The Autonomous Systems Tidal Wave

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Unmanned systems technology has advanced significantly from Nikola Tesla's 1898 radio-controlled model boat. Yet, today's remotely operated systems remain coupled to human operators, limiting the systems' performance, reach, and impact. To extend unmanned system capabilities, Lincoln Laboratory has been actively pursuing research and development in autonomous systems—the focus of this special issue.

» **Arising from decades of Department** of Defense (DoD) research in advanced computer networking, the Internet of 20 years ago had matured to a state at which nascent commercial activity would begin to prove the economic value of the technology. A deluge of investments soon followed, further advancing Internet technology and reach to realize its present global impact. Autonomous systems, which employ software intelligence to achieve objectives in complex environments without continuous human input, are now at a similar inflection point: commercial entities are starting to leverage DoD-supported research in autonomy algorithms and robotics technologies for manufacturing, logistics, transportation, and health-care applications. The potential economic value of autonomous systems suggests that, like the Internet, early commercial successes will lead to compounding growth in investments and thus far-reaching advances in capabilities. The coming autonomous systems era will have a profound impact on all aspects of society, including national security and disaster response, by reducing risks to human personnel, increasing efficiency, and enhancing mission performance.

While a rigorous taxonomy is elusive, autonomous systems can be generally categorized by their operating environment. Autonomous systems "at rest" operate in a virtual environment, processing a large volume of archived and streaming data to inform human decisions, such as providing diagnoses for challenging disease cases, or to take cyber actions, like defending against an active network attack. "In motion" autono-

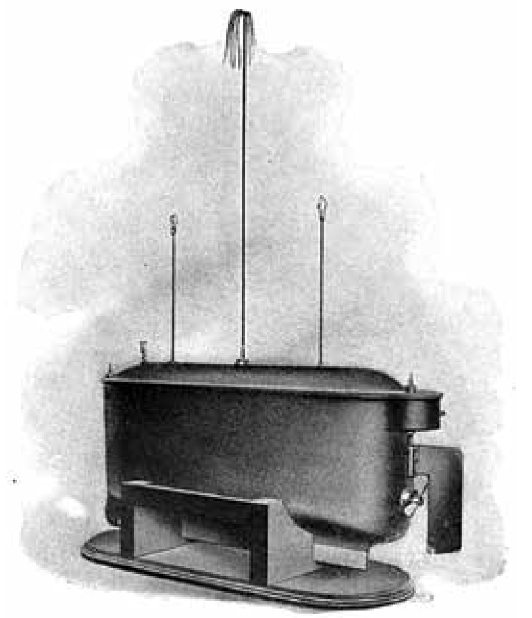

FIGURE 1. In addition to a radio antenna (center), Tesla's iron-hulled radio-controlled model boat included a pair of elevated lights to assist an on-shore operator with keeping the vessel on course at night [2].

mous systems, which are the focus of this issue, perceive and act in a physical air, land, maritime, or space domain. Since antiquity, humans have imagined the utility of "in motion" autonomous systems to augment human labor or perform dangerous tasks. However, it was not until the advent of unmanned systems in the 20th century that the operational value of remote agents was realized.

Remotely Operated Unmanned Systems

In 1898, Nikola Tesla demonstrated the world's first wireless remotely operated unmanned system [1]. The four-foot-long electrically powered model boat (Figure 1) used a coherer (a primitive radio signal detector) and electromechanical logic to sequentially rotate, stop, and reverse the rudder to turn the vessel in response to radio pulses from a human-operated control box. Recognizing its asymmetric potential, Tesla proposed using his invention as a land-launched naval torpedo that would prevent future wars by deterring the mightiest of battleships from occupying a harbor. Perennially ahead of his time, Tesla failed to convince the U.S. Navy to support development of his idea. Soon thereafter, other pioneers extended radio-controlled technology to full-size maritime vessels (J.H. Hammond Jr., 1911) [2], airships (A.J. Roberts, 1912) [2], and aircraft (A.M. Low, 1917) [3]. The operating range, sophistication, and reliability of remote-control systems have advanced significantly since the early 1900s, with present-day unmanned systems routinely performing national security missions in land, air, and maritime domains (Figure 2).

