

Normative and Descriptive Models for Test & Evaluation of Unmanned and Autonomous Systems of Systems

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Abstract

The United States Department of Defense (DoD) has purchased and deployed many unmanned autonomous systems and is expected to do so at an ever-increasing rate in the years to come. These autonomous systems are often expected to operate in system of systems environments. Our research aims to address a number of questions posed by members of DoD's acquisition workforce regarding test and evaluation of these systems.

In this paper we present a small set of normative (ideal) and descriptive (actual) models for test and evaluation. We describe test strategies used in the DARPA Grand Challenge competition and the SPHERES test bed, and extract lessons learned from each case study. We will use these models as a step toward identifying prescriptive models for testing unmanned and autonomous systems of systems. The prescriptive models will be implemented within PATFrame (Prescriptive and Adaptive Testing Framework), the decision support system that we are developing.

Background and Motivation

The advent of Unmanned and Autonomous Systems (UAS) and Systems of Systems (SoS) presents the U.S. Department of Defense (DoD) with incredible capabilities, but also daunting challenges across the acquisition cycle. Those charged with the Test and Evaluation (T&E) must grapple with several of these challenges such as testing for failure modes not yet discovered and economically testing in a complex system of systems environment.

It is critical that Unmanned and Autonomous Systems Test (UAST) meets the tempo of UAS deployment. Technology in this realm is advancing rapidly, and this pace is being matched by the DoD's efforts to procure these systems. The DoD's budget for unmanned vehicles has grown 37.5% in the past two fiscal years alone from \$3.9B to \$5.4B [Keller 2009]. Failure of the T&E

community to keep up, and the subsequent inability to reduce program risk would be extremely costly for the DoD in time, treasure, and capability.

Through our research, we are aiming to address a number of problems faced by the DoD community as they make the transition to testing autonomous systems. As a means to advancing the state of T&E, we seek to define normative (ideal) and descriptive (actual) models of T&E of UAS and SoS. These normative and descriptive models will be used to inform a set of prescriptive solutions aimed to support decision making of testers. Prescriptive solutions will be captured in a Prescriptive and Adaptive Testing Framework (PATFrame), a software prototype which will be developed over the coming years. PATFrame will address several questions posed by testers, such as:

1. How much testing is enough?
2. How should I prioritize tests?
3. How do I test effectively in a compressed schedule?
4. How to I test system of systems performance without explicit requirements?
5. How do I test the unique requirements of unmanned autonomous systems?

For the purposes of this discussion, we will adopt the following definitions of relevant terms. Some of these definitions are not universally accepted. These are used only to provide context for the reader.

Unmanned System (UMS): “An electro-mechanical system, with no human operator aboard, that is able to exert its power to perform designed missions. May be mobile or stationary. Includes categories of unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), unmanned underwater vehicles (UUV), unmanned surface vehicles (USV), unattended munitions (UM) and unattended ground sensors (UGS). Missiles, rockets, and their sub-munitions, and artillery are not considered unmanned systems”. [AIAA 2009]

Autonomy: A system’s ability to “Observe, Orient, Decide, and Act” [Osinga 2006] to achieve its goals as assigned by its human operator(s).

System of Systems: A system of systems is a set of collaboratively integrated systems that possess two additional properties: operational independence of the components and managerial independence of the components. [Maier 1998]

Normative, Descriptive and Prescriptive Models

Models for decision making are found in a number of fields, including: psychology, decision theory, and systems engineering. Bell, Raiffa, and Tversky [1988] provide a useful taxonomy for understanding the contributions made by various disciplines to decision making.

Normative models are comprised of logically consistent procedures for how decisions “should” be made. Descriptive models are based on observations of how people actually make decisions. Prescriptive models, such as heuristics, provide practical methods to help people make better decisions. Systems engineers may evaluate existing policies and guidance to understand normative models, conduct case studies to construct descriptive models, and leverage lessons learned to develop practical recommendations in the form of prescriptive models. Figure 1 shows a conceptual representation of the relations among normative, descriptive, and prescriptive models, which is also consistent with the psychological interpretation of bridging the gap between normative and descriptive behaviors.

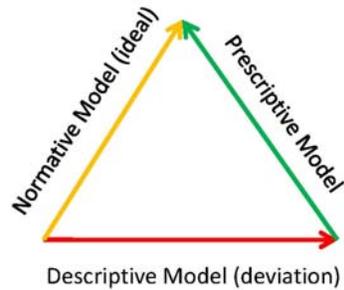


Figure 1. Prescriptive models bridge the gap between normative and descriptive models.

