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Services-Based Testing of Autonomy (SBTA)

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The test and evaluation (T&E) of autonomous systems, that adequately supports the verification and validation (V&V) process, is a significant challenge facing the test community. The ability to quickly and reliably test autonomy is necessary to provide a consistent T&E, V&V (TEVV) capability. A safe, efficient, and cost effective test capability, regardless of autonomy or sensor capability, is required. Autonomy and sensor capabilities, referred to as services, can be integrated easily into small Unmanned Aircraft Systems (sUAS) of differing capabilities and complexities. An integrated open-source architecture, for both software and hardware, implemented on multiple sUAS of varying capabilities can provide a robust test capability for emerging autonomous behaviors. The inclusion of a run time assurance (RTA) common safety watchdog and a Live-Virtual-Constructive (LVC) capability provides a consistent, robust, and safe test capability/ environment. The use of an open software and hardware architecture ensures cross-platform viability. These features will allow test teams to focus on the newly incorporated autonomy and sensor services, not on other ancillary capabilities and systems on the test vehicle. Testing of the services in this manner will enable a common TEVV approach, regardless of final platform integration while decreasing risk and accelerating the availability of autonomy services. Services-Based Testing of Autonomy (SBTA) provides a cost-effective and focused capability to test autonomous services, whether software, hardware, or both.

Keywords: Autonomy, Unmanned Aircraft Systems (UAS), Live-Virtual-Constructive (LVC), Unmanned Systems Autonomy Services (UxAS), Run Time Assurance (RTA)


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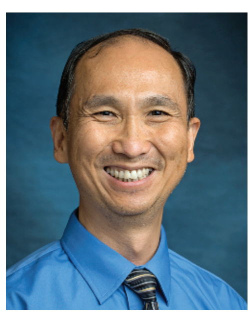
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Introduction

In April 2011, Secretary of Defense Robert Gates designated autonomy as one of seven technology priorities. In response, the United States Department of Defense (DoD) created an Autonomy Community of Interest (COI) to focus on the advancement of technology and capabilities to enable future autonomous systems (DoD 2015). In November 2014, Secretary of Defense Chuck

Hagel (Hagel 2014) announced the Defense Innovation Initiative, which would help the DoD develop autonomy as part of a third offset strategy. Specifically, Secretary Hagel discussed areas of new technology research and development:

"Our technology effort will establish a new Long-Range Research and Development Planning Program that will help identify, develop, and field breakthroughs in the most cutting-edge technologies and systems – especially from the fields of robotics, autonomous systems, miniaturization, big data, and advanced manufacturing, including 3D printing. This program will look toward the next decade and beyond.

Hagel's speech set the tone for future budget focus and research and development areas for the DoD. In June 2016, the Defense Science Board (DSB) Summer Study of Autonomy (DoD 2016) concluded that autonomy had reached a "tipping point" in value.

One of the focus areas of the Autonomy COI was TEVV. The TEVV central technical challenge identified was: *"From algorithms to scalable teams of multiple agents—Developing new T&E, V&V technologies needed to enable the fielding of assured autonomous systems"* (DoD 2015). In June 2015, the Autonomy COI TEVV working group released a Technology Investment Strategy 2015–2018, which provided the framework for development of future TEVV needs and capabilities. This strategy provided five primary goals to align research of autonomy around:

1. Methods & Tools Assisting in Requirements Development and Analysis
2. Evidence-Based Design and Implementation
3. Cumulative Evidence through Research, Development, Test and Evaluation (RDT&E), Developmental Testing (DT) & Operational Testing (OT)
4. Run-Time Behavior Prediction and Recovery
5. Assurance Arguments for Autonomous Systems

The DSB autonomy study also noted that current DT and OT methods are in direct conflict with more advanced commercial methods that are better suited for testing of adaptive software (DoD 2016). The ability to bring in software very early to get user feedback via incremental upgrades interspersed with test is a key commercial capability. The DSB report recommended, among other things, that a new T&E paradigm for testing software that learns and adapts be established.

