AIR FORCE RESEARCH LABORATORY AUTONOMY SCIENCE AND TECHNOLOGY STRATEGY

THOMAS J. MASIELLO
Major General, USAF
Commander

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Introduction

The Air Force Chief Scientist's 2010 Science & Technology (S&T) Vision, "Technology Horizons," identifies the use of autonomy and autonomous systems that will allow the Air Force (AF) to achieve capability increases and cost savings via increased manpower efficiencies and reduced manpower needs. The true potential and value of autonomous systems is not to replace the Airmen, but to build man-machine teams that complement each other and extend the team's capability to perform a mission.[1] Acknowledging the need for further Autonomy S&T as mentioned in "Technology Horizons," the Air Force 2010 S&T Strategy identifies priorities for increased emphasis in the development of autonomous systems and robust situation awareness to enhance decision-makers' understanding and knowledge by improving intelligence, surveillance, reconnaissance (ISR) as well as data planning and direction; collection; processing and exploitation; analysis and production; and dissemination (PCPAD). In 2011, then Secretary of Defense, Robert Gates, issued seven department-level S&T priorities for 2013-2017 which included autonomy. He highlighted the need to develop and demonstrate autonomous technologies that reliably and safely accomplish complex tasks in all environments.

Air Force autonomy and autonomous systems refers to a range of machines and systems that include unmanned aircraft, satellites, weapons, information technology (IT), and the many sub-systems within each. Autonomous technology also includes tools for ISR analysis, campaign and mission planning, and communication. To date, the AF has developed and fielded technologies with different levels of autonomous functionality. Yet no single application has reached a level of "full" self-government/self-direction.

Many times, autonomy and automation are used interchangeably. These terms do, however, have different meanings, and for the purpose of this document each are defined as:

> Automation: The system functions with no/little human operator involvement; however, the system performance is limited to the specific actions it has been designed to do.[2] Typically these are well-defined tasks that have predetermined responses (i.e., simple rule-based responses.
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> Autonomy: Systems which have a set of intelligence-based capabilities that allow it to respond to situations that were not pre-programmed or anticipated in the design (i.e., decision-based responses). Autonomous systems have a degree of self-government and self-directed behavior (with the human's proxy for decisions).

Notionally, automation and autonomy are the two ends of a continuum. In a static environment with a static mission, automation and autonomy converge. However, when dynamic missions take place in dynamic environments, automation can only support a small fraction of autonomy requirements. While the distinction is important, both have utility within various systems. Increased capability of autonomous systems will be a critical component to assure future Air Force power in air, space, and cyberspace within future budget constraints. Therefore, Air Force Research Laboratory (AFRL) leadership commissioned the development of the AFRL S&T

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[1] DoD Defense Science Board, TASK FORCE REPORT: The Role of Autonomy in DoD Systems, July 2012

[2] Spacecraft Autonomy Technology: A Survey. Erwin, R. Scott and Paul Zetocha, AFRL/RV

Autonomy Vision and Strategy to identify the major goals and technical challenges focusing AFRL's Autonomy portfolio investment to discover, develop, and demonstrate warfighter-relevant S&T to enhance air, space, and cyberspace dominance.

AFRL Autonomy Science and Technology Vision for 2020

AFRL seeks to enable the *right balance* of human and machine capability to meet Air Force challenges in the future. We will focus on growing autonomous system capability, integrated with the human capacity to perform in a high-tempo, complex decision environment, and to optimize humans working together with machines both effectively and efficiently. Simply stated, the Autonomy S&T vision is:

Intelligent machines seamlessly integrated with humans - maximizing mission performance in complex and contested environments

Embedded in the vision are the following key concepts tied to example technologies:

- Highly effective human-agent teaming will harness the machine's ability to digest data and the human's ability to deal with uncertainties to improve the system performance
- Multiple agents will actively coordinate their actions to achieve the mission intent
- Systems with enhanced intelligence and self-government will enable operation in complex, contested environments that create challenges exceeding human performance limits

AF Autonomy Program Tenets

AFRL has adapted the tenets identified in the 2010 Air Force S&T Strategy to guide the AFRL Autonomy S&T Strategy:

- Autonomy cuts across AF domains to include air (aircraft and weapons), space, and cyber
- Prepare for highly competitive and contested environments
- Investigate game-changing technologies that advance self-governing and self-directing systems and transition them into military capabilities
- Maintain in-house capability with a diverse expertise to ensure a strong foundation for developing technologies and assessing contractor and commercial advancements in autonomous systems
- Remain vigilant over global science and technology developments and emerging capabilities and technologies that advance autonomous systems
- Leverage the large investments in autonomous system development by commercial (domestic and foreign) entities and other DoD and government agencies. These leveraged investment areas enable more highly focused AFRL investment

Environmental Assessment

Current and future military operations are moving toward greater interconnectivity and reduced timelines, while dealing with the proliferation of technologies across the world. The recent push by the President and Secretary of Defense to shift the Department's focus toward operations in highly contested, anti-access, area denial (A2AD) environments will require, among other things, an unprecedented reliance on autonomous systems to deal with the speed, complexity, and uncertainty inherent within them. This ever greater reliance on autonomous systems is consistent with the vision of the AF's "Technology Horizons."

Success in recent engagements of the autonomous or remotely piloted platforms can be partially attributed to continuous, largely uninterrupted streams of imagery, data, and communications. For future engagements, the AF must assume it will need to maintain operations during times of intermittent, interrupted, and possibly loss of communications with air, space, and cyber platforms.

Autonomous systems must operate rationally in contested environments and still perform missions within commander's intent. These systems must be able to compensate for denied GPS and degraded communication by either completing the mission or executing an acceptable "fall back" response. For non-vehicle systems, the systems must also have the ability to continue communications, analysis, and other operations. Systems must be safeguarded from unauthorized communication and control intrusions via robust security measures.

Autonomous systems will continue to increase in use to provide more capability and protect humans from unnecessary harm. In effect, these systems will provide a "capability-multiplication" such that a set of forces can simultaneously focus and engage adversary aggression in multiple regions. This capability multiplication effect is an enabling approach to the "Deter and Defeat Aggression" mission identified in the DoD's "Sustaining U.S. Global Leadership: Priorities for the 21st Century Defense." [3]

The AF must find ways to remain vigilant and maintain its presence across the globe even in times of shrinking budgets. With decreases in manpower but no commensurate reduction in mission scope, the AF must find ways to effectively execute the mission with fewer people. Tools to analyze and exploit intelligence, surveillance, and reconnaissance data must provide real-time situational awareness without adding, or while decreasing, manpower requirements. Autonomous technologies must ensure mission performance within an acceptable system-user and personnel footprint. The greater use of autonomous systems will support United States forces' ability to execute well within the adversaries' decision loops. Such increases in machine autonomy will require humans and automated systems to work as a team with some level of decision-making delegated to the machine counterpart.

Recent technological developments have been the catalyst for a rapid growth of automation systems and their capabilities. The automotive, agriculture, commercial freight-service, and manufacturing industries, as well as academia, are adopting and driving the state-of-the-art in

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[3] "Sustaining U.S. Global Leadership: Priorities for the 21st Century Defense", Department of Defense, January 2012.

automated technology and capabilities. Autonomous systems and capabilities are becoming commercial products available to the world, and AFRL must vigilantly stay aware of these advances in order to sustain our world-class capabilities.

Currently, systems are tested to demonstrate that they meet requirements (verification) and operate as intended (validation). Autonomous systems are usually intended to operate in situations that were not explicitly envisioned by the system designer. As technologies with greater levels of autonomy mature, the number of test parameters will explode exponentially, becoming virtually infinite. This explosion will make it impractical to verify and validate autonomous systems cost-effectively using current methods. As stated in 2010 S&T Vision, “Technology Horizons,” “it is possible to develop systems having high levels of autonomy, but it is the lack of suitable Verification and Validation (V&V) methods that prevents all but relatively low levels of autonomy from being certified for use."

AFRL Autonomy S&T Strategic Goals

To achieve the autonomy vision in an environment shaped by fiscal constraints and ascending threats, AFRL developed the following strategic goals for S&T autonomy efforts. Achievement of these goals will provide the AF with autonomous system capabilities that enable greater resiliency, capability, and versatility.

Goal #1: Deliver flexible autonomy systems with highly effective human-machine teaming

> ***Enable Airmen and machines to work together, as a high-performing team, with each understanding mission context, sharing understanding and situation awareness, and adapting to the needs/capabilities of the other.***

The keys to maximizing the human-machine interaction are: instilling confidence and trust among the team members; understanding of each member's tasks, intentions, capabilities, and progress; and ensuring effective and timely communication. All of which must be provided within a flexible architecture for autonomy; facilitating different levels of authority, control, and collaboration. This goal has three objectives to enable a high-performing, human-machine team.