Despite these advances, modern unmanned systems depend on nearly constant human control and supervision—a remaining vestige of Tesla's invention. Reliance on remote human operators limits the reach, performance, impact, and manpower efficiency of unmanned systems. The need for low-latency, high-bandwidth, and high-availability data links to transmit commands and telemetry precludes unmanned operation in areas where communication signals are unavailable, congested, or denied by adversaries. Current systems typically require the full attention of one or more operators and, in hostile environments, additional personnel to provide overwatch. Furthermore, human reaction time, communication latencies, and the sparse nature of situational awareness conveyed over a computer screen constrain unmanned system performance, particularly in dynamic environments. While continued improvements in remote-control technology can mitigate some of these limitations, an alternative control paradigm is needed to operate unmanned systems in challenging environments and to support new missions across a range of domains.

Autonomous Systems

The inherent limitations of teleoperated systems are overcome by providing machines with autonomy, i.e., the ability and authority to execute self-directed actions in response to observations of the environment in pursuit of human-directed objectives. By decoupling a human operator from every control decision and leveraging the speed of digital computation, an "autonomous system" gains significant operational advantages beyond remotely controlled systems; these advantages include

- Access. With reduced reliance on communication and navigation signals, autonomous systems can access environments in which these signals are limited or un-

FIGURE 2. Today's remotely operated systems perform missions in the air, on the ground, and at sea. Like Tesla's model boat, most systems depend on nearly continuous human control and supervision.

available, such as inside structures and rubble, under canopy, and within contested regions.

- Force amplification. Autonomous systems can enhance the effectiveness of individuals and teams by reducing the burden of routine tasks, freeing personnel to concentrate on activities that specifically require human judgment or social interaction. For example, soldiers riding in a convoy of self-driving vehicles, such as the one highlighted in the "Automation of Armored Four-Wheel-Counter-Steer Vehicles" article, can focus on providing security rather than driving.
- Agility. Capable of rapid decision making and coordination, autonomous systems can effectively respond to highly dynamic environments and threats.
- Scalability. Growth in human-controlled systems is limited by the availability of personnel and the time needed for their training—factors that are difficult to change quickly. In contrast, autonomous systems can be rapidly produced and deployed in large numbers to, for example, assist search and rescue teams responding to an unexpected natural disaster.

Autonomy

While the term autonomy often invokes philosophical notions of complete independence from external control, the autonomy actually granted to an autonomous system is bounded by both design and the limitations of the underlying technology. Although most effectively described in the context of a specific mission and human-machine team [4], the bounds of a system's autonomous capability can be generally characterized along three dimensions: degree of independence from human control, complexity of the task or mission, and predictability of the environment.

An effective autonomous system's degree of independence from human control depends on the mission and objectives. A rescue robot rapidly searching a burning building for victims may only need to be autonomous for seconds at a time to avoid hazards while a firefighter provides it with frequent high-level directions. Alternatively, an environment monitoring robot may prove burdensome if it requires weekly guidance. In other systems, the frequency and nature of human interaction may be adapted dynamically; an adjustable autonomy architecture for a natural disaster relief scenario is discussed in the "Autonomous Robot Control via Autonomy Levels" article in this issue.

Figure 3 depicts autonomous capability as a function of task complexity and environment predictability. Typical industrial robots, for example, perform complex

