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Recent Flight Test Experience with Uninhabited Aerial Vehicles at the NASA Dryden Flight Research Center

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April 1998

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Abstract

The NASA Dryden Flight Research Center has had substantial involvement with uninhabited aerial vehicles (UAVs) in the past. These vehicles include the Highly Maneuverable Aircraft Technology (HiMAT) aircraft and a new breed of UAVs, such as the X-36 and the Pathfinder. This article describes lessons learned with the current UAVs which may help others in any stage of UAV design or flight testing. Topics discussed include airspace factors, weather factors, frequency availability, range safety, human factors and crew station design, hardware and software design redundancy, ground testing, simulator use, flight testing procedures, crew training, and environmental testing.

Introduction

Over the years, uninhabited aerial vehicles (UAVs), also called remotely piloted vehicles or aircraft (RPVs or RPAs), have played supporting roles in the development of aircraft technology. These vehicles were typically viewed as tools which provided low-risk and low-cost means for testing new concepts.

In the military arena, UAVs are also used for reconnaissance and target practice. Typically, UAVs are thought of as vehicles which are reusable, unlike missiles which are considered expendable, one-use vehicles. However, missiles do have much in common with UAVs.

Recently, as computational power has grown by leaps and bounds and the packaging of related electronics has been miniaturized, UAVs are being viewed with increased interest to perform a variety of new missions. The missions considered for such "robot warriors" are commonly described as being either too dull, dirty, dangerous, or long for piloted aircraft to carry out. Some examples of missions which are under consideration are listed below.

- Military applications include combat UAVs capable of maneuvering beyond human g-limits.
- Commercial interests involve determining the viability of UAVs as long endurance platforms to carry telecommunications equipment. In this application, the UAVs function as very low-altitude satellites.
- Scientists have a variety of missions in mind, such as remote sensing and collecting atmospheric samples for environmental study of Earth.

The NASA Dryden Flight Research Center (DFRC), Edwards, California, has had varied levels of involvement with UAVs over the years. One of the most complex was a technology demonstrator called HiMAT (Highly Maneuverable Aircraft Technology) (figure 1). Experience gained with the HiMAT over 15 years ago and other UAVs helped shape a test philosophy which the current generation of UAVs continue to build upon.

ECN-14281

Figure 1. The Highly Maneuverable Aircraft Technology (HiMAT) uninhabited aerial vehicle.

This article describes lessons learned from recent DFRC experiences with the X-36 and the Pathfinder aircraft (figures 2 and 3) and with other UAV flight projects. These lessons are recorded to help future UAV developers, cognizant test organizations, or both, to conduct a safe and successful flight program. Conducting such programs creates a tall order for any team because they are probably faced with a common dilemma.

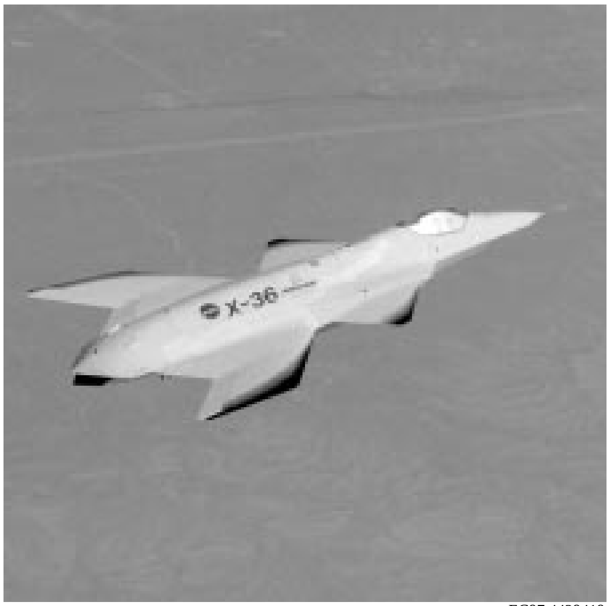

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Figure 2. The X-36 uninhabited aerial vehicle.

