainment and education.

### Local Competitions

Local competitions are a part of many robotics courses; often they are the culmination of a sequence of laboratory exercises for building and programming a robot. Such labs effectively link

learned knowledge to real-world application, but suffer from several challenges. The first challenge is structural: how to both reinforce the learned knowledge and ensure that it excites and motivates students. An instructor must balance between open-ended competition problems that may cause stress and more routine, step-by-step competitions that may not stimulate students intellectually. A second challenge involves supporting the cross-disciplinary contributions of most robotic laboratory exercises, while still developing a skill set relevant to the overarching course. As a means of addressing these two challenges, low-cost robotic platforms allow students to work with systems of sufficient complexity to engage them at an appropriate level; instructor-provided abstractions ease the difficulty as appropriate. Low-cost robot platforms further allow a multidisciplinary approach to AI education in which diverse student learning styles are valued and expanded. Successful variations in laboratory organization have included segmenting the class into teams of different majors, as well as pairing together novice and beginning students into one unified group (Weinberg et al. 2005).

Local competitions ultimately provide students with a goal to strive toward. Whether through the use of laboratory exercises or through design teams with a faculty advisor, local competitions provide a safe atmosphere in which to stretch the creativity of the student, while validating the theory behind robotic usage. What's more, a capstone experience need not require competition between student teams. Student groups may instead aim toward meeting a set of prespecified criteria (Parsons and Sklar 2004) or in the creation of a creative exhibition (Turbak and Berg 2002).

### National Competitions

The last five years have seen a number of wide-reaching robotics competitions grow in scope. Three of the most influential are RoboCup, AAI's Mobile Robot Competition, and Bot-Ball. All of these competitions integrate several types of engineering and science to solve specific problems within a given domain. These different domains, such as mechanical structure, software, and electronics, must be fused into a common platform to create a functional system for diverse problem sets. There has been considerable recent concern with the large amount of effort required of the students for competition—especially at the national level. To complement this trend, aspects of outreach, coupled with the competition environment, have begun to permeate the community

Topics	Platform
Knowledge representation	Lego RCX with off-robot processing
Heuristic search	<i>Resource:</i> <a href="http://www.csc.villanova.edu/~klassner">www.csc.villanova.edu/~klassner</a>
Landmark navigation	
Multirobot communication	
Probabilistic localization (particle filtering)	Evolution ER-1
Machine vision	<i>Resource:</i> <a href="http://www.cs.hmc.edu/~dodds/courses/">www.cs.hmc.edu/~dodds/courses/</a>
Planning	Lego RCX, Handy Board
Wave-front navigation	<i>Resource:</i> <a href="http://roboti.cs.siue.edu/">roboti.cs.siue.edu/</a>
Hybrid control	
Neural and Bayesian networks	Handy Board with on- and off-robot processing; Lego RCX
Probabilistic planning	<i>Resource:</i> <a href="http://www.cs.hmc.edu/roboteducation/">www.cs.hmc.edu/roboteducation/</a>
Vector field histogram mapping and navigation	
Probabilistic localization (particle filtering)	
Neural networks	Pyro simulator
Computer vision	<i>Resource:</i> <a href="http://emergent.brynmawr.edu/~dblank/pyro/">emergent.brynmawr.edu/~dblank/pyro/</a>
Genetic algorithms	
Uncertainty	Lego RCX
Planning and control	<i>Resource:</i> <a href="http://www.cs.brown.edu/courses/cs148/">www.cs.brown.edu/courses/cs148/</a>
Additional Resources	
Layers of abstraction, kinematics, behavior-based control, dead reckoning	Byo-bots, Robix Rascal (robotic arm), Rug Warrior <i>Resource:</i> <a href="http://www.cs.usna.edu/~crabbe/teaching.html">www.cs.usna.edu/~crabbe/teaching.html</a>
Reactive and behavior-based control	Lego Mindstorms, eLeague robot soccer <i>Resource:</i> <a href="http://www.cs.columbia.edu/~sklar/">www.cs.columbia.edu/~sklar/</a>
Behavior-based control, planning, wave-front navigation, sensors, kinematics	Lego Mindstorms, Handy Board, Xport <i>Resource:</i> <a href="http://roboti.cs.siue.edu/">roboti.cs.siue.edu/</a>
Behavior-based control, neural networks	Pyro simulator <i>Resource:</i> <a href="http://www.cs.uml.edu/~holly/#teaching">www.cs.uml.edu/~holly/#teaching</a>
Behavior-based control, planning, computer vision, multirobot communication	Sony AIBO <i>Resource:</i> <a href="http://www-2.cs.cmu.edu/~mmv/">www-2.cs.cmu.edu/~mmv/</a>
Behavior-based control, navigation, multirobot interaction	Sony AIBO, Lego Mindstorms, Byo-bots, Gamebots <i>Resource:</i> <a href="http://www.cs.uno.edu/~sheila/">www.cs.uno.edu/~sheila/</a>
Behavior-based control	PPRK, Handy Board, Lego Mindstorms <i>Resource:</i> <a href="http://www.personal.psu.edu/faculty/r/l/rla5/">www.personal.psu.edu/faculty/r/l/rla5/</a>
Integrated engineering	Handy Board <i>Resource:</i> <a href="http://www.generalrobotics.org">www.generalrobotics.org</a>
Sensors	Lego Mindstorms, Handy Board <i>Resource:</i> <a href="http://www.philohome.com/sensors.htm">www.philohome.com/sensors.htm</a>
Message board	Lego Mindstorms, Handy Board <i>Resource:</i> <a href="http://news.lugnet.com/robotics/">news.lugnet.com/robotics/</a>

*Table 1. A Sampling of AI Topics Implemented on Low-Cost Robot Platforms.*

*Top:* A sampling of advanced AI topics taught using low-cost robotics with URLs.

