# NSF Sponsored Workshop: Research Issues at the Boundary of AI and Robotics

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## Introduction

The National Science Foundation made funds available to sponsor a workshop on research issues at the boundary of Artificial Intelligence and Robotics. This was the result of a cooperative initiative between AAAI and IEEE. The meeting will be a one-day meeting to be held on Sunday, January 25, 2015 at the AAAI-15 venue in Austin, TX.

The workshop is intended to bring together AI and robotics experts, including senior researchers, to compile a list of recommendations to funding agencies, professional organizations and individual researchers for how to push the boundary of AI and robotics, including research areas that stand to benefit most from the collaboration of AI and robotics researchers and activities that bring these researchers together, such as possible challenge problems. The meeting will consist of short invited talks by the invited participants as well as panels and discussion sessions (that involve all participants) to find common ground among the participants. The result will be a roadmap that will be made available to the public via the world wide web as well as distributed to funding agencies and within AAAI and IEEE RAS.

Invitations were sent to interested AI researchers that will attend AAAI-15 (in Austin), interested robotics researchers that will attend the ICRA-15 senior program committee meeting (to be held in College Station, directly before), and program directors at US-based National funding agencies.

As preparation for the workshop, the organizers requested that attendees provide position statements. These are collected in this document.

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*What specific problems do you feel lie at the boundary between AI and robotics? How can these be tackled, and the boundary pushed?*

I believe that with the advances in robotic technologies we are able to measure and hence model the human physical behavior and its capabilities and limitations using kinematic and dynamic models anchored in first principles of newton mechanics. This capabilities are facilitated with new/improved sensors, computational resources and new algorithms. We will show some examples on analysis of physical exercises.

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**Towards a Watson System for Robotic Agents Performing Human-scale Manipulation Actions**

We are currently witnessing the first robotic agents autonomously **performing everyday manipulation activities** such as loading a dishwasher and setting a table. While these agents successfully accomplish single instances of such tasks, they are still far from **mastering them**. They can perform them only within the narrow range of conditions they have carefully been designed for. Humans, in contrast, can easily perform vaguely stated instructions such as "set the table", and flexibly adapt the execution of these instructions to a wide range of contexts. Mastering everyday activities similarly to humans will enable robots to become competent (co-)workers, assistants, and companions, which are widely considered to be necessary means for dealing with some of the challenges caused by our aging societies.

Transitioning from performing to mastering complex manipulation activities will require us to focus on two aspects of robot agency that have been largely neglected in the field of AI robotics so far. First, we need substantial research that investigates **how** actions are to be executed to be successful. Second, action control in robotic agents has to be **knowledge intensive**. Knowledge must be embodied that is tightly coupled to perception and action and make the robot aware of the continuous parameter space in which actions need to be

Figure 1: Variations of performing a pouring action

parameterized and behaviors being generated instead of abstracting away from it.

Consider, for example, different variations of pouring actions and the level of sophistication that is needed to perform such tasks successfully as depicted in Figure 1. A robotic agent mastering pouring actions needs to decide whether to perform the action with one or two hands, using a tool, with additional action constraints such as holding the lid while pouring, or with very specific motion skills as in the case of pouring a "Weissbier" into a glass. Robotic agents mastering such manipulation actions they have to know *how* pouring actions have to be performed to be successful, what their desired and undesired effects are, and how to map desired effects into the action parameters that can be controlled, which tools they have to use and how, and so on. Robotic agents mastering their activities have to **know what they are doing.**

Meeting this challenge requires robotic agents to be equipped with the knowledge that is needed to refine incompletely described actions for particular (often only partly observable) contexts. They also have to perform complex reasoning tasks such as reasoning about the stability of object configurations, visibility, reachability, etc. fast enough such that reasoning will not substantially delay the execution of everyday activity plans.

I propose that building a Watson-like system for everyday manipulation actions would be an appropriate picture to guide our research activities. A Watson-like system would have to acquire the common sense and naive physics knowledge needed to master everyday activity and provide the knowledge using a query answering subsystem: given a vague action description such as flip the pancake and a scene as perceived by the robot the "RobotWatson" system would be capable of answering questions such as which tool to use, how to grasp the tool, which hand to use, which grasp type to apply, where to position the grippers, which pose the robot should take to perform the action, how much force to apply. "RobotWatson" also has to inform the control system about possible action consequences as, for example, what is expected to happen if the spatula is pushed too hard or too soft.

In order to build a Watson-like system I suggest to

- **investigate artificial episodic memory systems indexed through symbolic narratives**. The episodic memory is an essential component of the human memory system that lets humans re-experience and mentally visualize past experience and

reconsider and inspect the past experience to realize powerful cognitive processes including a number of important common sense and naive physics reasoning tasks. The experience data have to be linked and annotated with a narrative structure in order to make the robot knowledgeable about what it did, how, why, how it behaved, what happened, what it saw, etc.

- interpret the low-level episodic memories together with the narrative structure through an **unstructured information management and experience analytics** to form informative, effective, and efficient naive physics and common sense knowledge bases.

- provide the episodic memories and the naive physics and common sense knowledge as **open cloud-based knowledge services** for robots and AI/robotics researchers.

We are currently working on **openEASE (www.open-ease.org)**, a web-based knowledge service providing robot and human activity data. openEASE contains semantically annotated data of manipulation actions, including the environment the agent is acting in, the objects it manipulates, the task it performs, and the behavior it generates. The episode representations can include images captured by the robot, other sensor datastreams as well as full-body poses. A powerful query language and inference tools, allow reasoning about the data and retrieving requested information based on semantic queries. Based on the data and using the inference tools robots can answer queries regarding to what they did, why, how, what happened, and what they saw. Some of the ideas presented here are shared in the work of the robobrain project (www.robobrain.me, Saxena and colleagues) and Nuxoll and Laird with respect to artificial episodic memories.

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The Medical field faces strong challenges in which AI and Robotics should meet, an example is the growing interest in Cognitive Robot Assisted Surgery, CRAS. Medical applications are still far from the availability of autonomous systems, however, providing robots with some degree of intelligence strongly enriches human robot cooperation and sets the basis for future autonomous assistive systems. In this field, some specific problems are: The need of haptic feedback in surgery, robot programming towards objectives, or the interpretation of the human's will for volitional robot control.

The lack of sensors to measure the forces and torques applied by the surgical instruments to the human tissues is due to the strong requirements of their design: miniaturization

to be integrated on the surgical instruments, biocompatibility, resistance to the medium (sterilization), and the associated electronics. Therefore, indirect measurement systems are needed, based on sensors located far from the point of application of the forces (on the robot wrist, on the joints. . . ) or use other sensing techniques as vision. The estimation of forces through sensors far from the target points suffer from the lack of adequate models to compute the force transmission which is affected by disturbances due to friction and other mechanical constraints. The use of vision requires image processing techniques for deformation analysis and the availability of adequate deformation models related to the involved tissues, which differ from person to person.

Robot programming towards objectives, which avoids the need of explicit programming of trajectories, is necessary to program routinely tasks as suturing, task that follows a pattern but different from patient to patient, presenting anatomic variances, scene deformability, environment constraints or the need to deal with incidences. Such tasks may involve multiarm cooperation, and thus, intelligent distribution of robot tasks allocation, collision avoidance, safety, etc.

In prosthesis or orthosis control the interpretation of the human's will through neuroperception, force control, physiological sensing and external perception has to deal with the integration of heterogeneous and uncertain data and signals that have to be used in critical control tasks, with risks of losing stability (walking), or facing patient's or operation's safety (grasping. . . ). As additional problem, the status of the patient (fatigue, stress. . . ) can change the operation conditions and thus, the goal, the trajectory, the speed. . . which implies a continuous adaptation to changing situations.

How to push? **Competitions** have proven to be an efficient means to promote collaboration, imagination. . . In many sectors competition scenarios and rules can be easily defined. An example is chess competitions that have stimulated the development of efficient algorithms. However, in medicine everyone is different, there is no experience yet in defining patterns easy to reproduce, for instance, a stenosis in a 2 mm vein. Planning new scenarios for competitions in this context could be a stimulus for cooperative research between roboticists and AI researchers to find solutions to real robotic problems. In image processing, google has made the first steps in searching images similar to a one of reference. However, looking for similitudes between images is not the same as interpreting them. Interpretation is what is necessary in many applications, such as human-robot interaction, in which interpretation of human intention passes through gesture recognition, then action interpretation as means to recognize human activity and, from this data being able to generate robot behaviors for a proactive cooperation, assistive robotics. As mentioned, significant AI applications have succeed having a data base as input, defined patterns. . . now the challenge is applying and adapting the developed AI techniques to the robotic world, uncertain, variable, with

unexpected disturbances and heterogeneous data.

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*What do you see as particular research areas that stand to benefit more from the collaboration of AI and robotics researchers? What specific problems do you feel lie at the boundary between AI and robotics? How can these be tackled, and the boundary pushed?*

As robotic and AI systems advance to the stage where they must **effectively** perform **complex operations** in **unstructured** and **dynamic** environments in a variety of **real-world** settings while **meaningfully interacting** in useful ways with a **diversity of biological and technological agents**, the boundaries between AI and Robotics necessarily fade.