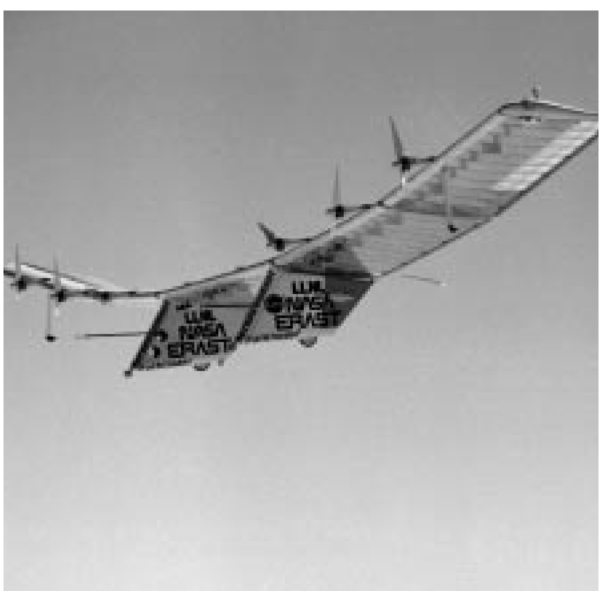

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Figure 3. The Pathfinder uninhabited aerial vehicle.

On one side of the dilemma is the widely held perception that UAVs are simple, inexpensive, and easy to operate and fly. On the other side is the reality that UAVs are not trivial systems, and control and operation of these vehicles may be quite complex. Because the pilot is not present in the UAV cockpit, his/her conscious and subconscious cues are not typically available. As a result, the control systems and other systems must compensate for these missing sensory inputs to give the pilot of the UAVs sufficient information to safely fly the missions. Couple these factors with the mission requirements thrown at the UAV designer that make only minimal volume, weight, and power available for aircraft systems and payloads, and the result is as was previously mentioned, a tall order.

The new generation of UAVs tested recently at DFRC includes the following:

- Perseus A and B and Theseus (built and operated by Aurora Flight Sciences Corporation, Manassas, Virginia)
- Pathfinder (built and operated by AeroVironment, Monrovia, California)
- Altus (built and operated by General Atomics–Aeronautical Systems Inc., San Diego, California)
- X-36 (built by Boeing Phantom Works, St. Louis, Missouri, and flown by Boeing and NASA)

These UAVs are laying the ground work for the following aircraft:

- X-38 (built by Scaled Composites, Mojave, California, and to be flown by NASA)
- X-34 (built by Orbital Sciences Corporation, Dulles, Virginia, and operated by Orbital Sciences Corporation and NASA)
- Centurion and Helios (built and operated by AeroVironment, Simi Valley, California)
- Alliance 1 (built and operated by the Environmental Research Aircraft and Sensor Technology (ERAST) Alliance)

This article discusses testing in the right environment, hardware and software, and human factors. Topics, such as providing the right airspace environment, range safety, human factors, reliability, redundancy, ground testing, use of simulators, procedures, crew training, and environmental testing, are addressed.

Testing in the Right Environment

Testing of UAVs requires the "right" environment. Elements to be considered in determining the appropriate location include airspace factors, weather factors, and frequency availability. These elements are discussed in this section.

Airspace Factors

The fact that the Edwards Air Force Base (AFB), California, complex and Rogers Dry Lake qualify as the "right" airspace environment for conducting flight test research has been known and demonstrated for over 50 years. Recent research shows that this fact also applies to flight testing of UAVs. A remote, well-protected, and tightly controlled range and airspace with little population and few facilities contained within it make a safe environment for the operation of even high energy UAVs. The expansive dry lakebed and the natural runways it provides offer a risk-mitigating solution to the problems of the first-flight of a new and complex UAV, safely separated by several miles from manned-flight operations conducted at Edwards Main Base. Emergency recovery of UAVs via a parachute system is greatly facilitated by the large, flat, and obstruction-free surfaces provided by the lakebeds.

In addition to the surface features, the range airspace above Edwards AFB with its well-defined boundaries is large enough for the flight of high-speed UAVs, such as the X-36, and can be cleared up to altitudes of interest for slow-flying, high-altitude UAVs, such as the ERAST aircraft. Three requirements for effectively and safely using this range are delineated below; that is, boundary and tracking information, incorporation of a flight termination system (FTS), and maintenance in real-time of an estimate of where the vehicle would impact if the FTS were activated.

