Embracing "Fly Fix Fly"

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Abstract

This paper focuses on embracement of the “Fly-Fix-Fly” testing method using a scaled application approach accelerating engineering learnings to optimize efficient fiscal and schedule design advancements. Small scale unmanned aerial systems serve as the target center point for applying this methodology. Rapid prototype development and testing yields the opportunity for powerful early learning. The key to success lies in development of a knowledge point capture scheme tailored to the design objectives that yields a comprehensive data set enabling accurate and timely advancements to the final design solution. These considerations will be discussed by review of several recent varied small unmanned prototype aerial systems and lessons learned through results obtained in the course of investigating test incidents and mishaps.

Introduction

Beginning at the birth of flight dating back to the inaugural days of the Wright brothers through the 1940s, the concept of “fly fix fly” was acceptable. This basic concept consists of the following: developing, building and flying a testbed aircraft, accepting the high likelihood risk of experiencing an incident or mishap including total loss of airframe (with possible inclusion of injuries or fatalities), applying corrective actions for the most likely cause, and returning to flight with a repaired or replaced aircraft. As fatalities mounted and product development investment escalated over the years, this concept was abandoned and more proactive and predictive approaches to design and test safety of aircraft were introduced. Proactive and predictive approach to managing risk in the aviation industry had been around some time, but an extra emphasis was placed on this concept as Safety Management Systems (SMS) came online to in the 2000s.

Rapid Prototyping

Rapid prototyping, for the purpose of this paper, is defined as the expeditious creation of a small scale unmanned aerial system absent the costs associated with detailed analytics and assessments for a typical full-scale production representative vehicle. This agile strategy optimizes efficient use of fiscal, personnel and schedule resources to attain powerful early learnings while demonstrating with reasonably high confidence a majority of the functional design technical requirements considered for a final production vehicle. The comprehensive data set obtained during this phase contributes immensely to the final design solution for a vehicle.

However, the authors caution this approach should be embraced only if risk to personnel safety is acceptable (after assessing the risk and managing to reduce exposure to personnel) and it produces potential cost savings, especially in the realm of unmanned experimental prototypes.

The ability to gain knowledge from getting a flight up in the air for testing, without years of costly predictive analysis, offers a large return on real collected data to analyze. Four incidents from three different unmanned prototype platforms will be reviewed along with comparing and contrasting the causal factors. At the conclusion of discussing these events, a retrospective observation will be shared addressing process development moving forward. The organization approached their testing in an enthusiastic method to try and achieve maximum benefits in accelerated time frame.

Overview of Dominator

Dominator is a cargo aircraft container sized vehicle designed for air launch, self-unfolding flight surfaces, with air start capability, powered by heavy gas. As part of the risk reduction approach, the first versions and configurations were ground launched from a roof top rack mounted on a truck. Additional risk reduction testing included an air dropped version of a simulated shape to validate the flight surface deployment system. Finally, all these tests were morphed together into a "full up" vehicle which recovers on a "skyhook" recovery system similar to ScanEagle UAVs.

Dominator Incidents

Seven successful ground launch and air launch flight tests were accomplished prior to this mission attempt. The objective of this flight attempt was to validate a new payload could be flown in this size of an air vehicle and it would have no interference on the air vehicle and vice versa.

On flight number 8 the Dominator vehicle was preloaded onto the ground launch platform. The Vehicle Initialization Computer (VIC) operator, the Carriage Operator, and the Driver were stationed at the hangar to initialize and start the vehicle. The balance of the test team (Test Conductor (TC), Flight and Navigation Subject Matter Experts (SMEs), Ground Control Station