*What particular activities could bring these communities of researchers together? Do you have ideas for the way the various stakeholders such as funding agencies, professional organizations and individual researchers should play a role?*

One of the most powerful uniting forces of communities that otherwise disagree is a battle against a common foe. As Stephen G. Fritz stated, "Nothing unites people more than shared rage against something or someone." Therefore, we should identify challenging important problems that plague our world today that necessitate collaboration between the AI and Robotics communities. We then need to invest significant resources and provide opportunities and pathways for real impact so that researchers are motivated to collaboratively solve these problems. In 2015 where global leaders are examining the world's progress on meeting the Millennium Development Goals, perhaps it is opportune for us to join the battle against common foes such as poverty, human trafficking, and terrorism.

*Do you have recommendations such as possible challenge problems, or task-force activities which could solidify various efforts?*

**Accessible smart world**: Enable people with different disabilities to accomplish a variety of complex tasks, such as international travel, independently and safely

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## Jeanne Dietsch

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**Intelligent transportation systems model for optimizing productivity while retaining individual freedom in a complex artificial, human & robot intelligence environment**

Stephen Hawking, Elon Musk and many others less prominent are sounding tocsins for AI regulation. Warnings range from humans replacement by superior general intelligences [Kurzweil, Goertzel] to humans harmed through overly narrow utility functions [Omohundro, Hibbard]. Given the broadness of concerns, a governmental body would be hard put to draft AI regulations, much less enforce them. The fact is that interactions of people, software and machines form dynamic, non-linear systems; consequences are unpredictable. To reduce the entropy of such systems, we can best start with models and test potential design norms. Intelligent vehicles, which combine AI and robotics, offer an ideal starting point for such investigation. A competition to design a robust model intelligent system of roadways and vehicles, consistent with democratic principles, would advance the state of AI norm-setting, improve the competitive position of US vehicle and logistics industries, integrate efforts of AI and robotics researchers and help retain individual freedom in an increasingly monitored, integrated and potentially constrained world.

AI's power is indisputably increasing. Computer processing speed and available memory continue to increase with Moore's Law; information capture is surging exponentially, with more people collecting more images and more sensors gathering more data and more software crawling and analyzing it for patterns. Artificial General Intelligences are under development on at least three continents. Meanwhile, human-machine-human connections have tightened so that mind-driven devices are no longer shocking news. It is now not a question of human vs. machine, but humans and machines evolving into a heretofore-unimagined combination that makes us question our ability to retain individual control over our lives and decisions. [Dietsch, 2014]

Intelligent transportation systems offer an excellent testbed for initial investigation of such compound intelligences because of their readiness, economic impact, levels of authority and integration requirements. Our individual vehicles have already incorporated intelligence: first through interoceptive feedback within the vehicle, secondly in logistics among related vehicles, thirdly in crash avoidance, fourthly in navigation assistance and fifthly in autonomous navigation. Roadway and driver integration are the next steps. Vehicles, parts and logistics account for approximately a trillion dollars annually in the US economy so improvements in this arena will have major economic impact on our nation. Intelligent transportation deploys powerful machines whose control levels must balance safety, security and individual freedom in human-machine interface. The potential for unforeseen consequences is enormous: from abuse by competitors, autocrats, demagogues, and terrorists and even just sheer complexity. Safety requires autonomous control, but freedom requires the ability to override it [Dietsch,

2012]. Research in interface, controls, security, navigation, logistics, distributed intelligence, sensing, decision-making, complexity and many other aspects of AI and robotics all combine in intelligent transportation.

Targeting design norms, rather than regulation, is the right choice because norms can be agreed upon among technical specialists who best understand the systems and their impacts, then communicated to the public who can enforce AI Best Practices through their purchasing decisions. This will be far more effective than trying to push laws through national legislative bodies, which, even if enacted, would only cause companies to move to the site of least regulation. If norms can be embedded into the design of systems, particularly as physical constraints, system predictability will be enhanced. Agencies and organizations such as NIST, IEEE, ASME, AAAI, the Institute for Ethics in Emerging Technologies might assist in promoting research, deriving standards and/or communicating them to practitioners.

To increase participation and encourage innovative thinking, NSF could design a contest in collaboration with US Department of Transportation, auto manufacturers, smart-car researchers, systems engineers, NIST and relevant NGO's such as Sapiens Plurum. Universities and private teams might compete. To focus on system design, teams should deploy off-the-shelf bases. The chief goals should be to balance safety, security, efficiency and personal freedom. Variables might be: rules of the road for several types of roads/streets, means to determine levels of autonomous vs. manual control, inter-vehicle communications and control options and human interface options. Scoring might include number of successful deliveries, number of accidents, range of delivery rates and number of abuses of control. Teams score points both for withstanding a competitor's attack and for successfully attacking an opposing team's design, to discover best practices and weaknesses.

We cannot draft best practices or support norms for safer AI until we better understand how human, software and robot intelligence interact. A competition in Intelligent Transportation Design can reveal dangers while it builds innovation, collaboration and competence in critical applications and industries.

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### Robot-human Teamwork

The future of problem solving lies not in general, autonomous intelligence but in close collaboration between people and computers. For problem solving, people bring to bear a wealth of commonsense knowledge and heuristic reasoning ability that reflects their broad experience in the physical world. They are, however, physically vulnerable to their environment, and subject to sensor failure and to errors in computation and memory. In contrast, robots offer precise recall, rapid calculation, and a variety of sensors whose percepts may provide useful information when human sensors cannot. Robots, however, lack world knowledge and peoples ability to focus their attention on the salient aspects of a situation, and are uncertain about likely responses from humans. Thus robots experience tasks in the same world differently.

AI is the necessary bridge between people and robots engaged in collaborative problem solving. AI has a long tradition of innovative knowledge representation, heuristic search, and modeling to support the solution of hard problems. It offers explicit models of reasoning tailored to how people see their world and how computation efficiently solves problems there. Theoretically strong or cognitively plausible AI approaches, however, often stumble when confronted by real-world uncertainty and noise.

A limited common language for human-robot problem solving is a crucial boundary problem between AI and robotics. For people and robots to solve problems together, they must inform one another of their goals, percepts, plans and actions, as well as the ancillary knowledge that guides them. This communication goes beyond declarations of fact; it requires the ability to formulate and answer questions, to explain, and to express and agree upon choices. The best teamwork will derive from full, transparent disclosure of all participants current states and decision-making processes. It must reveal their preferences, heuristics, percepts, and beliefs, along with the certainty they assign to them. Construction of such a language would clarify and ultimately speed decision making to support goals. It would require dialogue protocols, models for negotiation to resolve differences, and models for emotion that

would allow a robot to process human behavior it perceives as irrational. Development of this language would require extensive work with human subjects, and the formation of a variety of policies that explicitly assign decision-making authority.

One activity that would bring AI and robotics researchers together to address these issues is a building competition. For example, a person and a robot would assemble a piece of IKEA furniture together, an item so large that it requires two agents. Given the appropriate tools and printed directions, the performance metrics would be successful assembly and elapsed time. This requires world knowledge, subgoal ordering and assignment, and object recognition. A second activity is a competition among teams of soccer players, where a team must be composed of one person and four robots. This requires strategy, planning, the ability to take and receive directions, and real-time task allocation in the context of a fast-paced, real-world game with a clear performance metric. RoboCup would be a natural host for this competition.

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*What do you see as particular research areas that stand to benefit more from the collaboration of AI and robotics researchers? What specific problems do you feel lie at the boundary between AI and robotics? How can these be tackled, and the boundary pushed?*

A large amount of early robotics work, most notably robot programming and navigation, started in the AI community and moved later to the robotics/engineering community. Robotics today is mostly covered in IEEE robotics conferences and journals, much less in AI.

I believe the area of multi-robot coordination, distributed decision making, and task allocation are areas where collaboration between AI and robotics researchers will be specially fruitful.

The AI community has developed numerous approaches to deal with those problems, ranging from negotiation protocols for agents to distributed planning, team and coalition formation, distributed methods for task allocation, and more. Methods for expressing preferences of agents, for reaching consensus, for measuring utility at the individual and collective level, for dealing with uncertain or unknown information, are all examples of AI methods useful in robotics. For example, auctions have become a popular method for task allocation in robotics because of their simplicity and flexibility. The robotics community has largely adopted these methods.

Machine learning is another area where collaboration will benefit both the robotics and the AI communities. One benefit will be to make the terminology used by the two communities more consistent, since the current situation makes collaboration difficult. There is interest for AI in the robotics community, but some of the robotics researchers have a limited knowledge of AI, in particular of its newer developments. The same can be said about AI researchers not knowing recent advances in robotics and control theory.

*What particular activities could bring these communities of researchers together? Do you have ideas for the way the various stakeholders such as funding agencies, professional organizations and individual researchers should play a role?*

While it will be difficult to get the professional organizations in the two communities to cooperate on a regular base, organizing meetings with multiple stakeholders is a good starting step. RoboCup has grown too big to be attached to an AI conference like it used to be, but smaller specialized events could be held at AI conferences to increase collaboration and understanding of approaches from other areas.