1.1. **Enable & calibrate trust between human and machines**: For humans and machines to function as an effective team, there must be an understanding of and confidence in its behaviors and decision making across a range of conditions. This understanding will enable an appropriate level of reliance on, or trust in, each team member for a given situation.

1.2. **Develop common understanding and shared perception between humans and machines:** For humans and machines to have shared understanding, perception, and situational awareness, data and information must be in common languages and transmittable in discernible formats and timescales. Machine transparency enables the human to understand what the machine is doing and why.

1.3. **Create an environment for flexible and effective decision making:** The environment in which the human and machine work together must allow for fluid, free-flowing, and prompt interactions. Hand-off of task execution and decision making must be graceful and flexible. The human must also be able to adjust the level of authority and decision-making given to the machine based on the mission situation and comfort-level of the individual.

Near-, mid-, and far-term targets are as follows:

Targets for Goal #1

	Enable and calibrate trust between human and machines	**Develop common understanding and shared perception between humans and machines**	**Create an environment for flexible and effective decision making**
Near	• Objective measures of human trust in automation	• Operation mission readiness increased thru adaptive, human-system interface	• Measure cyber operator stress and vigilance analysis • Decision making improvements – 2x's with <10% false alarms
Mid	• Trusted autonomy for co-op weapon systems • Competency based training for trusted human-machine interactions	• Cognitive control for increased situational awareness • Autonomous system that augment human performance • Demonstrate multivehicle control	• Flexible & effective decision making improvements - 4x's with <5% false alarms • Improved accuracy/ coverage – 95%
Far	• Trusted autonomy – 1,000's of adaptive collaborating autonomous agents teaming with humans	• Full human-machine shared situation awareness for full spectrum responses	• Flexible, cognitive human/machine decision making

Goal #2: Create actively coordinated teams of multiple machines to achieve mission goals

Intelligent machines that can self-organize into teams and are capable of initiating and completing complex mission tasks (as a team or as individuals).

Today there is little cross-platform interaction or coordination without direct human involvement. Cooperation schemes will allow machines to synchronize activity and information. Systems that coordinate location, status, mission intent, intelligence, and surveillance data can provide redundancy, increased coverage, decreased costs, and increased capability. On-board "intelligence," such that machines can negotiate and operate directly with other machines with or without a centralized planner, is key. Machines will be able to share information efficiently and securely with each other to complete missions in contested environments. This goal has three objectives to build machine capability to autonomously coordinate, cooperate, and collaborate based on mission and commander's needs.

2.1. **Mature machine Intelligence:** The ability for a machine to sense, perceive, plan, decide, and act requires advancements in machine intelligence.[4] For a machine to perceive its environment, it must not just sense it but also be able to extract information. Planning involves task development, sequencing, and future state prediction which will require significant advancements in machine intelligence. Teaching a machine how to select an option, act, and then validate that its selection and action is appropriate is a key part of demonstrating autonomous technologies. For machines to become intelligent, they must have the ability to learn and adapt state, knowledge, behaviors, decision-making processes, and teammate interactions through learning. Knowledge representation and transfer (symbolic and sub-symbolic reasoning) are key areas to develop and mature machine intelligence. The ability to detect, isolate, and reconfigure due to faults means a system can better perform on its own and in concert with other team members.

2.2. **Develop and manage fractionated and composable systems**: Advanced autonomous systems must be able, as individuals and as teams, to analyze their missions, goals, and responsibilities; and decompose them into actionable, individual tasks and functions. They must dynamically organize into a team to effectively perform the mission tasks and to efficiently utilize their collective resources. Test and validation methodologies that prove agents will perform within prescribed boundaries/limits are critical to verify the desired individual and team behavior (Goal #4 details specific objectives for V&V).

2.3. **Develop reliable, secure, interoperable communication:** Communication links that dynamically adapt to operational and situational conditions will enable machine-to-machine operations. This communication must adaptively manage bandwidth to optimize the costs on information transmission, as well as bridge between different communication protocols and standards. In addition, machines must have communication links that can dynamically adapt to operational requirements, demonstrate resiliency to communication degradation, ensure robustness to morphing networks, and adaptively manage bandwidth based on the reliability, pedigree, and value of information flows.