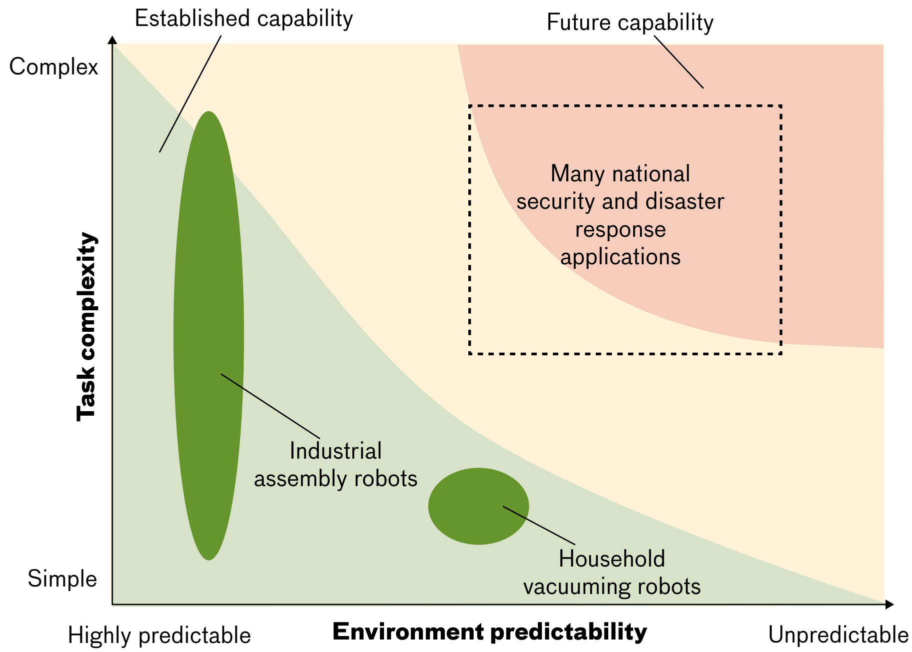

FIGURE 3. Today's operational autonomous systems can perform simple tasks in semi-unknown environments or complex tasks in well-known environments. Many anticipated national security and disaster response applications for autonomous systems demand complex task execution in largely unknown environments. Task complexity and environment predictability are just two dimensions describing the capability of autonomous systems. Other dimensions include frequency of human input, i.e., teleoperation to long-term independence, and task uncertainty.

functions, such as product assembly and packaging, but can only operate in well-known or controlled environments. Because these robots rely heavily on preprogrammed actions, they lack the ability to respond to unexpected situations. On the other hand, a vacuum cleaner robot carries out a relatively simple assignment but can do so in semi-unknown environments with large variations in room shape, size, and contents. The simple behavioral rules that guide the vacuuming robot's navigation (e.g., turn to a random direction after bumping into a wall) are sufficient to accomplish the floor-cleaning task but are difficult to extend to objectives with performance constraints or interdependent steps. Other approaches beyond preprogramming and straightforward behavioral rules are needed to develop autonomous systems capable of performing complex tasks in unknown environments—a capability required for many national security and disaster response applications.

Developing the autonomy needed for systems to reliably carry out useful work in relevant mission environments is challenging. An autonomous system may need to parse a large quantity of heterogeneous data; extract critical information from those data; develop and update a model of the task, environment, and its own internal state; conceive and evaluate plans relative to goals defined by humans; coordinate actions with other robots and human teams; command actuators to execute plans; assess its own performance; and adapt future behavior. Although control systems, statistics, computer science, cognitive science, and other disciplines have provided a strong foundation for developing autonomous systems, finding solutions for achieving higher levels of autonomy has required focused autonomous systems research conducted over the past half century.

Synthesis of Autonomy

Research efforts have advanced the understanding of autonomous systems science and produced approaches for synthesizing autonomy with artificial intelligence algorithms. These efforts, along with developments in computation, sensing, energy systems, and algorithms, are supporting the transition of advanced autonomy from research institutions to the field.

Computing Hardware

The exponential increase in computational capacity per unit cost, volume, and power (i.e., Moore's Law) over 50 years has enabled a new golden age of artificial intelligence as some of the difficult problems from the past have become tractable today. Processors with 1000s of parallel cores can compute parameters for neural networks at a scale that was unimaginable 10 years ago. Advances have also decreased the size and power needed for computation. For example, the processing capacity of a computer cluster used to perform perceptive off-road vehicle navigation in 2005 [5] is equivalent to that of a present-day laptop. Furthermore, computer-based autonomy is not limited to the processing available on board an autonomous system. The Shared Perception for Autonomous Systems program described in this issue seeks to use off-board, networked computation and data resources to support autonomy on small platforms.