In 2014, the National Research Council released a report on "Autonomy Research for Civil Aviation: Toward a New Era of Flight" that identified the need to develop standards and procedures for verification, validation, and certification of autonomous systems (NRC 2014). In 2016, the American Institute of Aeronautics & Astronautics Intelligent Systems Technical Committee developed a "Roadmap for Intelligent Systems in Aerospace" that identified the need for critical research in V&V methods to enable operations of adaptive systems in future vehicles (AIAA 2016).

To achieve improvement in the TEVV of autonomous systems, approaches to enable flexible and focused testing of autonomy are critical. The most challenging of components in these systems is the software embedded within them, specifically intelligent, learning, and adaptive software. While significant modeling and simulation, along with hardware in the loop testing, can be used, the ability to test autonomous capabilities in realistic scenarios is critical to the success of these types of systems. The cost and difficulty of performing significant flight testing of autonomous unmanned aircraft systems (UAS) are highly dependent on the vehicles and the integrated autonomous services. This paper provides the Services-Based Testing of Autonomy (SBTA) approach to testing these critical autonomy software and hardware capabilities, or autonomous services, in a rapid, repeatable, safe, and effective manner.

SBTA

Software and hardware to enable autonomy are critical focus areas for development of autonomous systems. A significant amount of research and development has been performed in the areas of path planning and safety controls algorithms (Eaton 2016). Hardware, especially sensors to enable decision making, continues to be developed and improved, especially in the commercial arena. Autonomy services can be a combination of hardware and software to enable autonomous actions for a vehicle.

In most traditional acquisition programs, a new aircraft is procured with a significant amount of development of both the vehicle and the software. The advent of autonomy currently appears to be focused on developing capabilities to integrate into existing vehicles and systems. The cost to integrate autonomy into existing platforms can be expensive and time-consuming. Providing a means to perform early testing of autonomy services is, therefore, critical. The intersection between the cyber and autonomy worlds raises yet another source of TEVV difficulty: can the perception sensors feeding the autonomy engine be spoofed (GPS, signature imagery, etc.) and can the autonomy engine understand that the "perceived world view" has been hacked?

Complex cyber-physical systems, such as autonomous UASs, are difficult to test with traditional methods currently used for standard UASs and manned aircraft. Testing of autonomy requires a different approach from initial software development through the end-of-life of the system. As autonomy becomes more complex, it becomes difficult to test all functions and capabilities due to the increasing size and complexity of the algorithms. Preventing the systems under test from getting into an undesirable or uncontrollable state while also challenging the autonomy is difficult. Providing a robust, reliable, and reusable approach to testing autonomy is key; this is why the SBTA method has been developed. This approach will provide a heterogeneous fleet of UASs that are simple and cost effective to modify and operate. These vehicles will be modified to have an open system architecture that will enable easy reconfiguration and installation of autonomy or other services that will enable testing. The approach is adaptable to different vehicles across a large operational envelope.

Platform & Operations Requirements

In April 2016, the United States Air Force (USAF) released the small Unmanned Aircraft Systems (sUAS) Flight Plan, which provided vision and strategy for development, operation, and sustainment of sUAS (USAF 2016). The USAF grouped sUAS into three categories, as defined in Table 1. These groups provide different levels of capability that are useful for not only actual operations but also for methods supporting TEVV.

Table 1: sUAS Platform Characteristics by Group

Group	Max Weight (lbs)	Normal Ops Alt (ft AGL)	Speed (kts)
1	0-20	<1,200	<100
2	21-55	<3,500	<250
3	<1320	<FL 180	<250

The sUAS Flight Plan identifies significant future USAF operations for sUAS and autonomous capabilities. The ability to provide support across multiple scenarios to support numerous dull, dirty, and dangerous missions for the USAF is becoming more common. Additionally, the concept of interoperability and modularity between systems is a key capability for enabling future sUAS operations. Providing an open architecture capability for sUAS will enable these concepts. The affordability of acquisition and operations of sUAS is important not only for mission operations, but also for test and evaluation. Providing a test capability that meets these requirements will help enable future TEVV of autonomous services.

The commercial off the shelf (COTS) availability of numerous sUAS allows for rapid acquisition and cost effective operations. The majority of these COTS systems use existing commercially available controllers and autopilots that are easy to integrate and modify. Additionally, the ability to easily modify and add capabilities to these vehicles allows for flexible test assets. This modifiability and flexibility is a critical capability to enable SBTA. The only disadvantage to the majority of these systems is the limitation in size, weight, and power capabilities. The smaller the vehicle, the larger the limitation, primarily in the ability to add the autonomy which will require the integration of new and different sensors.