Near-, mid-, and far-term targets are as follows:

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[4] Nikita A. Visnevski and Mauricio Castillo-Effen. "A UAS Capability Description Framework: Reactive, Adaptive, and Cognition Capabilities in Robotics", IEEEAC Paper #1259, Version 4 Updated December 3, 2008.

Targets for Goal #2

	Mature Machine Intelligence	**Develop and manage fractionated and composable systems**	**Develop reliable, secure, interoperable communication**
Near	• Adaptive content analytics • System health awareness • Unsupervised transfer learning in contested environments • Large data mining feature extraction • Collaborative agent communication, distributed control, distributed sensing • Learning compact environment representation	• Collaborative control of 6 or less agents • Sense and avoid for UAS Integration • Space-to-space asset collaboration and cross queuing	• Mission aware routing • Minimally sized protocol for collaborative agent communication
Mid	• Reinforcement Learning scaled to complex real-time problem solving • Activity-based intelligence tools • Transfer learning	• Survivable weapons that can maneuver at high speeds • Airspace integration – autonomous terminal ops • C2ISR planning synchronization for improved timelines <30min • Defensive systems management • Combat systems management • Distributed knowledge transfer to multi-agent autonomous systems	• Communication techniques to enable interoperability
Far	• Exa-scale computing for compressive sampling • Adaptive text analytics • State-aware performance optimization • Trusted autonomous machines • Validation and Verification of autonomous machines • Ad-hoc domain knowledge transfer	• Integrated planning & situational awareness for air, space, and cyber • Agile swarming weapons • 1,000s of adaptive C2ISR collaborating agents • Inspector satellite	• Autonomous air-space-cyber execution & reconfiguration in contested environment

Goal #3: Ensure operations in complex, contested environments

Ensure mission continuation in environments with kinetic and non-kinetic threats.

For all domains, navigating and communicating in complex environments will become more challenging in the presence of kinetic and non-kinetic threats. Future systems must be able to sense the environment and protect themselves and/or adapt to the environment faster than an adversary. Machine intelligence and protection techniques will provide a robust, adaptive, and secure capability. Enhanced dynamic learning will enable systems to identify unfamiliar threats and then adapt and respond as necessary to protect themselves. This goal has two objectives to ensure operations are safe and can continue in dynamic and contested environments.

3.1. **Develop technologies that assure robust system and self-protection capabilities:** Assured, secure, robust communication, surveillance, and navigation are necessary for effective operations in an adversarial environment. Protection techniques for human-to-machine and machine-to-machine communication are essential to maintain operations in contested battlespace and to enable effective responses to a dynamic, unpredictable adversary. For vehicle-based autonomous systems, alternative navigation techniques will enable stand-off operations as well as engagement in GPS-denied or degraded environments. Enhanced communication, surveillance, and navigation capabilities will improve the ability of autonomous systems to self-protect in both physical and cyber realms.

3.2. **Develop technologies that enable situational understanding of the contested environment:** Machines must have the ability to anticipate, sense, and respond to dynamically-changing threats. They will learn from situational and sensor cues to modify their actions in preparation for (or in response to) a wide range of kinetic and non-kinetic threats. Technologies that detect and respond to adversarial manipulation and deception are critical to operations in a contested environment. In addition, the machine must operate safely and competently when human communication is interrupted. The machine will also have an understanding of how and when it can or should communicate its situation to its teammates. Contested environment, Testing & Evaluation (T&E) and V&V, techniques and facilities are critical for ensuring robust machine performance (and are included in Goal #4).

Near-, mid-, and far-term targets are as follows:

Targets for Goal #3

	Develop technologies that assure robust system and self-protection capabilities	**Develop technologies that enable situational understanding of the contested environment**
Near	• GPS degraded/denied navigation for weapons • Laser communication • Laser-assisted imaging and targeting	• Automated Indications & Warning Tool • Discover C2 threats w/<10% false alarm rates
Mid	• Survivable terminal phase: maneuver and maintain very high speeds • Satellites operate autonomously through anomalies and threats	• Tactical Off-Board Sensing - teaming behaviors • Assess effects of full-spectrum force options w/ improved accuracy/coverage • Near real-time awareness of space events
Far	• Extreme agility, compatibility with many and various types of platforms	• Autonomous sensor management/exploitation • Integrated air/space/cyber situation awareness

Goal #4: Ensure safe and effective systems in unanticipated and dynamic environments

T&E, V&V enabling more rapid and cost effective fielding of new technology

To maximize the operational gains of advanced autonomy, design for certification must be accomplished in early requirements development. Through design for certification (formalized design) at the beginning, substantial gains can be realized throughout the development and sustainment lifecycle. In addressing V&V of autonomous systems, several core factors must be addressed: decision-making and logic of the system; ability to handle the unexpected, information integrity, and uncertainty; human interaction and trust; and system interactions in an overall system of systems context. This goal has four objectives to ensure autonomous systems are safe and effective.