Accurate tracking of UAVs by range control may involve carrying a transponder-beacon as well as a traditional air traffic control altitude-encoding transponder for Federal Aviation Administration (FAA) radar detection. From these signals, range-monitoring equipment may generate a depiction of the aircraft as it moves within the range boundaries. This spatial information must also be provided to the UAV's pilot. In the case of the X-36 aircraft, this information was provided via down-linked global positioning system (GPS) data. An independent Range Safety Officer (RSO) located in the NASA DRFC control room had his/her own display of range boundaries and relied on C-band beacon transponder information of vehicle position. In the event of beacon failure, the RSO's displays could be driven by a radar skin track, albeit less reliably because of the smaller size and composite construction of UAVs.

In addition to knowing the location of the UAVs, knowing where the vehicle is likely to impact the ground should the FTS be employed is important. This position is typically generated using the known location of the vehicle, characteristics of the vehicle, and current wind profiles with respect to altitude. Bauer and Teets, 1997, describes this process and the algorithm employed. The impact location is displayed for the RSO and the flight crew. This location is also used in real-time for flight planning. Knowing the position of the UAV and the predicted impact point within the sterilized restricted airspace accurately is paramount to maintaining range safety with enforcement via an FTS.

Without exception, UAVs wishing to operate from DFRC and the Edwards AFB complex must incorporate an FTS to ensure range safety and ultimate compliance with range boundaries. The FTS must, at a minimum, produce flight vehicle conditions of zero lift and zero thrust upon activation, resulting in vehicle impact zones well within the restricted area. As part of the FTS, projects can elect to employ a recovery system. Perhaps such a system would consist of a parachute to increase the chances of vehicle recovery upon termination, minimize the impact damage, or both.

Weather Factors

The right weather conditions are necessary for testing UAVs. Recently Pathfinder flight test requirements for flight above altitudes of 70,000 ft required the test team to find a range larger than that previously used at Edwards AFB. (The higher the UAVs fly, the greater downwind drift distance if the FTS is activated.) Careful consideration of the historical weather patterns to determine the optimum location for an attempt on the world solar-powered altitude record was required. This extremely light wing-loaded solar-powered aircraft was poised to fly up to over 70,000 ft, and the right weather all the way up and back down (12 hours later) was critical. Factors to consider include wind, turbulence, and cloud cover; therefore although Pathfinder set its initial altitude record over Edwards AFB, its recent altitude attempt and subsequent success took the vehicle to the Hawaiian island of Kauai. There, operating from the U.S. Navy Pacific Missile Range Facility, the right weather conditions were found in conjunction with other operational requirements, such as airspace availability, adequate runway, low aircraft traffic, low frequency traffic, as well as the length of the solar day and sun angle (because of the lower latitude).

Three other key weather elements to monitor include humidity, temperature, and pressure. Moisture or icing (which is possible even when no moisture is visible) can adversely affect the performance of all UAVs. Particularly sensitive to icing are unheated air data probes (or pitot static probes). Unheated probes are used sometimes because of size and power constraints. In this case, mission rules should prohibit flying in possible icing conditions. Such were the rules with the X-36 aircraft although air data override modes were included and tested during training.

Also worthy of note is the likelihood that the UAVs will not be flying in the same conditions as those found in standard atmosphere reference tables. The amount that the actual temperature varies in comparison with the tables is surprising. This fact requires a careful consideration of temperature operating limits of all UAV components with local and seasonal variations. Temperature should be monitored using thermocouples in the vicinity of critical aircraft components or experimental packages.

Frequency Availability

The right frequency availability is also essential for successful flight testing. In Southern California, the available frequency spectrum is highly constrained because of the high volume of local demand. This fact, combined with the reality that the majority of UAVs use a great deal of bandwidth, makes the job of deconflicting frequencies increasingly difficult everyday. To make matters more complex, in the future, multiple UAVs will be required to share the local airspace, making frequency deconflicting even more difficult. Satellite communications with the UAVs offer the only relief in sight.

Hardware and Software

The fundamental practices employed in the design and fabrication of a UAV’s hardware and software require, at least in principle, the same care given to piloted aircraft. Compromises made that are not well considered or understood can affect mission success to an unacceptable degree. Del Frate (1996) notes that hardware and procedural deficiencies contributed greatly to a number of mishaps. Vehicles involved in such mishaps include the Perseus A, Perseus B, Pathfinder, and Raptor Demonstrator (D-1). Some issues that have recently had to be dealt with are delineated below.