*Do you have recommendations such as possible challenge problems, or task-force activities which could solidify various efforts?*

It is important to have a robotics presence in the ongoing efforts by the AI community to coordinate the various international AI groups and societies (e.g., joint conference in 2017). By being part of the conversation, the connections between the two fields will be strengthened.

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## Challenges and Opportunities for Underwater Robotics

The recent deepwater horizon oil spill has posed great challenges to both robotics and ocean engineering communities. This event exposed the challenges of understanding even the most basic aspects of such a disaster. It took months to estimate the extent of the underwater plume, and the accuracy of these estimates will likely be debated for years to come. These challenges will continue to grow as energy production continues to happen in ever deeper water.

Using groups of autonomous mobile robots to detect, monitor, and track the propagation of oil plumes is extremely important to the environment and eventually to the human's health. In spite of recent progress in deep sea survey and oil detection, increasing attention has been paid utilizing advanced robotics techniques to improve the capability of ocean robots in conducting autonomous cooperating tasks. The fields of robotic science research and applied robotics are often surprisingly disjoint resulting in a gap between new algorithmic approaches and field deployments that impact our ability to observe, explore and manage ocean resources.

During the past decade, robotics and controls communities have experienced rapid development in distributed methods to solve information consensus, formation, and multi-robot cooperation tasks. Successful applications are seen for forest fire surveillance, environmental monitoring, and underwater sampling. However, most field deployment strategies focus on planar (2D) based methods and have limited applicability in 3D underwater environments. Gaps exist between cooperating robotics and its real world applications. Emerging underwater applications call for new ocean vehicle technology with novel high-dimensional multi-robot deployment schemes, and assessment of innovative algorithms through real-world experimental validation.

Opportunities for underwater robotics include:

- The development of advanced multi-robot cooperative deployment algorithms for oceanographical applications;

- The development of authentic dynamic models of operational ocean robots (such as the new wave glider platform) to integrate in advanced cooperative control algorithms;

- The implementation and integration of advanced algorithms on heterogeneous ocean

robots, and experimental demonstration of the efficacy in real-world coastal environments.

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### Intelligent Social Robots and Cognitive Robotics Benchmarks

Many applications developed by using either Robotics or Artificial Intelligent (AI) techniques have been successfully demonstrated. Very sophisticated robotic systems have been developed and deployed in industrial, military and medical domains, while AI systems have been demontrstaed in games, software agents, medical diagnsis, etc. On the other hand, there are not so many applications where AI and Robotics are properly integrated.

In our opinion, the ability of a mobile robot to properly act in an environment populated by humans, with the goal of understanding and satisfying user needs, requires a proper integration of the two technologies. While abstraction and explicit high-level representation of knowledge and information may not be needed in some robotic applications with minimal interaction with humans, an "intelligent social robot", that has to properly interact with non-expert users, must represent and express the information it can gather from the environment and from people at the same abstraction level of a human.

All the problems in the boundary between AI and Robotics must thus face this representation issue, in order to relate high-level abstract representation of the information with some low-level concrete implementation of methods, functionalities, sensor processing, etc.

While some benchmarks for Robotics and for AI methods separately have been defined and for many functionalities it is possible to actually measure performance and compare different methods and technologies, this has not yet been achieved for integrated AI and Robotics systems.

We believe that the notion of *Cognitive Robotics Benchmarks* should be studied and developed, in order to provide with effective measuring tools for performance analysis. Tasks characterizing the integration of AI and Robotics (and thus that cannot be solved by using either only robotics techniques or only AI methods) must be defined, in order to provide for clearly specifications of what is expected by the integration between AI and Robotics. Flexibility and versatility must be considered as the most important features of an AI and Robotics integrated system.

Integrating AI and Robotics should be considered as an *important* research area. The contribution of this research is characterized not by the development of new algorithms/methods

in one of the two disciplines, but by a proper integration that brings increased flexibility and versatility in executing complex tasks in complex environments, specially characterized by the interaction with non-expert users.

The development of such cognitive robotics benchmarks could be achieved by defining a set of challenging problems and the corresponding performance measures, in order to evaluate and compare different solutions and to measure the progresses in this area.

Proper challenges for AI and Robotics integrated systems should consider the execution of many different tasks by the same system, possibly interacting with users. In this way, general solutions are encouraged and rewarded with respect to ad-hoc hard-coded solutions and general solutions necessarily require Artificial Intelligence techniques applied to robotic systems.

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Techniques from artificial intelligence (AI) and robotics are often complementary and their combination thus has the potential to result in more powerful systems. AI techniques that stand to benefit robotics, for example, include search/planning, multi-agent systems and machine learning.

However, there are entry barriers to collaborations among researchers of both research communities. For example, robots can be expensive and, more importantly, require infrastructure support and effort that is best spread across several people. This makes it often difficult for AI researchers to run a robotics project in addition to other research projects. Furthermore, researchers predominantly attend events that are attended also by their peers, and AI and robotics are largely different research communities. For example, both the International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS) and the International Conference on Automated Planning and Scheduling (ICAPS) currently have robotics tracks but these tracks have difficulty attracting robotics researchers that are not yet part of the AI research community. This results in both research communities basically attacking the same problem with little interaction between the efforts, as is currently happening in multi-robot path planning. It is therefore important for researchers of both research communities to mix more, for example, to understand each others' research better but also to overcome issues caused by the different research cultures:

- The former issue is important because AI researchers need to understand robot hardware, tools (like ROS), problems and techniques. They would likely start to use robotics

problems as motivating problems once they learn about them. Our research group, for example, realized that construction planning for the Harvard TERMES robots, published in the robotics literature (Robotics: Science and Systems), is an interesting search/planning problem amenable to AI techniques. We then developed planning techniques for them and published them in the AI literature (ICAPS).

- The latter issue is often overlooked. For example, AI researchers tend to be interested in algorithms of broad applicability and abstract perception and actuation away to be able to concentrate on the core cognitive processes, while robotics researchers tend to be interested in systems and validate their research often on hardware rather than in simulation. AI researchers place less emphasis on journal publications due to more stringently reviewed conferences, which makes it harder for robotics researchers to publish in them (especially if they are unfamiliar with the research tastes of the audience).

The top conferences of both research communities could invite speakers, tutorial presentations and students from the other research community. They could also co-locate. Both research communities could have joint workshops or summer schools that, to boost attendance, co-locate one year with a top conference of one of the research communities and the next year with a top conference of the other research community.

AAAI-15, for example, started collaborations with the IEEE Robotics and Automation Society, the Robotics: Science and Systems Foundation and the RoboCup Federation to introduce AI researchers to current developments in the robotics research community and to attract robotics researchers to AAAI-15 and introduce them to current developments in the AI research community. Funding from NSF (and others) enabled AAAI-15 to offer a variety of robotics events and attract robotics researchers via a track with 10 selected talks from the 2014 Robotics: Science and Systems conference and more junior robotics Ph.D. students (who want to learn about AI techniques of relevance to them) via a track with 13 talks and accompanying posters.

Challenge problems (and perhaps competitions) could be created. They need to be chosen so that they have low-entry barriers, require the collaboration of researchers of both research communities and allow for participation in hardware or simulation, such as RoboCup. Multi-robot path planning (as needed for the robots from KIVA Systems) would make a good challenge problem, perhaps including just-in-time scheduling for manufacturing rather than packaging.

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## AI Robotics: Finding Common Ground

A significant gap exists between the AI and robotics communities. Bridging this gap at this time is of critical importance, because robots have the potential to both provide the common ground for reintegrating the various fragments of AI, and for providing a rich source of research questions that address real-world problems. Similarly, AI techniques are now becoming necessary for us to fulfill the potential of available hardware, which far exceeds our current capability to program.

I propose that the simplest and most natural way to bridge this gap is through *models*. Most subareas of the AI community are founded on the shared assumption of a *common model*, which provides both a language for framing the set of problems of interest, and as a means of comparison. For example, the reinforcement learning community has largely standardized on the Markov decision process (MDP) as a formal model of reinforcement learning problems. Such models have the virtue of being generic and very clearly defined; a good model abstractly captures just the relevant properties of the class of problems we care about, and discards all the extraneous detail.

Unfortunately, many researchers in these communities make the mistake of *assuming their models are real*. Those of us who work with real robots know that things are not so simple—a great deal of expert knowledge and engineering effort goes into applying AI techniques on robots, and the majority of it is *getting from the robot to the model*. I therefore propose that the major focus of attempts to reunite AI and robotics should be on developing methods for bridging the gap between real robots and AI models.

From the robotics side, this would consist of methods that automatically construct models that the AI community uses. For example, the task planning community has standardized on describing symbolic planning tasks using PDDL. Robots using high-level planners based on PDDL have required immense engineering effort to create the appropriate symbolic model *by hand*. My recent research has focused on automatically constructing PDDL descriptions of a task, given a robot and a set of motor controllers. Somewhat surprisingly, this is both possible and effective.