Open Software & Hardware Architecture

A service-oriented architecture (SOA) is a software design style that enables service provision to other components through a communication protocol (Sprott 2004). The advantage of a SOA is that it provides a common interface for any developer to use. Providing a SOA-like interface for sUAS to enable integration of new autonomy services is a key to enabling SBTA. One SOA in development is the Unmanned Systems Autonomy Services (UxAS) architecture being developed by the Air Force Research Laboratory (AFRL). The UxAS provides a common software interface architecture that can be integrated on any aircraft and provides some early autonomy capability developed by AFRL (Kingston 2016). Recently, AFRL held a Summer of Innovation (SoI) event to improve the capabilities and documentation of UxAS (Kingston 2017) (AFRL 2017).

The majority of sUAS on the market use one of several standard autopilots for vehicle control. The UxAS architecture either already integrates with these standard autopilots or can easily be adapted via a new service interface. The AFRL has already generated multiple autonomy services on the UxAS architecture baseline that can be used for some mission scenarios. The results of the SoI provided improved capabilities and documentation of UxAS. Adopting a common architecture from initial development through flight testing on sUAS provides a robust TEVV capability.

Integrating the UxAS software onto a processor, such as a Raspberry Pi, oDroid, or Gumstix, and interfacing it with the sUAS autopilot will provide an initial capability for testing autonomy. Figure 1 provides an example UxAS architecture for SBTA. This architecture shows the segregation of existing known services and services

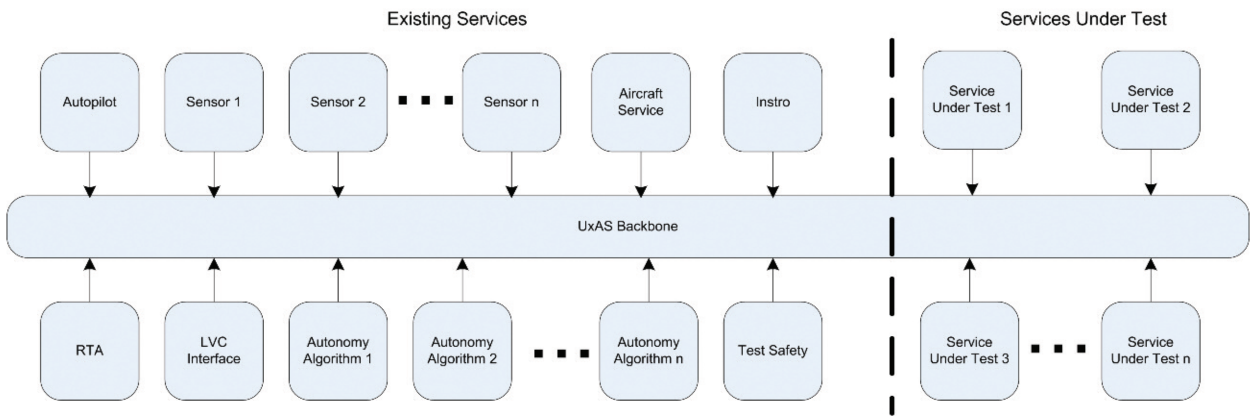

Figure 1: SBTA UxAS Architecture

under test. Having a UAS with an UxAS backbone and fully tested services will provide the framework for testing new services. These existing services will have known capabilities enabling testers to focus on the integration and performance of the new services under test.

Run Time Assurance (RTA)

Assurance, as defined by the IEEE Standard Glossary of Software Engineering Terminology, is "a planned and systematic pattern of all actions necessary to provide adequate confidence that an item or product conforms to established technical requirements" (IEEE 1990). For most systems, assurance will be primarily completed during the design, development, and lab-testing phases of a project. Limited assurance testing is performed during flight testing, owing to the risks of putting a vehicle in an undesired condition. For autonomous systems with runtime variation in performance and decision, assurance that the system will not become inconsistent and unsafe is of critical importance (Scheidt 2014).