4.1. **Provide assurance for machine intelligence and decision-making in complex, uncertain, and dynamic environments**: Provable performance bounds must be formulated to reduce the reliance on comprehensive, off-line verification, shifting more of the analysis and testing burden to more provable run-time assurance technologies. Safe operation of an autonomous system must be ensured even though the machine's behavior and performance may not be exhaustively verified according to current development or certification standards. Key tenets are to reduce the amount of testing through up-front analysis and to reduce the burden for off-line certification through run-time assurances.

4.2 **Develop methods to ensure reliability of human-machine communication and interaction**: Mutual understanding and clear communication between autonomous systems and humans is critical to employ these systems effectively. Methods must be developed to directly and indirectly measure parameters of human performance during machine supervision. Metrics to quantitatively describe operator performance in relationship to dynamic mission requirements are necessary. To optimize human-machine teaming and to allow the human to augment the safety of the autonomy mechanisms for sensing, it is necessary to expand the two-way flow of information and "mutual awareness" between human and machine.

4.3 **Develop rigorous and verifiable architecture systems for data centric autonomous systems**: To ensure machines operate safely and correctly, information assurance, integrity, and system security must be addressed. With autonomous systems, the human ability to determine if a system is performing as expected or not, must now be contained within the system software. Autonomous systems must be able to assess the uncertainty in information real-time and make appropriate decisions based on that assessment. Safe decisions must be made based on partial, incomplete, conflicting, uncertain, and purposely misleading or malicious information.

4.4. **Develop methodology to V&V fractionated and composable systems**: New V&V methods must eliminate excessive certification as fractionated machines are combined into systems of systems. Preventing unintended emergent behavior will allow systems to be evaluated at the individual machine level while maintaining safety guarantees at the system level. Also, this technology must allow one element of a fractionated capability to be modified while minimizing the re-certification requirements of other components.

The area of T&E, V&V has proven to be a challenge for technology development and investment and will drive collaborations with the other services, government agencies, industry and academia. Near-, mid-, and far-term targets are as follows:

Targets for Goal #4

	Provide assurance for machine intelligence and decision-making in complex, uncertain, and dynamic environments	**Develop methods to ensure reliability of human-machine communication and interaction**	**Develop rigorous and verifiable architecture systems for data centric autonomous systems**	**Develop methodology to V&V fractionated and composable systems**
Near	• Performance bounds	• Mission Support through Cognitive Task Analysis	• Information analysis techniques	• Evaluation techniques for identifying unintended emergent behaviors

Mid	• Up-front analysis to reduce the amount of testing • Managing Emergent Behavior in Multi-Agent Systems	• Adaptive interfaces increase situational awareness	• Verification & validation of adaptive autonomous systems	• Verification & validation of adaptive, multi-vehicle sub-systems
Far	• Reduced burden for off-line certification through run-time assurances	• Full SA for full spectrum responses	• Analysis that utilize on-board and off-board, flight data for certification	• Macro system through verified and controlled interactions

Summary

As the Defense Department prepares for the next battle, reliance on more capable machines will continue, and increase, as budgets and manpower availability shrink. Future battle challenges, like those identified in Air-Sea Battle, further emphasize the utility of and the need for autonomous systems. These autonomous systems will depend upon technologies that enable human-machine and machine-machine teams to efficiently collaborate, sharing perception and decision-making for effective mission execution with trusted, verified performance. These systems will have the robustness and flexibility to assure operations in complex, contested, and dynamic environments.

The AFRL Autonomy Strategy is aligned with Air Force Chief Scientist's "Technology Horizons" technology vision and the Air Force 2010 S&T Strategy. AFRL will focus its Autonomy investment to discover, develop, demonstrate, and deliver the technologies that achieve the vision:

Intelligent machines seamlessly integrated with humans - maximizing mission performance in complex and contested environments.