Normative models are based in theory. They describe the “best” action to take. In the case of decision theory, this assumes an ideal decision maker is rational [Apostolakis 2009] and is fully informed. While the axioms of rationality are often controversial, it is conventionally accepted that a decision maker who satisfies the following basic axioms is rational or coherent [von Winterfeldt 1989]:

- The laws of probability
- Independence of irrelevant alternatives
- Dominance
- Transitivity

Normative decision research is concerned with the identification of logical properties or criteria with which decision making should conform [Keller 1989]. For example, expected utility theory which is derived from axioms by von Neumann and Morgenstern [1947], is considered a normative theory of decision making since it is based on the foundational properties listed above.

To model real-life situations, it may be necessary to relax the assumptions of rationality and availability of perfect information. For example, SoS testing introduces socio-technical challenges due to the involvement of multiple independent stakeholders in control of the constituent technologies. Human behavior often does not adhere to normative criteria, thereby motivating models based on descriptive research.

Descriptive models attempt to identify what people actually do. Through descriptive research, it has been observed that people do not always behave in ideal or expected ways [Tversky 1974]. Often, descriptive research uses observations to compare choices made in reality to choices that would be made using normative models. For example, bounded rationality and satisficing [Simon 1957] are descriptive models of decision making and violations of normative principles.

The gaps between normative and descriptive models can be addressed through **prescriptive models**, which provide practical methods to improve decision making. Prescriptive models are based on both the strong theoretical foundation of normative theory in combination with the observations of descriptive theory.

Heuristics are an example of prescriptive advice. They may not describe normative behaviors but can improve performance. For example, one might tell someone new to the game of blackjack to always “hit” if they have less than 17. Certainly, this isn’t perfect advice, but it will help

some people to improve their performance (arguably, if someone needs this advice, a better heuristic might be “stop playing blackjack”).

To develop a prescriptive model that can support test decisions for the T&E community, we first seek to understand normative and descriptive models of T&E, particularly T&E of unmanned autonomous systems in the context of SoS.

Normative Models of UAS and SoS Testing

In this paper, we do not propose a comprehensive normative model of Test and Evaluation conforming to the strict criteria of decision theory. The normative models presented here reflect institutional ideals and describe how Unmanned and Autonomous Systems Test “should” be conducted from the perspective of these institutions.

Department of Defense. Given that a significant amount of T&E for UAS and SoS is done for the DoD, of particular interest is the model the DoD requires Program Managers (PMs) and testers to follow.

We have identified the primary normative model of T&E within the Department of Defense through literature review of academic materials and US government guidance. The normative model of the current DoD T&E process is described in the Defense Acquisition Guidebook (DAG) and DoD Directives 5000.01 and 5000.02. It is augmented by evidence found in the Joint Test and Evaluation Methodology (JTEM) and Joint Capabilities Integration Development System (JCIDS) [Defense Acquisition Guidebook].

The hallmark of the DoD process is the progression from Developmental Test and Evaluation (DT&E) through Operational Test and Evaluation (OT&E), Live Fire Test and Evaluation (LFT&E), and Operational Assessment (OA). A comprehensive description of this process is beyond the scope of this paper, but is thoroughly addressed in the references.

This model, based on the legacy DoD guidance, has a number of strengths, but does not address the unique challenges of UAST and SoS testing. According to a report by the Defense Science Board, “The current acquisition process and methodologies are, for the most part, optimized to single system acquisitions.” Furthermore, “Testing all the SoS requirements of all systems is impossible” [Defense Science Board].

Test and Evaluation in the DoD does not always adhere to this model; however, this serves as a normative model since it provides testing policy and guidance, assuming ideal behavior.

SPHERES. The Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) test bed at MIT is a test system for distributed satellite systems. SPHERES, established in 1999, consists of six micro satellites, three used for testing at the International Space Station, and three for terrestrial testing at the MIT facilities. MIT created the testing environment to provide DARPA, NASA, and other researchers with a long-term, replenishable, and upgradable testbed for the validation of high risk metrology, control, and autonomy technologies for use in formation flight and autonomous docking, rendezvous, and reconfiguration algorithms [Mohan 2009] [Saenz-Otero 1998]. SPHERES is a unique case because not only is the system a test bed for docking technologies, but SPHERES itself also required rigorous testing.

Developing algorithms of unprecedented complexity for formation flight and docking control, and applying the algorithms to real systems carries a high degree of risk, because the loss of a single system can run into the billions of dollars. SPHERES provides an avenue for testing in a

microgravity environment to reduce this risk and is an intermediate step for algorithm development: proof of concept testing.