*Bottom:* Additional resources of use to educators who incorporate robots within an AI course.

(Baltes, Sklar, and Anderson 2004; Miller and Winton 2004; Stein, Schein, and Miller 2002).

National outreach efforts complement robotics competitions through mentoring, open-source web curriculum, as well as other traditional means of outreach. Specific programs, such as the Carnegie Mellon University Sum-

mer Robotic Camp (Nourbakhsh et al. 2005) and NASA's Athena Student Interns Program have engaged groups of students in hands-on activities that reinforce math and science skills through robotic tasks. Colleges with a history of competition have begun to establish programs to mentor less experienced teams. Outreach al-

so focuses on providing robotics learning tools to students and educators. On-line web-based services such as NASA's Robotics Education Project and Imagiverse Robotics have disseminated lesson plans, interviews, and classroom activities. Whether competition- or outreach-based, these programs support the same goals: to motivate and encourage students through physically embodied computation.

## Perspective

This overview of educational robotics—platforms, curricula, and contests—sets the stage for the five papers that follow. Each one investigates a facet of the robotics resources that can support undergraduate AI education. Each, too, emphasizes the considerable common ground between the fields of “artificial intelligence” and “robotics.” Although those terms can be used to connote distinct fields of research, it is often the overlap between the two that motivates undergraduate interest in each. To characterize this synergy, Frederic Crabbe describes a framework in this issue of *AI Magazine* in which AI robotics serves as a unifying theme for a broad spectrum of topics in both of these fields.

The educational resources available for AI robotics also highlight these fields' common ground. Frank Klassner's article brings a ubiquitous AI tool, Lisp, to the Lego Mindstorms platform, facilitating the incorporation of robotics into existing curricula. The Pyro project by Douglas Blank, Deepak Kumar, Lisa Meeden, and Holly Yanco uses Python to provide a widely scalable abstraction for teaching AI across a variety of hardware and software platforms. Both of these articles provide concrete starting points for smoothly integrating real or simulated physical agents into an AI classroom.

Physical agents can support existing AI curricula; they, too, can motivate topics relatively new to undergraduate AI. Lloyd Greenwald, Donovan Artz, Yogi Mehta, and Babak Shirmohammadi outline a curriculum in which students implement and investigate probabilistic spatial reasoning and machine learning algorithms using the inexpensive Lego Mindstorms and Handy Board platforms. The article by Manuela Veloso, Paul Rybski, Scott Lenser, Sonia Chernova, and Douglas Vail spotlights the capabilities of Sony's AIBO robotic dog as a pedagogical tool that bridges with RoboCup competitions and a vibrant research community.

This introduction necessarily falls short of a complete accounting of available resources for teaching AI robotics to undergraduates. Any such list would quickly succumb to next sea-

son's set of products and publications. To provide a jumping-off point for further investigation of the available platforms, topics, and contests, we have a web page that offers an online compendium of the information in this article.<sup>8</sup> We hope that this issue's overview of robot resources will serve as an invitation for AI educators of all backgrounds to reflect on their AI classes and the role of physically embodied agents in them.

## Notes

1. [www.ridgesoft.com](http://www.ridgesoft.com).
2. [www.kipr.org](http://www.kipr.org).
3. [www.irobot.com](http://www.irobot.com).
4. [www.roombacommunity.com](http://www.roombacommunity.com).
5. [www.nimbro.net/rs](http://www.nimbro.net/rs).
6. [www.lugnet.com](http://www.lugnet.com).
7. [www.hitechnic.com](http://www.hitechnic.com).
8. [www.cs.hmc.edu/roboteducation](http://www.cs.hmc.edu/roboteducation).

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## AAAI Mobile Robot Competition and Exhibition

The Fifteenth Annual Robot Competition and Exhibition will be held in Boston, MA, from July 16–20, 2006, in conjunction with the Twenty-First National Conference on Artificial Intelligence. We invite your participation in this exciting competition, which will feature a scavenger hunt, and open interaction task and robot challenge, and a robot exhibition, as well as a workshop that takes place on the last day of the conference.

For details visit [www.aaai.org/Conferences/AAAI/2006/aaai06robots.php](http://www.aaai.org/Conferences/AAAI/2006/aaai06robots.php) or [palantir.swarthmore.edu/aaai06/](http://palantir.swarthmore.edu/aaai06/)

Hurry! The deadline for participation is  
May 15th.

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