To provide a safe and robust test asset, an independent watchdog supervisory monitor and controller to provide RTA coverage will be critical. In October 2017, ASTM International released ASTM F3269-17, Standard Practice for Methods to Safely Bound Flight Behavior of Unmanned Aircraft Systems Containing Complex Functions, which provides guidance for RTA architecture evidence on highly automated UAS (ASTM 2017). While the primary concept provided in the specification relates to production RTA, the same concept can be exploited for test safety RTA. The ability to have both onboard and off-board RTA coverage will be critical during the testing of autonomous systems. These RTA watchdogs will need to provide user-defined capabilities to include loss of link, geo-fence, aircraft limit control, control override, object avoidance, and aircraft collision avoidance. Some of these systems may require off-board information (e.g., object and aircraft collision avoidance) while others will be required to be onboard (e.g., aircraft limits and geo-fence). Additionally, the ability to completely isolate the autonomy under test and revert to basic aircraft controls will be a critical, fail-safe feature.

Several test aircraft have had similar capabilities installed on them for safety of test purposes. One example is the F-16 Variable stability In-flight Simulator Test Aircraft (VISTA) operated by the USAF Test Pilot School, which has also been used for early testing of autonomy (Warwick 2017). This system allows changes to the commands, stability, and performance of the aircraft that can be turned off based upon pilot input or violation of any implemented safety limits. Similarly, Calspan has created a variable stability Learjet with a similar implementation (Calspan n.d.). Additionally, NASA Armstrong has been developing their Expandable Variable-Autonomy Architecture (EVAA), which provides a production watchdog capability (Norris 2016).

For sUAS, an RTA system currently under development for implementation is the Safe Testing of Autonomy in Complex, Interactive Environments (TACE) by the Johns Hopkins University Applied Physics Lab (JHU/APL) (Scheidt 2015). This system can provide a variable RTA watchdog for both onboard and offboard controls as well as interfaces for Live-Virtual-Constructive (LVC). The TACE system is currently being installed on a 412th Test Wing aircraft for initial capability demonstration and evaluation for testing of autonomy. The 412 Test Wing has recently purchased three Swift Radioplanes Lynx (SRP 2017) aircraft that will be modified with a watchdog controller and an autonomy processor for demonstration of the RTA and LVC capabilities as the baseline for their Services Based Testing of Autonomy efforts.

