Evaluating Cognitive Architectures for Intelligent and Autonomous Unmanned Vehicles

Lyle N. Long and Scott D. Hanford

The Pennsylvania State University
229 Hammond Building, University Park, PA 16802
lnl@psu.edu and sdh187@psu.edu

Introduction

Unmanned vehicles (air-, ground-, and sea-based), or mobile robots, have become increasingly important for both civilian and military applications and both intelligence and autonomy are important for these vehicles and their continued success. Many of these vehicles, however, currently require significant human supervision. For example, the Predator and GlobalHawk are essentially remotely piloted aircraft and the ground vehicles that completed the DARPA Grand Challenge displayed impressive autonomy, but had very little onboard intelligence. Under-water vehicles and mobile robots used for planetary explorations could also benefit from increased intelligence and autonomy due to the delays and limited bandwidth typical of communication with these robots.

Using cognitive architectures in these systems presents an intriguing possibility for developing unmanned vehicles that can behave both intelligently and autonomously. It is extremely difficult, however, to compare the use of cognitive architectures for unmanned vehicles since the architectures have seldom been applied to the same problem or vehicle. Most of them are very difficult to use and different architectures may not be well suited to work on the same problems. This represents a significant barrier for someone who has limited experience with cognitive architectures and is interested in selecting an architecture to implement on an unmanned vehicle. We recently reviewed several possible software systems (Long et al. 2007) for unmanned vehicles. We have also recently documented our use of an intelligent controller in unmanned air vehicles (UAVs) (Sinsley et al. 2007, Miller et al. 2007).

What are the criteria for evaluation?

When selecting a cognitive architecture for an unmanned vehicle, the criteria will be quite different than the criteria that are important for projects that use cognitive architectures for other purposes, such as modeling human behavior. For unmanned vehicles, the applicability of the architecture to real-time systems is more important than features of the architecture that are important for its models to be able to predict data from psychological experiments. In fact, for unmanned vehicles, it is often valuable if the software can perform at levels above human processing speed (i.e. superhuman behavior can be desirable).

Intelligence and autonomy are desirable characteristics for unmanned vehicles and the ability of an architecture to support these characteristics is perhaps the most important criteria for which to evaluate potential approaches. It is important to distinguish between intelligence and autonomy, especially since there is still some debate about the definitions of these terms. Definitions of intelligence and autonomy that are useful for describing these traits in unmanned vehicles are given here as examples. Gottfredson (1997) states that:

> "Intelligence is a very general mental capability that, among other things, involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience."

Bekey (2005) proposes that:

> "Autonomy refers to systems capable of operating in the real-world environment without any form of external control for extended periods of time."

This definition of autonomy has an "emphasis on behaviors (Bekey 2005)."

Along with these definitions, Figure 1 helps illustrate how intelligence and autonomy are two distinct characteristics. It is possible for fairly unintelligent systems to be autonomous (e.g. an earthworm) and there are fairly "intelligent" systems that are not autonomous (e.g. a supercomputer). Supercomputers offer the promise of intelligence due to their massive computing power, which is now almost equivalent to human brains (Long and Gupta 2005 and Gupta and Long 2007). A good example of a system that is not intelligent or autonomous is a traditional radio-control (R/C) aircraft. Humans, of course, are very autonomous and very intelligent.

An intelligent and autonomous unmanned vehicle will need to incorporate the capabilities described above along with sensing, perception, collaboration, and communication in complex, dynamic environments. Some of the key criteria for an architecture to permit these capabilities in an unmanned vehicle are described here:

- It is vital that an architecture be easy to interface to external environments through a large number of sensors (inputs) and motors/servos (outputs). A successful architecture will likely need to use numerous sensors to obtain information about the vehicle and its surroundings and then use this information to make intelligent decisions about its behavior. For comparison, humans have more than 10^8 sensory inputs in each eye, 10^4 in each ear, and 10^4 for taste (SfN Brain Facts 2006). The sensor inputs can sometimes be noisy with large errors, so fuzzy logic can be beneficial (both in humans and in robots). Due to the need for large numbers of sensors and motors/servos, scalability is also very important.
- A mix of reactive, deliberative, and reflective behaviors: For vehicles to operate in real world environments, they need to be able to act quickly and instinctively (e.g. for obstacle avoidance) as well as reason about both their current performance and long-term behavior and plan future actions (maybe in consultation with other vehicles/robots).
- Learning is a very important component of intelligence and crucial for autonomous vehicles, since programmers cannot anticipate all possible scenarios that a vehicle will encounter. Ideally, learning would allow the vehicle to become more capable as time progresses. It would also be beneficial to be able to share this learned knowledge with other vehicles/robots.
- Collaboration: Unmanned vehicles will be most interesting and useful when there are many of them networked and working together (communicating and collaborating). The DOD defines 10 levels of autonomy (DOD Roadmap 2005) as shown in Figure 2, some of which include collaborative tasks (group coordination, group replanning, and group strategic goals). It will be important to have cognitive architectures that are able to work with multiple systems. Current small, inexpensive UAVs (e.g. Sinsley et al. 2007) are capable of Level 5 autonomy now.
- Unmanned vehicles will also have many other software components, in addition to the cognitive software. For example, our UAVs have onboard autopilots for inner-loop control. In addition, the vehicles have software for processing sensor data (e.g. neural networks or signal processing). The use of multiple software components will require the cognitive software to effectively and reliably interact with these other onboard software (and hardware) components, which may be running in a real-time operating system.