From the AI side, this would consist of adapting AI models to better suit robots. For example, the multi-agent planning community formalizes cooperative multi-agent planning problems as Dec-POMDPs (decentralized, partially observable Markov decision processes). This model is poorly suited to robotics, partly because even small Dec-POMDPs are ex-

tremely hard to solve, and partly because it assumes that all agents execute their actions concurrently, within a single time-step. Chris Amato and I recently generalized this model to use macro-actions to model robot motor controllers. The resulting model naturally models of multi-robot problems, and allowed us to scale up to reasonably sized robot problems. Here we find an example of robotics driving the development of AI methods by providing the rationale behind a new model that may prove generally useful.

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*What research areas stand to benefit more from the collaboration of AI and robotics researchers?*

Advanced autonomous system development is a significant priority for the U.S. Air Force and an area identified for science and technology investment growth. Indeed, numerous Air Force strategic studies (e.g., see *Air Force Technology Horizons 2010-2030, Cyberspace Vision 2025*, or *America's Air Force: A Call to the Future*) identify autonomous systems as a "game changing" technology, essential to future military and civil applications. The Air Force's concept for autonomy is that the technology should be considered part of a human-machine team where decision-making and action is shared. This is in stark contrast to the 'leftover principle' in which autonomy is seen as a means for replacing human activity, i.e., we automate as many tasks as possible and the human does whatever is leftover (*Brief on Autonomy Initiatives in the US DoD*, 2012). Rather, the vision is one of closer human-machine coupling in which intelligent machines are seamlessly integrated with human counterparts to maximize mission performance in complex and potentially dangerous environments. Of course, one important class of autonomy is systems comprised of sensors, physical effectors and sophisticated mobility capabilities that emulate animal or human abilities, i.e. robots. In anticipation of the eventual use of robots in a variety of military and civil operations, research is needed to better understand the dynamics of human-robot interaction and cooperation. This area is inherently interdisciplinary, involving a blend of artificial intelligence, robotics, mechatronics, social and cognitive science, in order to arrive at sufficiently compelling and effective human-robot partnerships.

Central to this goal is the establishment of *trust* between humans and robots. While there is considerable prior research on the cognitive and physical sensor/effector aspects of robotics, there has been relatively little work on how those come together to promote a trusted human-

robot team. Previous research has shown that the introduction of autonomous systems can have unintended consequences on human behavior related to trust and willingness to rely on technology under conditions of uncertainty. When people do trust autonomous systems, it can lead to overreliance and complacency — operators are out of the decision loop, lose situation awareness and are therefore slow to react when problems occur. When mistakes are observed or expectations are not met, people tend to rapidly lose trust, under-rely on their machine counterparts, and therefore the advantages of human-robot partnerships are not realized. In short, lack of trust will limit the use and effectiveness of robots, and overreliance will lead to loss of situation awareness and associated mistakes. Research is needed to investigate behaviors, processes and capabilities that support properly *calibrated* human-robot trust. Moreover, research is needed to understand how robots can establish trusted relationships with people, measure dynamic changes in trust and reliance, and repair breaches in trust.

Specific suggestions for research areas on trusted human-robot teaming include the following: (1) investigating socially-designed cues such as humanoid appearance, voice, personality, and other social elements on human trust and overall human-robot team performance, (2) physical embodiment features versus non-physical features to determine which have the most influence on human trust and performance, (3) sensing of human intent, cognitive and affective states, such as workload, stress, fatigue and fear, (4) modeling the processes of high performing human teams, such as teammate monitoring, backup behavior, joint attention, shared mental models, coordination and negotiation, (5) dynamic modeling of the human-robot partnerships to allow continuous improvement of joint performance in real-world applications, (6) investigations regarding the effectiveness of various models of human-robot interaction, such as delegation and supervisory control, (7) practical methods for robotic systems to sense and measure trust and changes in trust over time, (8) investigations of the impact of culture and cross-cultural interactions on reliance and human-machine cooperation.

*What particular activities could bring these communities of researchers together?*

Funding agencies (NSF, ONR, AFOSR, DARPA, etc) can play an active role in encouraging interdisciplinary work by soliciting and funding proposals that emphasize cross-discipline collaboration. The NSF National Robotics Initiative (NRI) is one example. The AFSOR basic research initiative on perceptual and social cues in human-like robotic interactions also encouraged multidisciplinary approaches.

Interdisciplinary workshops designed to bring together a diverse collection of scholars and researchers could be used as a process for encouraging collaboration across the AI and robotics communities. For instance, a workshop might organize interdisciplinary teams to develop research proposal topics and working whitepapers through a series of breakout/brainstorming sessions. Direct involvement of funding agencies in these workshops would facilitate subsequent funding of the best ideas.

*Do you have recommendations such as possible challenge problems, or task-force activities which could solidify various efforts?*

A competition involving human-robot teams would be a significant challenge and is sure to push the boundaries of AI and robotics. For example, a simulated search and rescue task that has elements of autonomous performance, but is also interdependent, i.e., it cannot be completed by either robots or people alone, could provide the basis for a competition. Teams might be composed of a human and one or two robotic platforms, with metrics gathered for efficiency, effectiveness, trust and reliance. Ben Knott

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*What do you see as particular research areas that stand to benefit more from the collaboration of AI and robotics researchers? What specific problems do you feel lie at the boundary between AI and robotics? How can these be tackled, and the boundary pushed?*

From the perspective of robot perception, I believe that the area of knowledge representation and planning where the constraints of the task can be brought in, could benefit most from the interaction between AI and Robotics and Computer Vision. Computer Vision and Robot Perception made huge strides developing effective machine learning strategies for detectionand categorization of different objects and understanding of open scenes, yet many of them are considered in isolation and not tied to possible tasks, where many of these functionalities need to be deployed.

*What particular activities could bring these communities of researchers together? Do you have ideas for the way the various stakeholders such as funding agencies, professional organizations and individual researchers should play a role?*

The time is ripe for re-engaging in discussion between computer vision-robotics-AI communities. Workshops and panels at the leading conferences, where like minded and open minded experts in the respective fields could speak and interract provide a good venue for strengtening the synergies. Both the research community and the agencies could benefit from directly supporting this interdisciplinary program. Maintating robotics infrastructure typically requires a lot of resources which are concentrated at larger universities, with well supported programs. This limits the diversity and the amount of participation on working on interdisciplinary programs, which require large infrastructire. In computer vision the

progress in the last decade(s) was propelled by various challenge which the community as a whole participated in. It would be good to create more platforms to enable this for problems at the boundary of robotics, computer vision and AI comminities.

*Do you have recommendations such as possible challenge problems, or task-force activities which could solidify various efforts?*

I would be interested in support of creation of datasets for research on perception of cluttered real world scenes at different scales and from different environments which would support object search and mobile manipulation tasks. Some sampling of scenes relevant to different service robotics applications ranging from household and healthcare domains or seach and rescue domains or other application domains which already have some critical momentum.

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### Research Issues at the Boundary of AI and Robotics[1]

In AI, two difficult questions are: *Where do the symbols come from? How do they get their meaning?* In robotics and vision, the same questions arise as: *What are the right abstractions to tame the overwhelming complexity of perception and action in a realistic world?* Appropriate symbols, abstracting from the "blooming, buzzing confusion" of the sensorimotor stream, allow the robotic agent to make useful, reliable plans while respecting the complexity of the environment.

In the early days of AI, and for subsequent decades while these fields diverged, progress depended on human-designed symbolic abstractions. The cost of this "Intelligent Design" approach has been fragile, limited solutions to problems of real world complexity. Instead, the abstractions must be learned.

To drive research at the interface between AI, robotics, and vision, I propose the challenge of creating a learning agent that is general across robots, sensorimotor systems, and environments, and (when it succeeds) can learn appropriate abstractions for three critical foundational domains of commonsense knowledge — navigational space; objects and actions; and sensorimotor control.

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First, to make useful sense of a complex, large-scale environment, an agent needs to create the abstraction of navigational space. This "cognitive map" describes a stable structure for the world, organizing the affordances for the agent's travel within it, and abstracting away as noise most forms of dynamic change. Knowledge of navigational space makes it easy for the agent to plan travel to access different aspects of a large and complex environment.

Second, with a map of the static background, the agent must create linked abstractions for foreground objects and actions. Objects are abstractions with local state that explain coherent clusters of changing percepts within the perceptual stream. Individual objects can be identified and tracked. Object categories can be learned and recognized, allowing learned properties to be generalized across individuals. Actions are abstractions that organize control laws (or policies) that cause changes to objects, including for example the *move* action, which can cause changes to the location of the agent itself within the environment.

Third (or rather, Zeroth), when the robot starts with an unknown sensorimotor system in an unknown environment, the agent must be able to learn from unguided experience. It must learn regularities among its sensors, among its motor signals, and across its sensors and effectors, to allow it to create useful perceptual features and useful control laws. The criterion for adequacy is that the agent must be able to control the robot to move safely through free space in the large-scale environment. Safe motion is a prerequisite for exploring and building a cognitive map.

Success at these three challenges allows the agent to learn a concise set of foundational abstractions, suitable to its sensorimotor capabilities and its environment, from its own unguided experience. These abstractions provide a principled grounding for symbolic knowledge representation and reasoning in AI, and a principled target for research in computer vision and robotics.