Hardware Design

In the majority of cases because of being smaller than manned aircraft, UAVs suffer volume deficiencies that often preclude redundancy in critical aircraft systems. The recovery system and FTS can provide a redundant means of getting UAVs out of trouble. In the case of the X-36, having built a second aircraft offers redundancy in its most basic sense, thereby increasing the odds of mission success. A lesson learned at DRFC with respect to the operation of UAVs is redundancy, in any form, is likely to increase the chances of mission success.

Because of its critical importance in so-called "single-string" systems, hardware reliability must be built-in, not only during fabrication but also during the design process. Experience with the X-36 vehicles showed this principle clearly. Boeing Phantom Works conceived, designed, procured, and built the X-36 vehicles as miniature fighter aircraft, not model airplanes. No compromises, other than volumetric constraints and single-string systems, were made. The company, with NASA's encouragement, relied on its standard best practices in the design and fabrication of the aircraft. The result was a structurally sound, volumetrically efficient, and robust aircraft that would outlast its initial programmatic goals with life to spare. Single-string systems can suffice, but such systems are unforgiving in the extreme of compromise and inexperience.

Hardware Recommendations

Recent experience at DFRC has yielded several suggestions for increasing hardware reliability. The most significant of these suggestions are listed below.

- Test the airframe structure as much as practical before flight (suggest testing to design limit). This recommendation is particularly true for composite airframes. Such airframes are difficult to inspect for proper joint bonding. Coupon testing of various materials and bonding techniques can provide early information before airframe fabrication. Ground vibration testing (GVT) can identify the structural modes of an airframe. The GVT can be used not only to determine airworthiness but also to validate structural design methodology and analysis.
- Test the aircraft systems in an altitude chamber. Many aircraft components were never designed to operate at the extreme cold and low-pressure conditions encountered by the high-altitude science aircraft. Chamber testing is a must for components unless they are off-the-shelf with suitable prior qualification for expected environments.
- Recognize that like all aircraft, UAVs have a tendency toward weight gain. The weight gain causes a lower g airframe that will affect a multitude of other areas, such as center of gravity, range, speed, payload capacity, opening shock loads on a parachute, descent rate under the parachute, and landing gear limits.
- Maintain strict configuration control on the vehicle.
- Ensure that before switching between redundant systems, the system that is about to be activated is functional. Note that switching mechanism carries a separate risk for failure.
- Take several precautions if the aircraft systems are single-string. Carefully track the hours of the UAVs critical systems and sensors as they accumulate against their normal expected lifespan. Establish a conservative life-cycle margin and replace or service these systems and sensors at predetermined intervals. Also, determine in advance what actions to take if the critical single-string system malfunctions. (See Procedures and Training section.)

Software Design

Uninhabited aerial vehicles tend to rely on software for their well-being to an extent even greater than the full-scale, piloted aircraft. This fact is especially true in the case of completely autonomous (non-piloted) aircraft. In these systems, human intervention may be limited to only sending occasional commands to the executive software of the aircraft, invoking such preprogrammed actions as taking off, changing station coordinates, initiating data transmission, and requesting return-to-base and landing. Software core and regression testing as well as mission simulations are vital to the design and modification of flight software. Validation and verification testing along the way may eliminate surprises and delays.

Software Recommendations

Recent experience at DFRC has yielded several suggestions for increasing software reliability. The most significant of these suggestions are listed below.

- Computer-aided software engineering (CASE) tools applicable to the code, and methods used can be beneficial if brought into the software design process early.
- Hardware in-the-loop simulations are well worth the effort because the software, simulation, and vehicle systems can be thoroughly tested. The realism in the crew training also increases.
- Strict, well-designed software configuration controls are critical and should be implemented from the beginning.
- Having a pilot in-the-loop has saved the UAVs from damage or crashes on numerous occasions. Serious thought should be given before taking the pilot out-of-the-loop.

Human Factors and Cockpit Design

While automation usually plays a major role in even piloted UAVs, human factors must be considered. Several mishaps can be attributed to the absence of attention to details wherein high workload situations allowed human error in the interpretation of displays and controls.

The reality that UAVs require much more than meets the eye in terms of design care, materials and components, and piloting skills is slowly surfacing. One of the main issues to consider is that the pilot's five senses are not at work in a UAV's cockpit. Many of the cues the pilot consciously and subconsciously receives are not available in the ground control station (GCS). The physical cues, such as sights, sounds, and odors as well as the feel in the "seat of the pants" of sudden accelerations or vibrations, are naturally not part of the UAV pilot's environment. To mitigate this deficiency, the test teams have had to use a certain amount of ingenuity.