In planning tests, the SPHERES team identifies the most critical parts of the system and the environmental uncertainties. They then develop strategies to stress the algorithms under test and document any failures. Information gathered on these failures is used to reduce occurrence of failure or mitigate the effects.

The SPHERES team has developed a codified set of best practices for testing distributed satellite systems [Saenz-Otero 2005]. Presented here is the subset that is relevant to UAS and SoS testing. These can be leveraged in other space domain applications as well as land, air, water, and underwater risk management.

1. *Principle of Iterative Research* – “enable scientists to conduct iterative research through repetition of experiments to obtain the necessary data to support or refute a hypothesis; provide the capability for scientists to analyze that data and modify their theories on a flexible schedule, and allow reconfiguration of the facilities to allow for changes in experiments and hypothesis.”
2. *Principle of Optimized Utilization* – “the International Space Station (ISS) provides several special resources not available in any other space research environment: crew, power, long-term experimentation, and a benign environment/atmosphere. Successful laboratories must use these resources effectively, with the idea that the use of the resources adds value to the mission, rather than being a cost.”
3. *Principle of Remote Operation & Usability* – “operations aboard the ISS occur in a remote environment where it is practically impossible for the research scientist to be present in the operational environment. Therefore, it is essential that the operators have the necessary tools and information to conduct effective runs of experiments, while the scientists have efficient access to data obtained from the experiments for analysis. Ultimately, the operator should become a virtual extension of the scientists aboard the ISS.”
4. *Principle of Requirements Balance* – “for a laboratory to succeed...requirements must be balanced, ensuring that the hard requirements, which directly affect the ability to succeed in the mission, drive the mission efforts. Soft requirements, desired features not directly affecting the success of the mission, should only be implemented when they do not cause the mission to break its constraints and do not contradict any hard requirements.”

These practices are directly relatable to Test and Evaluation. *Iterative Research*, or iterative testing, suggests that testers are most effective when able to adapt their test processes. Because of the uncertainty involved, flexibility is valuable. *Optimized utilization* is associated with efficient use of resources, which will allow for better testing. *Remote Operation & Usability* is especially relevant to testing autonomous systems. Under normal circumstances, UASs operate remotely and, because of current operational demands, UASs are likely to be tested “in the field” where testers may not have ready access to the test article. Testers must work around their inability to physically handle the system under test. This highlights the necessity of coordination among multiple stakeholders, such as users, testers and evaluators. *Requirements balance* is critical.

When operating in a compressed schedule and budget, testers must focus on the most critical tests.

Descriptive Models of UAS and SoS Testing

We have compiled a number of descriptive models in the course of our literature review and interviews. Whereas the normative models presented in the previous section provide idealistic guidelines or principles for testing, descriptive models involve case studies of actual T&E practices. The disjointed nature and relative immaturity of the field of autonomous systems leads us to expect many more descriptive models from which to draw information as we continue our research.

DoD Rapid Acquisition Programs. Urgent wartime needs have prompted the DoD to deploy critical systems as fast as is practical. Critical systems may be commercial off-the-shelf (COTS) products or developmental prototypes. In these cases the DoD aims to turn war-fighter needs into fielded systems in weeks or months rather than the traditional years or even decades for programs of record. The test process currently used is of particular interest to UAST since the vast majority of rapid acquisition systems since the start of Operation Iraqi Freedom have been unmanned.

Testing in the case of rapid acquisition is usually limited to tests that can be conveniently conducted before deployment; fulfilling safety critical operational needs is unquestionably the first priority of a rapid acquisition program. Conventional requirements don't exist, and the DoD's normative test process is not followed. Informal testing brings an important downside: The DoD's test community is deploying dozens of systems without learning how to properly specify and test the unique requirements of UASs. Requirements engineering is a critical institutional skill, and failure to properly specify and test requirements on future UASs could be very costly.

RQ-4 Global Hawk. The Global Hawk is a long-range, long-endurance airborne surveillance platform. It originated as an Advanced Concept Technology Demonstrator. Upon realizing the need for the system's capabilities, the US Air Force transitioned the Global Hawk to a Program of Record and now uses the system operationally in Iraq and Afghanistan.

During developmental test of the system, the planners eschewed the conventional envelope expansion program. Instead of slowly expanding the flight envelope and eventually reaching maximum altitude, the Air Force cleared small combinations of speed and altitude to allow the aircraft to fly at its operational altitude where its sensor payload could be tested. This decision accelerated the test program by allowing the remainder of envelope expansion and sensor testing to occur in parallel rather than serially. This is particularly notable, as DoD testers often use test plans from previous systems as the baseline for new test programs. By doing so, testers may overlook substantial opportunities for improvement resulting from the unique characteristics of UASs.