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Robotics has progressed dramatically in the last few decades, both on the hardware side as well as on the software side. Low level operations such as obstacle avoidance in ground robots, aerial vehicles and mobile manipulators works well in most cases. The challenge is in making it work *all the time and under all conditions.* This last bit, I believe, is challenging and requires research into the fusion of AI-like approaches with the typical approaches to robotic control and planning. The following are few examples that pertain to planning in robotics and show how typical robot planning needs to be revised if we want to have robotic

systems that are fully autonomous.

Real-world in its full glory contains too many factors and unknowns to account for all of them upfront while developing an autonomous robot. The first challenge for planning therefore is to operate on a "deeper" level than just a static representation of the world. Planning representations need to "adapt" to the tasks the robot executes, the environment it works in, the experiences it gathers and demonstrations it receives. For example, human demonstrations for how to open doors, for how to sort items arriving on a conveyor or for how to assemble furniture shouldnt be used as simple re-play motions but instead should be used by the robot to infer how relevant objects behave and how to construct planning representations that are effective for given tasks.

The second challenge is in developing planning frameworks that integrate tighter with other modules in the system such as perception, control and task planning. The planners need to reason about the weaknesses and strengths of these modules and generate plans that avoid their weak spots and capitalize on their strengths. Furthermore, these weaknesses and strengths should be revised based on the robot experiences. For example, a micro-aerial vehicle has limited payload leading to noisy sensing and actuation. Generated plans should therefore exercise as much as possible the controllers that are robust such as visual servoing towards easily detectable landmarks, and avoid generating segments of the paths that require the use of fragile controllers. Similarly, a motion planner for a manipulator needs to reason about the limitations of grasping and the constraints of higher-level task planning. To address these challenges without the explosion of the state-space, we need to research planning representations that vary in their dimensionalities, model limitations and strengths of modules and revise all of it based on experience.

Clearly, the above challenges relate to some of the typical AI research areas such as Knowledge Representation in general and Commonsense Knowledge in particular. It is therefore very beneficial to hold meetings that gather researchers from both Robotics and AI communities. In particular, it would be great to have every so often a co-allocation of an AI and Robotics conference, for example, to have an ICAPS conference co-allocated with an RSS conference. Funding agencies, on the other hand, could facilitate such interchange further by creating programs that explicitly encourage collaborations between AI and Robotics researchers and require researchers to develop approaches that work on real robots but are general enough to be robust under a wide range of conditions.

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*Areas that can benefit from collaboration of AI and robotics researchers:*

Solving inverse problems, such as parameter estimations, for data-driven modeling, simulation, planning, control, and manipulation of complex robots (broadly defined) and/or autonomous agents under uncertainties. In particular, machine learning, statistical inference and optimization techniques from AI can be powerful in combination with traditional robotics approaches to address some of these most challenging problems in the field.

*Problems lie at the boundary between AI and robotics:*

Classical robotics problems, such as planning, scheduling, control, and manipulation problems, that take advantages of machine learning, are among some of these examples.

*Activities that could bring these communities of researchers together:*

Co-location of major Robotics and AI conferences (such as AAAI and ICRA, IROS, etc); special sessions and workshops that address specific problems at both AI/Robotics conferences not co-located; multi-country collaboration

*Stakeholders such as funding agencies, professional organizations and individual researchers who should play a role:*

NSF, DARPA, European Commission, Japanese Science and Technology Agency, Google, SpaceX, Automobile & Aerospace Industry, etc.

*Recommendations for possible challenge problems:*

- Traffic Control Robocops at Pedestrian/School Crossings

- Homecare Robots for Elderly, Disabled, and Children

- Dexterous Fluid-handling Robots in Assembly Lines & Hazardous Places

- (Cooperative)Autonomous (Aerial/Ground)Vehicles under Stormy Weather

- "Innerspace Robots" for Medical Treatment, Procedures, and Operations

*Recommendations for task-force activities that could solidify efforts:*

Organization of a series of focused workshops, organization of joint-conference sessions for 3-5 years, special sections in journals and conferences.

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### AI and Robotics: Are We Asking the Right Questions?

The 2012 Defense Science Board Task Force Report on the Role on Autonomy in DoD Systems explicitly describes how AI research would benefit unmanned systems and recommended a novel implementation of challenge problems. In contrast, a meta-analysis of autonomy at the 2013 DARPA Robotics Challenge Trials suggests that the robotics community is not familiar with AI and does not see sufficient benefit of AI to warrant incorporating it into the system design. Understanding why roboticists are unaware of AI or continually re-invent AIs successes and failures can help bring the two communities closer together.

The DSB report stated that advances were needed in six key enabling technologies in order for a user to trust an unmanned system to carry out a delegated task or portion of a task. The six areas were: perceptual processing, planning, learning, human-robot interaction, natural language understanding and multi-agent coordination. The report singled our four specific problems: Natural user interfaces and trusted human-system collaboration, Perception and situational awareness to operate in a complex battle space, Large-scale teaming of manned and unmanned systems, and Test and evaluation of autonomous systems. In order to tackle these problems, the report recommended that the DoD Science and Technology program create challenge problems based on real operational needs. Rather than express the challenge problems as competitions, the study proposed a different strategy. It envisioned events that would physically bring together academia, government and not-for-profit labs and industry and military operators to work on a problem, in effect mini-Los Alamos events.

The DSB study implicitly asserts that robotics needs AI, but my meta-analysis of autonomy at the 2013 DARPA Robotics Challenge Trials (in press) implies that the robotics community does not necessarily share that view. The DRC is an opportunity for roboticists to leverage AI given that the top priorities listed in the competition BAA are supervised autonomy, mobility, and dexterity and that the scoring favors onboard decision and control rather than teleoperation. The meta-analysis surveyed the 16 teams and received answers from 9 of the teams about their approach to autonomy. Of the 124 team members on the responding teams, the highest number were experts in manipulation (16.9%), guidance, nav-

igation, and control (12%), and biped robots (11.3%). In contrast, AI experts made up only 9.7% of the total, hinting that AI was not viewed as essential. Indeed, the majority of the teams appeared to be taking a bottom-up approach to their entry, focusing on basic hardware-oriented control and deferring AI to later; autonomy was not considered an integral component of the design. The teams reported no common references or motivating papers on autonomy, which is evidence that AI principles such as layered architectures and behavioral control are not known to among roboticists.

The lack of interest in, or awareness of, AI poses a slightly different set of questions for the workshop: What are the real incentives to incorporate AI-especially as there appears to be no recognized canon of principles? Are there practical alternatives to competitions that will ensure AI and roboticists from academia, industry, and government will interact? The answers to these questions will help avoid the pitfalls of yet another list of problems and another competition and move the robotics and AI closer.

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1. *What do you see as particular research areas that stand to benefit more from the collaboration of AI and robotics researchers?*

At a broad level, all of AI can benefit. Looking back, the introduction of the autonomous agent perspective by the first edition of Russell and Norvig's textbook in 1995 as an organizing principle for the field had a broad impact on how the field viewed itself. Looking forward, overviews such as Ingrand and Ghallab's recent AIJ article "Deliberation for autonomous robots: A survey", which recasts and reframes most of AI according to the major functionalities needed for robot autonomy, will have a similarly unifying, rejuvenating, and reorienting effect.

As for specific areas, planning and perception are certainly obvious choices. My sense is that these areas are also the bottlenecks causing the '20x' caveats in the corners of so many robot videos.

*What specific problems do you feel lie at the boundary between AI and robotics? How can these be tackled, and the boundary pushed?*

As a researcher in combinatorial search and planning, I see enormous promise in applying methods that are commonplace in AI, such as **abstraction-based heuristic guidance**, to motion planning problems in robotics. The combinatorial search and planning communities have developed a wealth of general and powerful techniques but those communities currently

favor benchmarks like the sliding tile puzzle and the task of moving many identical balls from one room to another. Robotics can provide a fresh set of exciting challenge problems to these communities, and define useful problem settings, constraints, and algorithm requirements.

I'm particularly excited about planning in dynamic environments, such as when working with humans. This can be motion planning, mobile manipulation, or combined motion and task planning. The search community has developed all sorts of **real-time search** algorithms that are ripe for this setting, where planning and acting unfold concurrently.

Coordinating between multiple levels of planning, as in motion and task planning, has received a lot of attention, and could clearly use a lot more. **Hierarchical search** has something to say about this. I believe that real-time responsiveness is key at all planning levels.

2. *What particular activities could bring these communities of researchers together? Do you have ideas for the way the various stakeholders such as funding agencies, professional organizations and individual researchers should play a role?*

Funders: 1) advertise funds for workshop invited speakers, 2) advertise funds for presentation of journal papers at conferences other than where the work originated, 3) fund workshops (like task and motion planning) that move between conferences.

Organizers: 1) emulate AAAI/IJCAI's umbrella model: present best papers of related conferences (talk and 2 pages in the proceedings), 'what's hot' talks, 2) follow AAAI-15's lead in cooperation between AAAI and IEEE, 3) at AAAI/IJCAI, segregate hobbyist from researcher robotics, have organizers of robotics events give overview talks on technical challenges and current approaches.

Researchers: one issue is how to encourage people to publish in diverse venues.