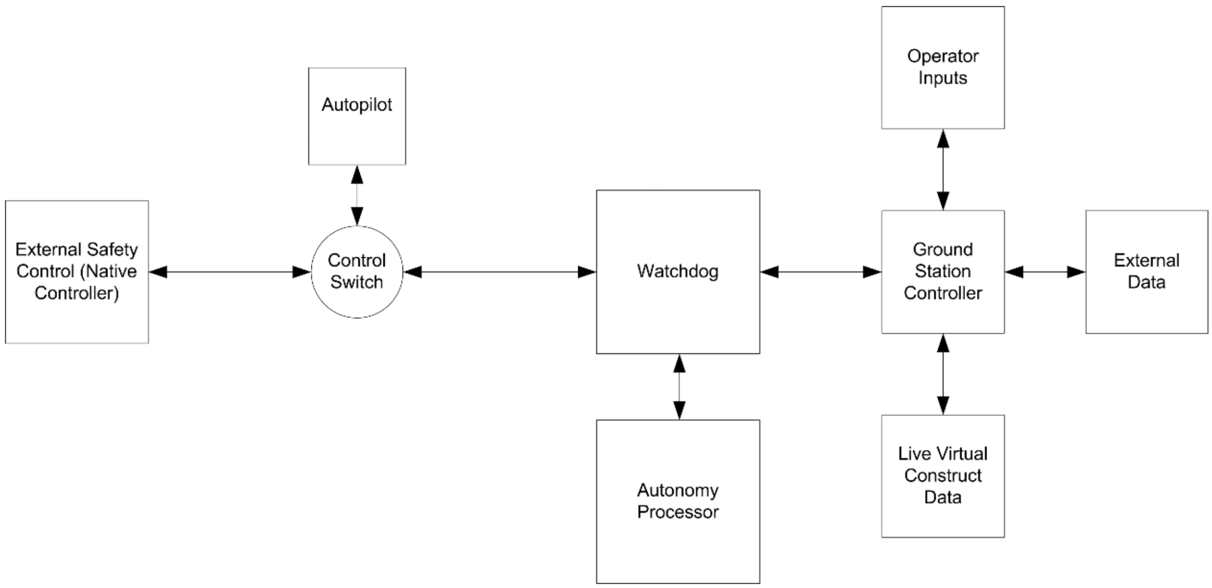

Figure 2: Example RTA Watchdog Implementation

This TACE RTA approach will provide the ability to manage, via a watchdog, the autonomous behavior of the vehicles in live flight to demonstrate the ability to mitigate violations of the watchdog. The watchdog will provide the interface between the native autopilot and the other control options (autonomy processor, automated on-board remediation, or ground control station). The native sUAS radio frequency (RF) Controller will be able to command the autopilot directly, overriding the watchdog inputs, as a redundant backup safety control. Figure 2 shows an example implementation of this approach. The TACE implementation will provide RTA watchdog coverage to keep the vehicles in a safe configuration. Initial capabilities for the TACE RTA implementation include protections and mitigations for airspace boundary violation, aircraft limit violation, aircraft collision avoidance, and lost link. The design of the TACE RTA allows for the addition or modification of protections and mitigations as system requirements change.

Test Approach

Testing of services in a block style approach from initial algorithms to full-up services on the platforms of varying capabilities is needed. For example, initial testing of a tracking service without a real sensor may be performed on a Group 1 sUAS using LVC to exercise the algorithm, while sensor capabilities are being developed for a larger vehicle implementation. The new sensor would then be integrated into a larger, more capable vehicle, if required, to evaluate the performance of that sensor service (i.e., tracking and target recognition capabilities) along with integration with the associated autonomy algorithm. Finally, full integration of the capability as one unique service onto another system to verify integration across platforms. These tests would show the capability of the sensor, algorithm, and integrated service on much less expensive platforms than the likely final product. As a result, when finally integrating on the final platform, the concerns become solely platform-unique implementation differences and not core service functionality.

There are several key capabilities, in addition to the core SBTA architecture, required to provide a robust SBTA capability. Installation of key instrumentation parameters and recording capabilities will be critical with unique challenges, depending on the size of the vehicle. In many cases, recording capabilities will be performed within the installed processors and autopilots without additional instrumentation capability. Independent Time-Space-Position Information (TSPI) instrumentation is likely the most critical independent data requirement that will be required, depending on the system under test. Additionally, telemetry data for standard vehicle performance will be required to ensure degraded system performance is not causing poor autonomy performance.

Critical to testing autonomy, especially as the requirements for multiple vehicles and complex mission requirements increase, will be the implementation of a LVC capability. The USAF continues to consider LVC as a critical capability for both training and testing (Machi 2017). In the case of SBTA, LVC will be used to provide synthetic forces, whether air, sea, or surface and friendly (blue) or adversarial (red) forces. Additionally, the LVC capability will be able to provide synthetic threats, topography, simulated loss of communications, and simulated GPS jamming/drifting. The LVC will allow a tester to design scenarios across an increased spectrum of the state space without requiring complex and expensive range capabilities or a significant number of UASs. This approach will improve flight test safety by requiring the live flight of fewer vehicles in a clean environment while providing a complex decision space for the autonomy. Virtual entities can be simulated as part of the flight test environment and sent to the live test aircraft at real-time speeds, reducing complexity and safety in open air. Several capabilities are in different stages of development for this type of testing.

The Test and Training Enabling Architecture (TENA) provides an interface for test control that will enable the testers to use existing simulation capabilities across the test and training environment (TRMC n.d.). These TENA environment models could be made available for the LVC environment. The Navy has developed their Joint Integrated Mission Model (JIMM) that has been used on other TACE efforts for integration of synthetic forces into system demonstrations (NAWC-AD n.d.). The Boeing Company and USAF have developed the Advanced Framework for Simulation, Integration, and Modeling (AFSIM), which has been used in numerous forms and can provide synthetic force generation capability for SBTA integration (Clive 2015).

Control of the autonomous systems will be performed initially using the JHU/APL developed TACE controller on a Linux laptop. However, over time, TACE could be integrated with other control capabilities with some additional development. Currently, AFRL is using the Vigilant Spirit Control System (VSCS), which has been released to numerous commercial companies (Cooper 2017). The VSCS is also being interfaced with the UxAS development by AFRL, and it provides many unique capabilities for future SBTA integration.