In the case of the X-36 aircraft, a major airframe company with a seasoned test pilot developed a pilot interface with as much of the feel of a fighter aircraft cockpit as possible. The pilot's station is a well-appointed pilot's cockpit with a normal "stick" and a heads up display (HUD). The view is nearly identical to what one would see if seated inside the X-36 aircraft (if that were possible).

The test pilot recognized the importance of auditory cues during the development of the pilot's station and urged the engineering team to incorporate the downlink of sound picked up by an onboard microphone. This microphone was located within the cockpit area of the vehicle. Its output modulated a subcarrier on the downlink video signal through a small audio amplifier. Inclusion of this downlink of sound proved invaluable and potentially saved the UAVs in some instances. (See Walker 1997.)

From whatever perspective that the pilot of the UAVs is given by his/her control station, situational awareness of where the vehicle is with respect to the range features and boundaries is critical. For the X-36 pilot, this information was provided by a 20-inch color monitor, just off to the pilot's left, showing clearly the range boundaries, runways, waypoints selected, and any other airspace features, with a real-time depiction of the vehicle's position within these boundaries. This display provided the primary information of vehicle flight path to the pilot and test director. In addition, analog displays of fuel quantity, engine power setting, yaw rate, uplink and downlink signal strength, and numerous caution, warning, and advisory symbols were provided. This display was called the horizontal situation indicator (HSI), and it became a primary range safety tool to the pilot.

Cockpit designs vary significantly from one test team to the next. A great deal is determined by the heritage of the aircraft design and the experience and resources of the organization. In the case of the Pathfinder, the situation is totally different. The Pathfinder's team has extensive remote control modeling experience, and the pilot's station is more like what would be expected from someone accustomed to flying an airplane from the outside of the airplane. A very complete display suite provides appropriate monitoring of the aircraft systems and of the navigational aides, but two things stand out to the casual on-looker. First, the stick is very nearly the same as those used in remotely controlled model airplanes. Second, the downlinked video is not a view out the front of the UAV but rather is a view from a camera positioned on the left wingtip looking inboard at the airframe. It is used primarily for monitoring the vehicle structure, motors, and propellers as opposed to looking at where the UAV is going.

From this comparison, it should be evident that the two flight teams perform takeoffs and landings differently, and this is indeed the case. In the case of the X-36 aircraft, the pilot does it all from the seat in the GCS. Conversely, the Pathfinder uses two crews. One crew performs the takeoff perched on the top of a van situated near the aircraft on the runway. This procedure allows the pilot to physically see the UAV, its orientation, and proximity to the ground. The pilot can also note any problems the vehicle may be experiencing and observe any potential traffic conflict. When the Pathfinder is approaching the visual limits of the first pilot, control is transferred to the second pilot and crew located inside a GCS. Upon return to the airport, the control of the Pathfinder is returned to the first crew for approach and landing.

Determining whether the X-36 approach or the Pathfinder approach is better is difficult. A lot of it has to do with what the flight test team has the most experience with. Another factor is the performance of the UAV with respect to its energy and speed. The X-36 approaches to landing were typically 2 to 3 miles. Landing and rollout distances were in excess of 2500 ft. It would have been extremely challenging for a ground-based pilot to see the aircraft approach or to control its final flare and touchdown. The pilot-in-the-seat approach was the best for X-36 aircraft. Both programs have been extremely successful with numerous difficult flights. (Incidentally, the Pathfinder has several night landings under its belt as well.)

The following features would be desirable in a well-designed cockpit and GCS. This list is in no way to be considered exhaustive.

- Downlinked video of views from the UAV.
- Sound from inside the UAV.
- Autopilot status clearly displayed and viewable by the entire flight crew.
- Switch functions clearly marked and guarded.
- Adequate separation between switches to prevent inadvertent activation.
- Multifunction switches should be limited or eliminated.
- Gauges which can be used to monitor more than one parameter should be eliminated. When this type of gauge cannot be eliminated, clear labeling of the parameters involved should be provided.
- Communications between flight crew members need to be clear. Use of high quality headsets and microphones is mandatory.
- Visual displays with critical information need to be within a comfortable scan range of the pilot's eyes.
- Use of different colors on the displays to enunciate health of systems is very desirable; for example, green for healthy, yellow for caution, and red for danger.
- Status of critical parameters should be easily observable by the entire test team.