3. *Do you have recommendations such as possible challenge problems, or task-force activities which could solidify various efforts?*

Common benchmarks and platforms create progress. The UBR-1 from Unbounded Robotics could have been a game-changer. Benchmarks must be meaningful in simulation: the physical TSP challenge is one example. A 'setting the table' challenge might be suitable for task and motion planning. Competitions encourage focus and enroll others but must be counterbalanced by explicit encouragement of exploratory research on new problem settings.

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**Integrated Embodied Cognitive Systems**

Several research areas stand to benefit significantly from a tight collaboration of AI and robotics researchers, in particular, the area called "embodied cognitive systems". Embodied cognitive systems attempt to deeply integrate higher-level cognitive and knowledge-based processes with lower-level perceptual and actuation control processes, using higher-level information (such as factual knowledge, goal, task and interaction context, high-level predictions, etc.) to constrain lower-level processing (such as action execution, object tracking, etc.), thus improving the performance of lower-level (robotic) components. Conversely, lower-level control processes in embodied cognitive systems are essentially used as part of higher-level cognitive deliberative processes (e.g., by utilizing physics in effector control processes or knowledge about bodily perspective in perceptual processing) to transform computational problems, speed up computations, and improve overall performance. In particular, robotic systems employed in social contexts where the robot is situated, has a perspective, and needs to interact with other agents, will benefit from a tight integration between robotic and cognitive systems. This includes computational models of social cognition and natural language understanding.

Several specific problems lie at this boundary between AI and robotics, in particular, the integration of cognitive components with robotics components in an integrated cognitive-robotic architecture where various representational and processing gaps have to be overcome such as (1) the real-time computations of low-level perceptual and actuation processes vs. the cycle-based time of higher-level cognitive components, (2) the continuous statistical representations of perceptual processes vs. the symbolic structured representations of high-level percepts, (3) the low-level action execution and control processes vs. the high-level goal management and action sequencing, and overall the (4) statistical algorithms employed in robotic systems vs the often non-statistical algorithms in cognitive systems. One way to tackle these issues is by building integrated cognitive robotic systems. We have previously proposed two generic ways to integrate robotic and cognitive architectures (Scheutz et al. 2013), which can effect bridges between the different kinds of representations and timing schemes without requiring a complete overhaul of either type of architecture.

To foster the integration of existing systems and the development of complex integrated cognitive-robotic architectures, funding agencies could strongly recommend the participation of both robotics and AI researchers in project teams and furthermore require annual

live demonstrations of the integrated robotic system developed in the project (this is common practice for large projects in the European Union and has led to a rapid improvement of the capability and quality of their integrated systems, while significantly strengthening robotics research in Europe). In addition to requiring multidisciplinary teams where research groups with different expertise have to work together to build an integrated architecture, it is critical that the expected outcomes not be limited to just integrating systems, but also include leveraging of synergies resulting from the integration and ideally system extensions that go significantly beyond what individual components could have achieved (e.g., a vision framework that can be augmented by new algorithms that together with the existing ones significantly improve object recognition rates, an NLU system that by way of parallelizing its components and including contextual constraints at any point in the processing can significantly outperform stand-alone NLU systems, etc.). Finally, to push this agenda and to ensure that truly integrated systems will be developed, it is critical to pick evaluation tasks such as open-world online tasking in natural language (where new goals, objects, actions, etc. have to be learned online) that are so challenging that none of the current robotic or AI systems will even be able to do any of the required aspects on their own.

References: Matthias Scheutz, Jack Harris, and Paul Schermerhorn (2013). "Systematic Integration of Cognitive and Robotic Architectures". *Advances of Cognitive Systems* 2, 277-296.

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Both AI and Robotics communities will undoubtedly contribute important research in bringing intelligent robots to fruition. Although the current separation between communities is stark, it is unsurprising. Producing an intelligent robot is an immense challenge that cuts across multiple traditional disciplines, each of which might naturally begin with a different part of the problem. But rather than being just a failure to converge, the separation feels like the product of a speciation process where communities continue to make progress but cross-pollination is prevented by some barrier. Technical challenges may have produced the barrier but social issues are increasingly responsible for maintaining it. The communities of researchers carry with them the baggage of value systems which are not compatible with one another and, I believe, are now largely vestigial.

This is illustrated by comparing appropriate insults and snubs for pieces of research in each community.[2] Any sort of work might be criticized for being inadequately practical or unlikely

to work on a real system, or inadequately abstract, deep, or generalizable, being simply too ad hoc and setting specific. But a *maximally pointed insult* will match the deprecation to the appropriate community. The difference in value system is illuminated by the fact that misjudging the researcher's community and consequently mismatching the insult, may mean your foe elicits nothing more than a mere shrug. This despite principled and generalizable methods for dealing with real robots being a worthy goal that the communities have in common.

Additionally, there is an asymmetry in the relationship between the communities. In the past, AI has experienced sub-areas and important applications detaching themselves (seemingly) as they begin to prosper, and losing out on credit fairly due to it. There are already signs of AI's skittishness especially when contrasted with the insouciant Robotics attitude, the latter's brashness perhaps born of being closer to the bare metal and thus being assured of its relevance. I believe that whatever recommendations are made to bridge the communities (e.g., workshops, best-of-'$x$' sessions), they must consider this asymmetry carefully. Placing mid-point meeting points may fail.

Caricaturing a roboticist's perspective: AI has lots of general results, algorithms, and techniques but the good needles, with assumptions that are workable for a given system, are buried in haystacks (of needle looking hay) with heaps of models that are a bemusing fiction. From the artificial intelligentsia's perspective: robotics research appears to be content to construct system after system, yet fail to extract general lessons or methods. Moreover, roboticists seem to develop systems while consistently failing to implement the right abstraction/model and, when they do build an effective system, the model is buried deeply almost as if hidden under a bushel.

*"...and the world so hard to understand, is the world you can't live without..."*
*— Smashing Pumpkins, Muzzle*

In Thomas Kuhn's famous book on revolutions in science, he describes how there is a period of time in which particular phenomena that fall outside the predictions of established theory are identified, often repeatedly and quite reliably. He points out that this critical period can be surprisingly protracted, continuing for years until the crisis is fully recognized. There is a comparable problem of selective attention (read: blindness) in the communities dealing with robots when examining models and abstractions, and their verisimilitude and utility. The difference compared to physical sciences is that we need not seek ultimate or unifying models, but rather practicable ones. My view is that if progress is to be made, it is by attempting to understand *sets* of abstractions: to study whole lattices of them, delineating successes and failures practically as well as theoretically, rather than looking for a single model. Abstractions for each place and a place for each abstraction. This needs

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[2]This directly based on Douglas E. Comer's essay "How To Criticize Computer Scientists or Avoiding Ineffective Deprecation And Making Insults More Pointed".

to become a first-class focus of research rather than the piecemeal exercise that it currently is. We need integrative reviews that give hierarchies of abstractions describing layerings of the simplifying assumptions. And these should be paired with experiences gained by employing them in robot settings. This obviously requires better thinking about how lessons can be learned from systems and systems papers. We must treasure more greatly papers that provide evidence of aspects of the real world which, when omitted from models/abstractions provide clearly identifiable limitations or critical failures. This must be addressed not just in models employed *by* the robotic agent, but in models *of* the robot. Finally, demonstration of an operational robot is some evidence of the utility of a model, but the boundaries of operation are infinitely more informative when we can relate those back to the underlying theoretical representations.

Research topics which seem immediate bridging points include: (1) The increasing attention being paid to motion planning problems enriched to include task constraints, especially through the use of satisfiability-based solvers. And (2) the application of particle filtering approaches to address belief-space planning problems, connecting approximate POMDP solvers to methods of optimal control (like LQG). Both of these are quite narrow examples, but show where the forms of the specific problem being tackled are in broad agreement and, at a high-level, the same ideas are employed. What remains to keep them apart are value-systems and narratives constructed to justify state representations, distributional assumptions, and the like. In (2) I cite particle filters because they are exactly an approach with which either camp can have some degree of philosophical comfort.

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### Emotional Intelligence and Robotics

Emotional Intelligence is often defined as the ability to identify and use emotions to interact successfully with others. It involves being aware of the cues others exhibit relating to their emotional state and providing cues as to one's own emotional state. In human-human interaction, Emotional Intelligence has been shown to be strongly correlated with success in business dealings and conflict resolution.

More specifically, when people interact with one another, they continually provide non-verbal cues that indicate their state of mind  whether they understand the conversation, whether they agree with the speaker, their attitude towards him/her, whether they are even paying attention, etc. These cues are provided through various mechanisms, including

gaze, gesture and body posture, both kinematically (e.g., where the person is looking, how their body is situated) and dynamically (e.g., how quickly or suddenly they move, what is the timing of the cue with respect to what the other is saying/doing). In addition, verbal behaviors, such as humor or swearing, often provide strong indications of a person's emotional state.