This test strategy had not been used on similar manned platforms, but was ideally suited to the Global Hawk because it was unmanned. The computerized flight controls could keep the aircraft in the very small altitude and airspeed envelope permitted during sensor testing, which may have been difficult for even a skilled test pilot. Furthermore, the fact that a pilot's life was not in danger made the risk of flying in such a narrow envelope much more palatable to the Air Force.

DARPA Grand and Urban Challenges. Over the last five years, the Defense Advanced Research Projects Agency (DARPA) has organized three prize-in-field competitions for driverless cars. “Grand Challenge 2004” and “Grand Challenge 2005” were held in the Mojave Desert in California and Nevada. The first year, no team successfully completed the course, but the second year four autonomous vehicles completed the route under the 10-hour limit required for prize eligibility. That year, the \$2 million prize was awarded to “Stanley”, the entry from Stanford University. [Martin 2007]

Building on the success of the 2004 and 2005 Grand Challenges, The DARPA organized the Urban Challenge, held on November 3, 2007, at the former George AFB in Victorville, California. This event required teams to build an autonomous vehicle capable of driving in traffic, performing complex maneuvers such as merging and passing, parking and negotiating intersections. This event was truly groundbreaking as the autonomous vehicles interacted with both manned and unmanned vehicle traffic in an urban environment. A \$1 million prize was awarded to the Carnegie Mellon University Team. [DARPA 2007]

The experiences of DARPA Grand Challenge and Urban Challenge competitors are an excellent source of information about T&E of autonomous vehicles, because most information is freely available (as opposed to being subject to government restrictions). In addition, most teams had no knowledge of DoD testing procedures and were not required to follow them; therefore, teams were free to apply novel approaches to testing. We have chosen to explore MIT team’s approach to testing for this paper for reasons of accessibility.



Figure 2. Talos II, MIT’s DARPA Grand Challenge Entry.

The Urban Challenge entry from MIT, Talos II (Figure 2), was a newcomer to the field, not having competed in the Grand Challenge in past years. The MIT team started from a clean slate, researched the successful entrants from past years, and decided to “Test Early, Test Often” (DARPA Lesson #1). Indicative of the fast-paced nature of their development, there was little formal structure to their test program. The team’s planning horizon was on the order of hours, and rarely, if ever, did they have tests planned more than two days in advance. The team decided what to test in meetings held every other day. Capabilities that were in doubt were then tested and refined if necessary. There was no master test plan, and no matrix tying tests to requirements.

The team’s development strategy, though not articulated at the time, was parallel development in “minispirals”. The team developed each software capability separately, and after developing a capability, they designed a simple test to assess the new functionality. If the vehicle did not perform as expected, the team refined and re-tested the vehicle’s software. If the vehicle did per-

form as expected, the level of complexity of tests was increased until the system failed or the team was satisfied with vehicle's performance.

The team did not embrace systems engineering principles. The team did not clearly define interfaces, and they did not test the interfaces. Often, new additions to the vehicles code base or capabilities would break existing functionality. Though the team incorporated a detailed logging system to help understand problems encountered in test, they found that the logs were difficult to store and share because of their size and complexity. As the deadline for demonstrating their vehicle was approaching, the team shifted their strategy from component-level testing to mission-level testing. According to a team leader, it was challenging to decide when to make this critical shift (DARPA Lesson #2).

In an interview with one of the team leaders, he stated that the test program was not ideal, and that if he began development again, he would use a different strategy that he has applied for other autonomous systems, in which full-up system tests were only executed to confirm successful outcomes of simulations (DARPA Lesson #3). Unfortunately there wasn't time or manpower to execute that type of testing. Going from a clean slate to a functioning car instead of improving a current car meant an extremely accelerated pace of development. He stressed that there is no substitute for testing, and that the results of the DARPA Challenges bear this out.

Conclusion

UAS development and use in a SoS environment is growing quickly, whereas the current state of UAS T&E is immature. The DoD provides normative guidance for testing to all of its acquisition programs, however this guidance is not well suited to testing UASs and SoS. In this paper, we discussed some normative and descriptive models of T&E through case studies of SPHERES and the DARPA Challenge. These models may provide insights into the development of a normative model for UAS and SoS T&E.

Over the coming months, we will continue our exploration of testing frameworks, drawing examples from areas such as the automotive and software industries, civilian space flight, and artificial intelligence. We will especially seek examples that involve test of unmanned autonomous systems operating in the context of SoS. Following our survey of existing normative models and best practices captured in the descriptive models we have observed, we will build a new normative model for testing of UAS and SoS.. This model will be used to inform the development of PATFrame, a prescriptive decision support system prototype.

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