V&V Approach

The key to SBTA providing a rapid testing focused on the autonomy services is well-defined hardware and software interfaces. The UxAS architecture for hardware and software integration will provide a known interface for any user to develop to, and test against, in a lab environment. Integration of the UxAS architecture and software backbone onto a heterogeneous fleet of aircraft will provide a baseline set of aircraft for testing. A series of initial testing and system verifications will be required prior to any vehicle being ready to be used as an autonomy test bed.

First, the basic aircraft will need to be verified and validated against baseline expectations. Depending on the complexity of known characteristics of a given vehicle the scope of baseline testing could range from minimal to complex. Once this initial characterization is completed, this known aircraft baseline will exist for comparison against new capabilities. These data are also critical for the implementation of autonomy services since many algorithms require knowledge of current vehicle capabilities.

Once the base aircraft has been verified, the UxAS or other system architecture, whether software or hardware, can be installed. The integrated hardware and software will then be tested to verify basic integration functionality to include basic aircraft control and communications. At the completion of this stage of testing, the system will provide an UxAS compliant test platform for integration of new autonomy services. The vehicle will then have baseline integrated performance information and will be considered an SBTA compliant aircraft.

A new autonomy service, whether software, hardware, or a combination, can then be integrated into the UxAS SBTA aircraft for service testing. This services testing will have two test phases. The first phase will be a verification of proper UxAS interface with the SBTA aircraft. This testing will verify that the communications paths between the newly installed services and the SBTA aircraft are functioning as demonstrated in the lab environment. Once the UxAS interface testing is completed, autonomy performance testing can be completed. Figure 3 shows the SBTA Autonomy V&V process from basic aircraft verification to autonomy performance testing.

Depending on the focus of the autonomy service, testing may be performed in a completely live environment or in a more complex LVC environment. If testing of the same service is required on multiple SBTA vehicle types, the same approach will be performed on each vehicle as required to verify integration

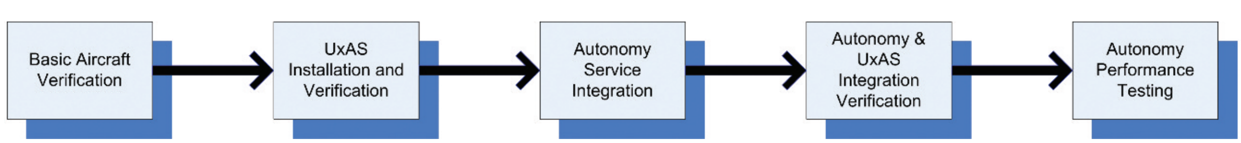

Figure 3: SBTA Autonomy V&V Process

Figure 4 - Potential SBTA Test Articles

and performance. Since the integration with UxAS will have been verified on the first vehicle, the integration testing on subsequent vehicle types should be minimal, and focused on vehicle capability differences.

Implementation

The Emerging Technologies Combined Test Force (ET-CTF) at the 412th Test Wing, Edwards AFB, CA in conjunction with the Air Force Research Lab Autonomy Division (AFRL/RQQA), Wright-Patterson AFB, OH is beginning to develop and acquire systems and capabilities necessary to implement SBTA.

The ET-CTF has provided three Swift Radioplanes Lynx aircraft to JHU/APL for modification and initial testing of their TACE system. The initial implementation will include use of existing JHU/APL autonomy capabilities installed on a Raspberry Pi processor, and the TACE watchdog and LVC on a second Raspberry Pi. This effort, funded by Test Resource Management Center (TRMC), will provide an integrated autonomy and watchdog capability on the Lynx vehicles to enable initial TACE LVC and watchdog functionality verification. The program will culminate in the Summer of 2018 with a multiple-vehicle single-operator demonstration of the LVC and watchdog implementation. The initial development and integration will enable improvements and upgrades of TACE watchdog (RTA) and TACE LVC into services that are an integral part of the UxAS architecture. The capability will also provide baseline development requirements for integration on other sUAS.