So, what does this have to do with robotics? I contend that peoples' perceptions of a robot's (rational) intelligence will be strongly influenced by their perceptions of its emotional intelligence. If we want people to believe that autonomous robots are more than just clever automata, the robots must exhibit a high Emotional Quotient (EQ) as well as a high IQ. For instance, in many studies, including some of our own, robots that utilize gaze appropriately are viewed as more intelligent than those that do not. Conversely, one of our studies on social navigation found that, while people felt that the robot acted more appropriately when it was following the accepted social norms, it was not seen as more human-like. When we drilled down into this, we found that people were expecting a true social robot to exhibit the subtle gaze behaviors that people use when passing in hallways. The fact that the robot did not gaze appropriately, even though it did move appropriately, significantly impacted perceptions of overall intelligence. Similarly, we have recent evidence that swearing when a robot makes a mistake significantly increases a person's desire to assist the robot that needs help.

Central to Emotional Intelligence is the ability to maintain mental models of the interaction partner and to do perspective taking (i.e., what would the other person be perceiving and thinking about in the current situation). This provides an ability to model how cues will be understood, as well as understanding the intent of the cues exhibited by others. Establishing common ground is necessary to synchronize the mental models of the interaction partners, so they are on the same wavelength. Clark's linguistic Common Ground Theory posits a presentation/acceptance approach to establishing common ground that we have found useful for both conversational and spatial interaction.

How can the community help? A big first step would be to acknowledge the importance of Emotional Intelligence, along with our traditional emphasis on (rational) Artificial Intelligence. Second, the AAAI community has a long history of holding competitions to foster research in certain areas, starting with the autonomous robot competitions in the early 90's. Having a competition that showcases the advantages of having strong Emotional Intelligence would be a big contribution. In summary, I, for one, look forward to the day when "robotic" is not a socially pejorative term, but instead connotes acting and understanding with high emotional intelligence.

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*What do you see as particular research areas that stand to benefit more from the collaboration of AI and robotics researchers? What specific problems do you feel lie at the boundary between AI and robotics? How can these be tackled, and the boundary pushed?*

In some sense, I think robotics brings together many of the threads of AI that have been disparate since the beginning of the field. People working on planning, vision, NLP, knowledge representation and reasoning, machine learning, multiagent systems, and reasoning under uncertainty can all motivate their research with robotics applications. Traditionally, they have had to abstract away the robot and assume that it carries out whatever actions they assign it. But we are now finally at the point where robots are capable enough that they can carry out tasks that are sophisticated enough to challenge researchers in these various areas. And indeed, in doing so, they are inevitably being forced to confront the fact that real robots don't behave the same as abstract robots. This discrepancy raises real research challenges.

Efforts to make robots interact with people over extended periods of time will inevitably bring together the capabilities of these various fields.

*What particular activities could bring these communities of researchers together? Do you have ideas for the way the various stakeholders such as funding agencies, professional organizations and individual researchers should play a role?*

I'm a big proponent of challenge problems. Challenges such as RoboCup Rescue and RoboCup@home force roboticists to get up to speed on the state of the art in vision, NLP, planning, etc. And they offer new challenges to researchers coming from these areas.

*Do you have recommendations such as possible challenge problems, or task-force activities which could solidify various efforts?*

I think we should continue developiong and engaging in challenge problems, but gear them specifically towards tasks that require cutting edge advances in the various subfields of AI — especially planning, vision, NLP, and learning.

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### Games and Robots: Two Related Human Interaction Problems

Working with a physical robot forces researchers to pay more attention to certain issues, which advances the field in specialized ways, but also diverts research away from other problems. Researchers who work with other types of intelligent systems, such as multi-agent simulations, games, and user interfaces, are freed from the constraints of sensors and manipulators but may lack data or compelling usage cases to validate their work. Research progress is best made by alternating the process of narrowing and broadening the scope of problems under consideration; there is much that can be learned from cross-pollination between communities.

For instance, game developers could benefit from greater collaboration with roboticists. As program/general chair of AIIDE 2012/2013 (AAAI Conference on AI and Interactive Digital Entertainment), I tried to encourage this by expanding the conference topics and invited talks to include robotics. This is a logical partnership since many games involve avatars moving and interacting with a physical world; hence an autonomous game bot needs to solve the same type of planning problems as a robot, but with different types of "sensor" information. Many of the popular robot path planning algorithms, such as RRTs and PRMs, are relatively unknown and rarely utilized by game developers. Similarly, integration of machine learning algorithms is common in robotics systems but occurs rarely in deployed game systems. The problem of learning from demonstration has been studied by both communities, and my group illustrated how inverse reinforcement learning algorithms used in robotics could be modified for learning and predicting bot movement policies. Games can also serve as a good source of demonstration data for robots.

On the other hand, the game development community has thought more about modeling the human element in order to please a demanding user population. To satisfy players, gaming user interfaces need to be able to support rapid action with a short learning curve. Rather than simply thinking about usability, when designing games we also need to consider fun, challenge, narrative flow, and immersion. Game developers are starting to view game systems in a more holistic way, studying social patterns across multiple human users simultaneously. Robotics could benefit from this type of data analytics approach in order to visualize, model, and debug the interaction of multiple humans with multi-robot systems.

Robotics systems in the future are likely to include robots, agents, and people. Instead of point-to-point interactions between one user and one robot, there will be a network of

robots and people, comprising a virtual organization. Studying these virtual organizations will require research teams with diverse expertise, in both social networks and robotics, to collect datasets that can be made publicly available. Large-scale testbeds that can support many robots, as well as a big user population, will expensive to deploy; NSF could help this process by encouraging Community Research Infrastructure proposals to support dataset collection.

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Successful completion of autonomous robotic tasks often involves motions, therefore tightly coupling the fields of AI and Robotics through planning and decision-making. However, many of these tasks involve high-dimensional search spaces (e.g., involving several degrees of freedom or large action spaces) or are complex (e.g., highly constrained by complex dynamics). Current AI tools often find solutions elusive, and approximate solutions including coarse-grained discretization or hierarchical resolution action selection have been applied. Learning approaches that provide solutions in high-dimensional continuous spaces are required for many of these robotics problems.

As learning solutions are developed, new challenges will emerge from working with physical environments and experimental platforms with noisy sensors. Novel approaches that additionally provide guarantees of learning stability will be required, even in these uncertain learning problems. Solutions from these approaches can contribute back to general AI problems, e.g., resilient solutions in the presence of operating uncertainties.

While there is currently unprecedented excitement about the combination of these two fields, there are several professional organizations/societies that operate independently to organize activities, e.g., the IEEE Robotics and Automation Society Technical Committee (RAS TC) on Algorithms for Planning and Control of Robot Motion, the IEEE RAS TC on Robot Learning, ACM SIGAI, and AAAI. It is important to start programs that cross these societies venues. For example, a workshop that regularly rotates between venues may help build dialog and community. We have found these workshops to be highly popular. In 2014, we co-organized the Intelligent Robotics and Systems (IROS) Machine Learning for Planning and Control Workshop. The workshop had unprecedented participation, over flowing the over 100 available seats. These cross-disciplinary interactions need to be continually fostered in order to grow the success of the field both by individual researchers who organize these workshops and by the professional societies that host and facilitate.

One of the primary challenges of encouraging collaborations from both AI and robotics

researchers is the often disparate vocabulary between the two fields. Activities such as workshops and challenge problems will encourage dialog. One such challenge problem could be decision making in high-dimensional vector spaces, e.g., manipulating vectors based on external feedback. There are many applications to this problem including multi-agent coordination and high-dimensional robotics. The task-force could develop paradigms, examples, and applications of these solutions for complex high-dimensional problems.

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## Automatic Control: From Mechanical and Electrical Engineering to Computer Science

*Research areas for collaboration between AI and Robotics*

The earliest automatic control systems were purely mechanical, consider the water clock or the flyball governor. As electricity was harnessed in the 20th century, electromechanical control systems became pervasive, leveraging motors and generators. Of course, nowadays most systems are computer-controlled. However, the lessons learned from mechanical systems can give insights into naturalistic and low-energy robot designs.

Automatic control is a promising area for interaction between AI and Robotics. Many robotic systems have a hierarchical control structure, with low-level discrete-time controllers interacting with the motors and encoders, primarily in hardware, and higher-level controllers with a cognitive architecture, using discrete-event control abstractions and visual information, primarily in software.

The aggregation and abstraction of visual sensing data and other dense real-time data into usable forms is a key challenge for AI. Much of the work in AI is based on large data sets, and learning from demonstration. In contrast, many control-oriented models, particularly in mechanical engineering, are grounded in physics or other first principles. Combining these models, using different mathematical frameworks, at different levels of abstraction, and for different purposes, may yield improved performance in robotic systems.

*Activities to bring AI and Robotics researchers together*

Workshops (such as this one) are always useful to get people talking to each other. Funding agencies can provide travel support, but more importantly, can issue calls for future funding.

Many researchers engage with their professional societies via Technical Committees (TCs). For example, the ASME has two divisions with interests in Robotics – the Dynamic Systems and Control Division (DSCD), and the Design Engineering Division (DED). The IEEE Control Systems Society has a TC on Manufacturing Automation and Robotic Control. Of course, the IEEE Robotics and Automation Society has many TCs interested in all aspects of robotics. A workshop could engage multiple TCs from different societies, or a pair of societies could jointly sponsor an invited session at an upcoming technical conference, etc.