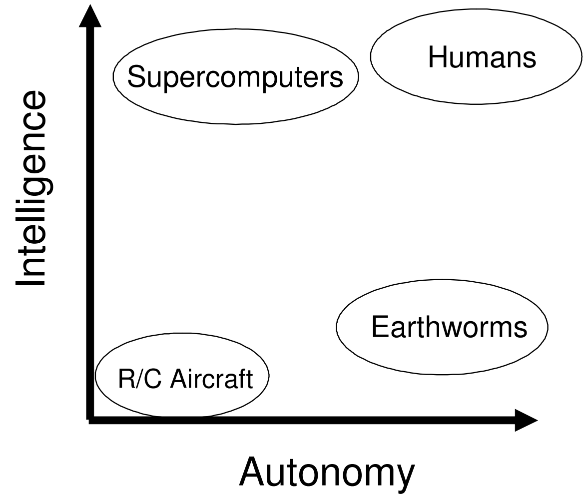

Figure 1: Intelligence vs. Autonomy

- To help make these unmanned vehicles as inexpensive as possible, there is a need for reliable open-source software (but certification will be an issue). Also, access to freely available architectures will allow researchers the opportunity to inexpensively experiment with several architectures.
- Since developers of unmanned vehicles interested in using cognitive architectures may not have much experience with these architectures, the ease of use of the architecture is an important selection criterion. The availability of tutorials and access to a community of more experienced users (e.g. as those currently available for Soar and ACT-R) is also very valuable.

How are architectures to be compared in an informative manner?

Two types of efforts have been made to compare cognitive architectures for applications other than unmanned vehicles: reviews of architecture features and experiments comparing different architectures. There have been several reviews of aspects of cognitive architectures that are important for behavior in simulations (Pew and Mavor 1998, Ritter et al. 2002, and Fletcher and Morrison 2007). The AMBR (Agent-Based Modeling and Behavior Representation) project used a common simulated environment to perform a direct comparison of four architectures performing air traffic control tasks that involved multi-tasking and learning (Gluck and Pew 2005). Efforts similar to these that focus on comparing aspects of cognitive architectures that are considered most important for unmanned vehicles would be a valuable resource for someone interested in selecting an architecture to implement on an unmanned vehicle. Such a project could also identify areas to improve these