Procedures and Training

One cannot say enough about developing and documenting a good set of procedures and practicing them. This requirement is especially needed for emergency procedures. Our experience has been on both extremes of this spectrum. Insufficient attention in this area has yielded disaster. On other occasions, the practice really paid off, and the UAVs were saved. Hopefully, the following examples will add emphasis to this point.

On one occasion, a UAV started to exhibit some erratic pitch, roll, and yaw behavior. It is believed that one of its critical sensors was failing. The flight crew noticed the behavior in time but responded to it incorrectly. As a result, the vehicle went out of control and broke-up in mid-air. It is believed that this UAV could have been saved. Although some thought had been given to in-flight emergencies, thorough procedures for all flight phases had not been completely established and rehearsed. For this particular situation, procedures for identifying and mitigating the loss of this sensor were lacking.

During the second X-36 flight, the value of well-defined and rehearsed emergency procedures was well illustrated (Walker 1997). A failing component in the ground station antenna caused link loss with the vehicle just as the UAV began to enter the test area (the furthest away it had been). Upon declaring link loss, the X-36 software took over just as it had been programmed (and tested through simulation). With the aid of GPS, this software navigated the vehicle over a waypoint on the north end of Rogers Dry Lake and loitered, waiting to be located by the failing antenna and to have the link reestablished. Crew training and preparation, documented emergency procedures, and cool and clear thinking that this preparation had inspired allowed control to be regained and the X-36 to be landed safely.

Procedural and Training Recommendations

The following practices have been observed in successful UAVs flight programs. This list is also not exhaustive.

- Emergency procedures exist for all critical sensor failure modes and for the resulting vehicle upset cases during all phases of flight. These procedures are practiced routinely. Typically, the flight crew must maintain a specified currency for a particular UAV, or the flight is delayed until the crew meets the currency requirements.
- Even more important than practicing the emergency procedures is practicing the normal procedures to the point that they are second nature. This familiarity allows anomalies to be addressed with increased attention.
- Crew rest requirements (for both flight test crew and ground crew) are well established.
- Hardware in-the-loop simulations are used to provide crew with realistic training and practice opportunities as well as to simulate anomalies and failures.
- Training recognizing the failure of critical sensors in real-time is provided. The need for such training is especially critical for UAVs with single-string systems.
- Checklists and test cards are routinely used.
- Good flight crew GCS discipline is maintained.
- Good communication practices and etiquette are used. Typical examples include sufficient isolation of the pilot to prevent distraction yet provide pertinent information for aircraft and status, mission progress, and fuel burn.
- Negative training situations should be avoided. For example, instances where training is taking place with either a GCS or with instruments which are different than those which will be used during the actual test flight pose several problems.
- The entire team should review and update the emergency procedures. Reviewers from outside the program may be brought in to independently evaluate the emergency procedures.

Mission Rules

Mission rules are also included in this Procedures and Training section because these rules are an essential element of UAV's flight crew training and documentation. These rules specify at the outset criteria for actions before and during flight with respect to go—no-go requirements, aircraft and environmental placards, minimum crew staffing, and emergency procedures. Such rules are best conceived and developed in a simulation environment, when levelheaded thinking prevails, and where alternatives can be tested and refined safely. Once documented and agreed to by the test team, these mission rules must be adhered to without question or alteration during the course of a flight. Adherence to mission rules also prevents the crew from exceeding well thought out limits when everything is going well or the continuation of a flight with less than optimal system health. Mission rules also summarize the critical and difficult decisions that must be made during emergencies when preoccupation with failures and unknowns would otherwise influence the test team in the heat of the moment.

Concluding Remarks

The NASA Dryden Flight Research Center, Edwards, California has been a participant in UAV testing in the past and continues this tradition as a new generation of UAVs are designed, developed and tested. Over the last 4 years numerous experiences have been accumulated. Lessons learned from these experiences along with resulting recommendations are presented here in an effort to help developers of UAVs to conduct safe and successful flight programs. Although not an attempt at being an exhaustive study of the topic, the purpose is to highlight the areas that repeatedly require attention in this type of program.

For example, a remote, well-protected, tightly controlled airspace with little population is essential for this UAV flight test research. Careful analysis of the historical weather patterns is needed to determine the optimum location. Availability of the right frequencies is also essential. In addition, hardware and software reliability is critical. Well-developed procedures, training, and mission rules are also needed.

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