Figure 4 shows the vehicles currently planned or under consideration for SBTA integration, from left to right: Swift Radioplanes Lynx (SRP 2017), UAV Factory Penguin (UAV Factory n.d.), and Arcturus T-20 (Arcturus n.d.). Table 2 provides key characteristics of each of the vehicles. The Swift Radioplanes Lynx Aircraft provide a low-cost, simple vehicle that is being used for initial TACE integration and evaluation. The Lynx offers the ability to do quick initial checkouts of autonomy algorithms without complex vehicle integration. The Lynx has limited sensor capability so the majority of testing will rely on LVC simulation. The UAV Factory Penguin provides a more robust lightweight test vehicle capability with larger and more robust sensor capability than the Lynx. The Penguin is offered in both electric and fuel configurations. The electric configuration minimizes the need to deal with fuel transportation and storage but has limited endurance. Both electric and fuel powered Penguins will be used. The Arcturus T-20 provides a larger vehicle payload, endurance, and altitude

Table 2: Key Charactristics of Potential SBTA Test Vehicles

	Lynx	**Penguin-B**	**Penguin-BE**	**Arcturus T-20**
Length	N/A[1]	7.45 ft	7.45 ft	9.5 ft
Wingspan	7.5 ft	10.82 ft	10.82 ft	17.5 ft
Max Airspeed	N/A	70 Kts	70 Kts	75 Kts
Cruise Speed	31.28 Kts	42 Kts	42 Kts	N/A
Max Altitude	N/A	N/A	N/A	15,000 ft
Max Endurance	3 hrs	20+ hrs	1.8 hrs	10-20 hrs
Empty Weight	6.6 lbs	22 lbs	32.8 lbs	105 lbs
Payload	1.6 lbs	22 lbs	14.5 lb	75 lbs
Fuel	Battery	Auto Fuel	Battery	Auto Fuel
Launch	Hand	Catapult, Runway	Catapult, Runway	Catapult
Recovery	Deep Stall	Runway	Runway	Belly

[1] *N/A=Not Available*

capability than the Lynx or Penguin. The Arcturus has a significantly larger payload capability and power capability to enable a larger range of autonomy payload service testing. The development of the capabilities on these sUAS will enable integration onto future larger, faster, and more capable unmanned systems beyond sUAS.

The initial test capability with the Lynx vehicles is planned for testing Summer of 2018. Follow-on integration of TACE and other services with UxAS and onto other platforms is planned for the 2018–2020 timeframe, with planned integration onto the Penguin and Arcturus, or similar, platforms. Future integration onto larger and faster vehicles are still under discussion and consideration with potential customers.

Using sUAS provides a significant cost advantage over the existing military aircraft fleet. First, the cost of sUAS operations is significantly lower than the thousands-of-dollars-per-hour of existing military aircraft (Thompson 2013). Since most sUAS can provide similar flight duration on either battery power (minimal electrical charge costs) or a few pounds of fuel (tens-of-dollars-per-hour), the cost advantage is significant. Second, sUAS provide a simple and modifiable system design that doesn't require the same significant software and hardware integration efforts necessary to support airworthiness requirements of existing USAF manned and unmanned aircraft. Because the sUAS are low cost vehicles that are not being integrated into the USAF fleet, the level of airworthiness requirements and data to support airworthiness are significantly less. Additionally, the implementation of the RTA watchdog allows for safe reversion to a baseline aircraft in the event of poor autonomy integration. The flexibility from sUAS implementation of SBTA is expected to provide implementation, cost, and schedule advantages over existing platforms.

Conclusions

Services-Based Testing of Autonomy, upon successful implementation, is expected to will provide a cost-effective, scalable, and efficient means to test the growing needs for autonomy services that are being developed across the industry. The use of a common open architecture should will allow for integration into diverse platforms rapidly for quick assessment of autonomy services. The cost to perform testing on sUAS is anticipated to be significantly less than on larger vehicles, and allows for rapid changes to hardware and software in a more flexible manner than traditional test vehicles. Implementation and future studies utilizing SBTA on sUAS will provide the data necessary to enable verification of the viability of the SBTA approach for testing of autonomy. Additionally, while this approach is primarily focused on sUAS implementation for cost-effective testing of vehicle operations, the same approach can be implemented directly on larger UASs or even manned aircraft with a subset of capability implementation via autonomy. ❑

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