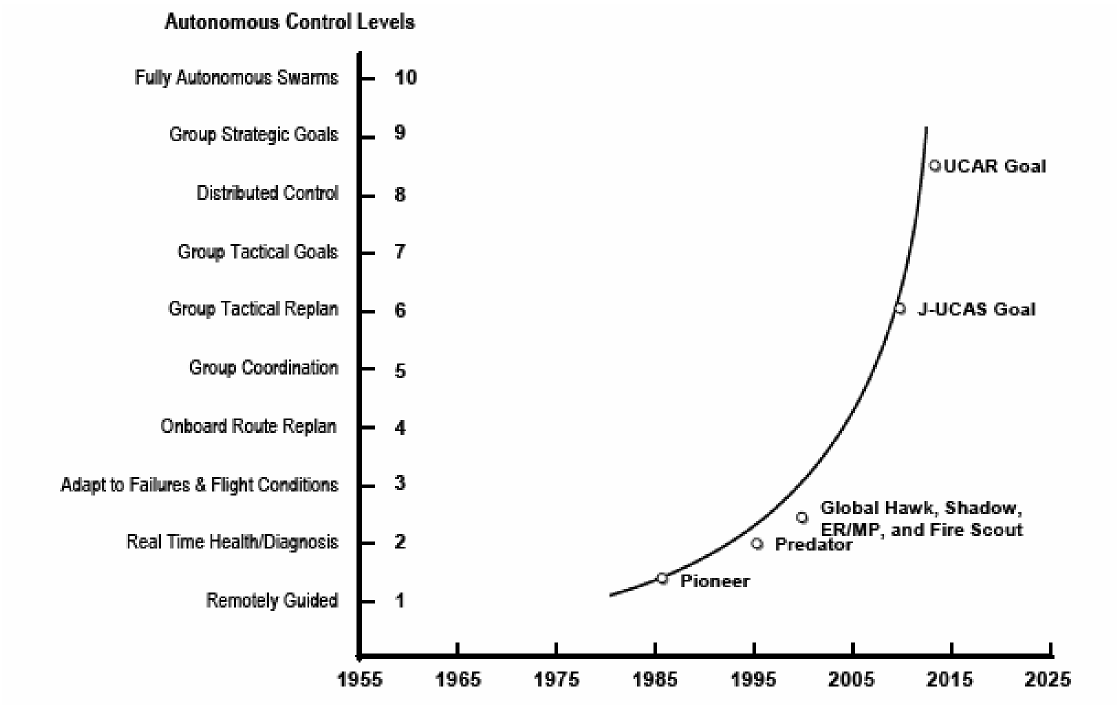

Figure 2: DOD Levels of Autonomy
[http://www.fas.org/irp/program/collect/uav_roadmap2005.pdf]

architectures for unmanned vehicles. It could be useful to compare both established cognitive architectures and architectures developed recently specifically for robotics such as ADAPT (Benjamin, Lyons, and Lonsdale 2004) and SS-RICS (Kelley 2006).

Long et al. (2007) compared several different software packages for use on unmanned vehicles. Some of the key characteristics considered were: learning, ease of sensor input, possibility for collaboration, and other features. None of the packages reviewed were ideal, but some of them have several desirable features. At the present time, Soar, ACT-R, and SS-RICS all seem to be interesting possibilities for the control of robots.

Perhaps the most useful method for comparing architectures for use in unmanned vehicles would be to specify a mission scenario or a Concept of Operation (ConOps) (Ammala 2000) to be performed by multiple architectures controlling the same vehicle using the same hardware and sensor suite. A similar approach of testing software from several research groups on the same vehicle for the same mission was used for the DARPA Learning applied to ground vehicles (LAGR) project (Jackel et al. 2006). The mission would be most informative if, like the task for the AMBR project, it challenged the capabilities of the cognitive architectures, such as emphasizing collaboration, learning, and sensor/data fusion. A search and rescue mission with multiple collaborating vehicles and multiple sensors (GPS, lasers, audio, vision, etc.) over complex terrain might be a useful scenario.

Systems Engineering

These intelligent and autonomous unmanned vehicles will be very complex *systems*, with multiple processors, numerous sensors, numerous motors/servos, and layers of software. In fact, multiple vehicles will make up a *system of systems*. The cognitive software will be just one part of the software in these systems. We need to consider hybrid systems that may include approaches from all areas of computational intelligence, e.g.:

- Cognitive architectures
- Neural networks
- Genetic algorithms
- Fuzzy logic
- Symbolic processing

Thus it is important to think about these systems from a systems engineering perspective. It is likely that a truly intelligent and autonomous mobile robot will use all the above approaches coupled to sophisticated sensor and motor systems. In addition, while there has been increasing interest in *consciousness* (e.g. LeDoux 2002, Dennett 1991, and Koch 1999), it is unlikely that any human-built system will exhibit consciousness until it is a system with the intelligence, sensory input, and motor control on the order of a mammal.

Software Engineering

Autonomous vehicles will eventually be used in safety-critical or mission-critical applications, and so the cognitive architecture software may require the same level of rigorous software engineering (Sommerville 2007) and standards that are used in current aircraft (e.g. FAA/RTCA DO-178B or ISO 12207). No existing cognitive architectures have been developed to these strict standards. Validation and Verification will also be an important, yet difficult, aspect of the development of these systems. Testing all possible software components may not be possible, which means formal methods may be especially important in certifying the vehicle software. The need for research and education in software development is crucial as these systems become more and more complex (Long 2007). Most engineers and scientists are not properly trained in professional software engineering approaches, yet are expected to develop software.

Conclusion

Cognitive architectures promise dramatic performance and capability improvements for unmanned air-, ground-, and sea-based autonomous vehicles. While this is not a traditional application of cognitive architectures, it is an area where they could have a profound effect. It is quite important to evaluate the suitability of existing architectures, as well as plan for the development of new ones. Robots controlled using cognitive architectures are now being developed, but it will take many more years before they fulfill their real promise.