Over the summer I attended an "Ideas Lab" sponsored by Intel and NSF (on the area of securing cyber-physical systems). This structured 5-day workshop intentionally mixed and matched small groups of participants to come up with new ideas in the domain. At the end of the workshop, some teams were invited to submit proposals (I learned via the website that in the UK, at the end of such workshops, the funds are distributed — now that would be motivation for working together!)

As small robotics companies move rapidly from start-up stage to product roll-out, it is important for university researchers to maintain close ties with industry activities. In the current environment, there is still significant funding from the federal government (particularly for military applications), but this is changing rapidly as consumer applications become more prevalent. Reliability challenges are significant in both domains. To address reliability, work is needed in mechanical design, control verification, software certification, environment modeling, etc.

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### UU: teaching robots to Understand situations and reason about Uncertainties

*What do you see as particular research areas that stand to benefit more from the collaboration of AI and robotics researchers?*

Probabilistic (manipulation) planning that takes into account the particularities of physical environments (as distinct from computer ones), namely:

- Actions not just have stochastic outcomes and associated costs, but may be irreversible (dead-ends), dangerous or have unpredictable effects.

- Actions to gather knowledge may supply noisy observations.

- World and robot states may be partially-known and dynamic, both intrinsically and by the action of other agents.

- State and motion spaces are continuous, thus provisions to link symbolic and actuator levels are needed.

Human-assisted (incremental) learning is crucial for robots to adapt to particular users and environments. In particular,

- Learning from demonstration would permit robots to be taught by laymen.

- Symbolic (task) learning and skill (motion) learning need to be integrated.

- Robot exploration is costly, thus failures/underperformance should be diagnosed in a way that permits providing guidance to the user as to what knowledge (cause-effects, actions) is missing to complete a task.

Knowledge-based (semantic) reasoning would allow robots to "understand" what is going on and thus enable them to cope with unforeseen situations. This includes:

- Semantic scene/situation understanding.

- Standardized object and procedural knowledge representations.

- Mechanisms for sharing knowledge and extracting it, e.g., from the web.

References showing my more detailed views on these topics can be found in: C. Torras: Robot manipulation in human environments: Challenges for learning algorithms, in "Robots Learning from Experiences", Dagstuhl Reports, vol. 4-2, pp. 99-101 (2014) as well as our recent contributions to AAAI'15, AIJ special issue "AI and Robotics", and EAAI-15.

*What particular activities could bring these communities of researchers together?*

- Robotics tracks, contests and activities at AI conferences, such as those at AAAI.

- Workshops on AI topics at Robotics conferences, such as ICRA and IROS, and vice versa.

- International Probabilistic Planning Competitions at ICAPS could become a very effective and productive meeting place if more realistic robotics problems were included.

*Do you have recommendations such as possible challenge problems, or task-force activities which could solidify various efforts?*

I particularly like the challenges and format of the RoboCup@Home initiative.

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### Position Paper — Some Thoughts on Intelligent Robots

*What do you see as particular research areas that stand to benet more from the collaboration of AI and robotics researchers? What specic problems do you feel lie at the boundary between AI and robotics? How can these be tackled, and the boundary pushed?*

**Connected Goals** I believe that AI aims at actually creating articial intelligent artifacts, such that an "intelligent" robot is inevitably an AI creature. Hence I see AI and robotics as very intertwined, and not easily separated. But there seems to be a common understanding that AI is more about the ability to represent knowledge and to reason, without the need to analyze the acquisition of knowledge by sensory machinery, and without the need to actually actuate decisions produced by the reasoner. In my experience with autonomous robots, all solutions to the perception-cognition-action loop include AI approaches to representation and planning. Intelligent mobile robots may have the core need to represent spatial features of an environment and reason about the spatial knowledge and make decisions about motion and actuators. For example, our CoBot robots need to have a map representation of buildings, proceed with route planning, and actually move in the space. As mobile robots become more intelligent in their tasks, other modalities of knowledge need to be represented, to enable capabilities beyond intelligent mobility, such as interaction through language, access to the information available on the web, record, analyze, and build upon past experience. It seems that aiming at having true intelligent robots brings together all of the core AI research.

**Planning Models and Execution** Thinking about planning as a research area, we should note that that planning algorithms that aim at solving very complex problems (with deterministic or probabilistic state representations) are not necessarily the task or motion planning algorithms that mobile robots use. Intelligent robots are able to plan routes and solve specic planning problems that are not worst-case scenarios of the general class of NP-hard planning problems. And in robotics, optimal solutions may not always be needed. In some sense, the planning problem in robotics is a problem of planning with an incremental level of detail, as the planning models inevitably cannot accurately capture the uncertainty of an environment. Robots can effectively plan with varied levels of detail, in which the planner uses models (usually probabilistic) as accurately as possible for the short immediate planning needs and then it relaxes the models to plan for future decisions all the way to the goal. One can say that we need different planning models and algorithms as a function of the accuracy of the available models of the environments where execution of the plans will proceed. Highly dynamic and adversarial environments offer very different planning

challenges than static, even if probabilistic, models. Planning has always been seen as a research area that bridges AI and robotics. Intelligent robots need planning, execution, and learning from experience.

**Purposeful Perception** Planning in robotics is highly dependent on the known models of the environment and the ability to extract "state" from the sensory machinery. Extracting information from sensory data is of crucial importance for reasoning. Perception (sensory processing and interpretation) and the signal-to-symbol problem are well known difficult problems addressed by robotics researchers. If a robot cannot extract the needed state (e.g., where is the ball? am I in front of GHC 7002?) from its sensors, it cannot make and execute planning decisions. An intelligent robot that can be driven by goals and tasks and actuation and learning from the environment can proceed with "purposeful perception," in which the robot may need to find my keys in the environment, but the actions that it will need to perform on the keys (pick them up, just announce that it found them, check if a particular key is there) lead into very different sensing and perceptual needs. Such perception is not only a property of the object to be found, but also of the action to be performed on the object. Purposeful perception is an area that would bridge AI and robotics.

**Symbiotic or Resourceful Autonomy** Because we increasingly aim at intelligent robots that perform tasks, also in human environments, we are naturally addressing AI and robotics areas. Intelligent robots now can make use of all the information available on the web and can interaction with humans in a symbiotic way. Basically, we can now restate the Newell-Simon problem solving paradigm in terms of having a complete state and a complete given set of actions. The new problem solving for AI includes being able to actively gather information as needed to solve a problem. The intelligent robot does not to be "given" all the information, it can acquire it as needed.

Robots then need to process and make use of an increasingly broad type of data, e.g., images, language, all formats of text, graphs. The main question for me seems to be to redefine autonomy as having an intelligent robot being able to be embedded in the physical and knowledge environment with the ability to use its own onboard sensors, planning and execution processes, as well as proactively ask for help from all sorts of available external sources, e.g., humans, web, other robots/sensors, past experience. We can pursue research towards such "symbiotic, or resourceful autonomy."

*What particular activities could bring these communities of researchers together? Do you have ideas for the way the various stakeholders such as funding agencies, professional organizations and individual researchers should play a role?*

**Reading/reviewing Joint Sessions** All the ongoing initiatives are of great value — workshops, invited talks, demonstrations, tutorials. An additional initiative could be joint reading/reviewing papers sessions at AAAI and other robotics conferences. For example, a set of papers would be selected to be read and reviewed by both AI and robotics researchers. The goal would be for core AI (robotics) papers, whose authors believe their work to be of

relevance to robotics (AI), to be read and questioned by robotics (AI) researchers.

**Passioned Specialization and Integration** Overall it seems to me that the challenge is on having people specialize in their own passioned research and still being able to understand how their research can be of relevance and of use to the ultimate goal of building an autonomous intelligent real articial creature. We face both a problem and discipline understanding, as well as an integration challenge.

*Do you have recommendations such as possible challenge problems, or task-force activities which could solidify various efforts?*

- A mobile robot navigating in any indoor environment, interacting with people, who can call 911, when needed, and assist the emergency in collaboration with humans.

- A mobile robot that can perform tasks in any house, by relying on its own capabilities and asking for remote help for things that it can do. Such robot should be able to perform all the tasks that a human, with the same hardware capabilities (wheels, not bending, limited arms and hands), would be able to do in the same environment.

- A mobile robot that can be taught through natural language to do tasks based on the composition of their built-in skills and primitives. Teaching and correcting a dance, a task, the way to interact with people.

- Given an unknown robot, write a computer program (or have a human) interact with the robot to nd out what the robot can do (its actions, goals, policies, plans).

- Given a set of unknown robots, write a computer program (or have a human) interact with the robots to nd out what the multiple robots can do, alone or together (their actions, their goals, their policies, plans).

- An experiment for 10 years, with mobile robots that continously and robustly actually live in different environments. Suppose that we would make N CoBots (or other service robots) available to be in K different environments, staying there for the next 10 years, interacting with other people and researchers with a variety of research interests (who would publish their results as papers and on the cloud). What would such robots become and be 10 years from now?

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One of my efforts to break down the boundaries between AI and Robotics is through my recent teaching effort. Starting in January 2015, my group began to teach an intense 3 week, 60 hour crash course in autonomous systems. The course teaches AI like a robotics course, where a set of reasoning methods are combined into a single executive that students use to control quad copters, in order to confront a pressing societal challenge — protecting civilization from alien invasion