Software and Algorithms

In parallel with hardware advances, the algorithms underlying autonomy are continually improving. Consider how robotic mapping algorithms have evolved: initial algorithms, dating back to the 1990s and early 2000s, were limited to mapping small spaces no larger than individual rooms [6]; algorithms are now capable of city-scale mapping [7]—an increase in scale far outpacing improvements in computation over the same time period. Lincoln Laboratory researchers have leveraged this progress, using tactical unmanned ground vehicles to map indoor sites suspected of chemical contamination (see the “Robotic Sensitive-Site Assessment” article). Planning algorithms have also advanced significantly. The “Automated Dynamic Resource Allocation for Wildfire Suppression” article describes the development of planning algorithms capable of exploring state and action spaces that are many times larger than those explored in previous approaches. Additionally, machine learning approaches, which employ large datasets to train an algorithm’s parameters, now rival human performance at narrow tasks, such as image classification.

Platform Technologies

To observe, move through, and manipulate the environment; exchange information with other systems; and interact with human commanders and teammates, autonomous systems “in motion” require advanced sensors, human-machine interfaces, communication systems, power sources, and other constituent technologies. The capabilities of these enabling technologies are also rapidly advancing. For example, Lincoln Laboratory and MIT researchers are developing an energy source to improve unmanned underwater vehicle range by a factor of 10 (see the “Aluminum-Water Energy System for Autonomous Undersea Vehicles” article).

The Future of Autonomous Systems

Supported by the DoD, research in academia, industry, and research laboratories has yielded demonstrations of incremental and leap-ahead autonomous systems capability. In addition to the work highlighted in this issue, recent demonstrations include a dozen unmanned surface vessels coordinating to escort high-value Navy ships through a narrow passage [8], an unmanned aerial vehicle performing a carrier-based arrested landing at sea [9], and self-driving vehicles obeying traffic laws as they navigate through an urban environment [5]. Extending these and similar capabilities to routinely support national security needs requires not only continued research in traditional autonomy topics, such as perception, planning, and learning, but also applied research to establish the utility of and trust in autonomous systems in operational settings. Applied research areas include

- Analysis: methodologies, models, and tools to predict autonomous systems’ impact on mission objectives at the conceptual phase of system development
- Validation: new test and evaluation approaches to assess autonomous systems with stochastic and adaptive behaviors
- Sustainment: technologies and processes to support prolonged operational use of autonomous systems
- Security: systems to safeguard autonomous systems from adversarial interference
- Ethics: technologies and policy to ensure advanced autonomy maintains alignment with human interests and values
- Counter-autonomy: technology to detect and mitigate adversarial adoption of advanced autonomy

National security and disaster response operations are currently predicated on human commanders and personnel observing the environment, making decisions, and taking actions to achieve tactical and strategic objectives. In the next 20 years, however, the human monopoly on complex understanding and decision making will diminish for many tasks as autonomy algorithms and computational capacity continue to improve. This transformation may have an unprecedented, and perhaps unimagined, impact on capability, operations, and force composition [4]. Like the Internet of the 1990s, autonomous system technology is likely to be a tidal wave of compounding advances in capability. Leveraging these advances for national security and disaster response will present an incredible opportunity, but also an incredible challenge. ■

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About the Author

Michael T. Boulet is the assistant leader of the Control and Autonomous Systems Engineering Group, where he focuses on applying autonomous systems technology to address challenging national security problems. He has helped guide the Laboratory's strategic plan for and applied research investments in robotics, autonomy, and human-robot interaction. In his previous role as a technical staff member, he developed perception and control algorithms for a variety of robotics research and prototyping efforts in the ground and air domains. An enthusiast of open-source robotics software, he created the Rapid Robotics and the Rapid Autonomous Complex-Environment Competing Ackermann-steering Robot (RACECAR) courses for MIT's Independent Activities Period, with the goal of introducing students to advanced autonomous robot capabilities. He joined Lincoln Laboratory in 2001 after graduating from Rensselaer Polytechnic Institute with a bachelor's degree in mechanical engineering. Through the Lincoln Scholars Program, he obtained a master's degree in mechanical engineering from MIT in 2008. He received a 2011 Early Career Technical Achievement Award for designing a strategy for the Laboratory's autonomous systems effort.