References

Ammala, D. “A New Application of CONOPS in Security Requirements Engineering.” CrossTalk Journal, Aug., 2000.

Bekey, G.A. Autonomous Robots: From Biological Inspiration to Implementation and Control. The MIT Press, 2005.

Benjamin, D.P., Lyons, D., and Lonsdale, D. “Designing a Robot Cognitive Architecture with Concurrency and Active Perception.” Proceedings of the AAAI Fall Symposium on the Intersection of Cognitive Science and Robotics, Washington, D.C., October, 2004.

Brain Facts: A Primer On The Brain And Nervous System, Society for Neuroscience, www.sfn.org, 2006 (www.sfn.org/skins/main/pdf/brainfacts/brainfacts.pdf).

Dennett, D.C. Consciousness Explained. Back Bay, Boston, 1991.

DOD Unmanned Air Vehicle (UAV) Roadmap, http://www.fas.org/irp/program/collect/uav_roadmap2005.pdf, 2005.

Fletcher, J.D. and Morrison, J.E. “Representing Cognition in Games and Simulations.” In E. Baker, J. Dickieson, W. Wulfeck and H. O'Neil (Eds.), Assessment of Problem Solving Using Simulations. Lawrence Erlbaum Associates, 2007.

Gluck, K.A. and Pew, R. (Eds.). Modeling Human Behavior with Integrated Architectures: Comparison, Evaluation, and Validation. Lawrence Erlbaum Associates, 2005.

Gottfredson, L.S. “Mainstream Science on Intelligence: An Editorial With 52 Signatories, History, and Bibliography.” Intelligence, Vol. 24, No. 1, 1997, pp. 13-23. [also appeared in Wall Street Journal, Dec. 13, 1994.]

Gupta, A. and Long, L.N. "Character Recognition using Spiking Neural Network." to be presented at the IEEE Neural Network Conference, Orlando, Florida, Aug. 12-17, 2007.

Jackel, L.D., Krotkov, E., Perschbacher, M., Pippine, J. and Sullivan, C. “The DARPA LAGR Program: Goals, Challenges, Methodology, and Phase I Results.” Journal of Field Robotics 23(11/12), 945–973 (2006).

Kelley, T.D. “Developing a Psychologically Inspired Cognitive Architecture for Robotic Control: The Symbolic and Subsymbolic Robotic Intelligence Control System (SS-RICS).” International Journal of Advanced Robotic Systems, Vol. 3, No. 3 (2006), pp. 219-222.

Koch, C. Biophysics of Computation. Roberts and Company, 1999.

LeDoux, J. Synaptic Self. Penguin, New York, 2002.

Long, L.N. “The Critical Need for Software Engineering Education for Aerospace Systems.” to appear Crosstalk Journal, 2007.

Long, L. N. and Gupta, A. "Scalable Massively Parallel Artificial Neural Networks." AIAA Paper No. 2005-7168, AIAA InfoTech@Aeropace Conference, Sept., 2005, Wash., D.C.

Long, L.N., Hanford, S.D., Janrathitikarn, O., Sinsley, G.L., and Miller, J.A. "A Review of Intelligent Systems Software for Autonomous Vehicles." IEEE Symposium Series in Computational Intelligence, Honolulu, Hawaii, April 1-5, 2007.

Miller, J.A., Minear, P.D., Niessner, Jr., A.F., DeLullo, A.M., Geiger, B.R., Long, L.N., and Horn, J.F. "Intelligent Unmanned Air Vehicle Flight Systems." Journal of Aerospace Computing, Information, and Communication (JACIC), May, 2007.

Pew, R.W., and Mavor, A.S. (Eds.). Modeling Human and Organizational Behavior: Applications to Military Simulations. Washington, DC: National Academy Press, 1998.

Ritter, F.E., Shadbolt, N.R., Elliman, D., Young, R., Gobet, F., and Baxter, G.D. Techniques for modeling human performance in synthetic environments: A supplementary review. Wright-Patterson Air Force Base, OH: Human Systems Information Analysis Center, 2002.

Sinsley, G.L., Miller, J.A., Long, L.N., Geiger, B.A., Niessner, Jr., A.F., and Horn, J.F. "An Intelligent Controller for Collaborative Unmanned Air Vehicles." IEEE Symposium Series in Computational Intelligence, Honolulu, Hawaii, April 1-5, 2007.

Sommerville, I. Software Engineering. 8th Ed., Addison-Wesley, 2007.