(GCS) operator, and Telemetry (TM) SME) were positioned at the GCS in preparation for the flight. At 6:30 a.m. on June 26th while personnel were entering the GCS, Navigation noticed the field south of the launch runway was occupied with civilians (i.e., farm workers). The flight test window of opportunity was 6:00 a.m. to 11:00 a.m., and with a 3.5-hour test flight planned, the delay was jeopardizing the opportunity to maximize the flight time in the allotted flight window. The team implemented the contingency plan, an offset flight path to the north, to avoid an unsafe condition of civilian overflight. At approximately 7:15 a.m., the TC initiated test protocol by walking through the test cards. VIC was commanded to initialize the vehicle at 7:16 a.m. Final details to determine proper Launch Mission offset and engine start warm-up was delayed to 7:25 a. m. At 7:33 a.m., engine start commenced, nose connector disconnected, and the Driver and Carriage operator took the Launch Initialization position preparing for launch. Per the test cards, the Carriage operator contacted the TC to verify launch truck was in position. After receiving a "GO", the TC called for GCS to initialize Intent to Launch (ITL), which prescribed scheduling the engine to full throttle and the elevators and flaps positioned for climb out once released from the carriage. The sequence was interrupted when the TC told the Driver and Carriage to hold at the Launch Initialization point. The test team held for approximately 30 seconds, which caused the engine cylinder head temperature to rise due to lack of airflow.

The cylinder head temperature continued to rise close to the maximum allowed temperature and the GCS operator notified the TC. Upon entering the launch window, and with a "GO" from the TC for launch, the Dominator vehicle was released from the carriage. Almost immediately, the Dominator vehicle struck the right-hand bed side of the launch truck, and skidded down the runway up-side-down. The test was aborted and initial investigation and wreckage recovery began.

Investigation 1

Preliminary findings indicated first, the team was distracted by last minute discussions on the proper launch mission offset (the mitigating procedure reducing the unacceptable risk of civilian overflight). Second, the ground launch dry run was not thorough. This practice run should have walked through the test cards with an active UAV atop the launch vehicle, all the way through simulated launch, but just short of actually releasing the vehicle. Instead, the launch vehicle was commanded to begin the live run (opposed to the planned simulated launch) prior to verifying RPM increase. TM notified TC of the cylinder head temperature situation contributing to the TC command initiating run in of launch vehicle, which was out of test card sequence (the rationale: get airflow over the cylinder head, thereby reducing the cylinder head temperature).

Findings:

The test cards did not explicitly state how to handle an overheat condition during this step of the test sequence. The original TC who authored the test cards and was present for all previous ground launches was no longer on the team and not available to train the current TC. Other experienced team members did not catch the oversights of the team. The Dominator UAV failed to attain a positive rate of climb during launch resulting in the UAV striking the right aft side of the launch truck, and skidding down the runway up-side-down. GCS Log files indicate the ITL was enabled, then disabled. The Intent to launch (ITL) command is a single on/off button on the GCS screen. This made possible an inadvertent “double-click” which only momentarily activated (a display issue due to limited parameters available per screen) and then deactivated the command. The ITL puts the throttles to 100% and the flight control surfaces into the correct position for launch. Test cards did not explicitly require a verification of ITL received from GUIDANCE, though it was implied. The new TC was not aware that GUIDANCE primary focus should have been ITL. A subsequent test card update was implemented to reflect this. Although the objective was not accomplished, several lessons learned were noted and passed on to future Dominator testing along with other Boeing small unmanned aerial programs. These lessons learned included; redesign of the double click issue, ensuring test cards were detailed and accurate, along with ensuring a very thorough "dry run" rehearsal to flush out any perceived gaps or out of sequence steps during a launch.

Second Dominator Incident

After a few months of digesting the lessons learned and implementing the corrective actions above, the team loaded a payload and went to a new range for flight attempt 9. Very similar to flight attempt 8, the objective of this test was to validate the operation of a payload on a UAS the size (~80lbs) of Dominator. Part of the mission included communication with another airborne UAS. The other subject small UAS was launched prior to the Dominator and had no anomalies during climb out and flight. The Dominator system was initialized at the GCS and cleared for flight. The Dominator launch truck proceeded to the hold point on the runway. The Pilot Vehicle Interface personnel reported the Dominator was not showing movement and the TC directed a vehicle hold while the team analyzed the problem. The Pilot Vehicle Interface team was able to reset and identify the Dominator vehicle. The TC directed the Dominator to set for launch, which was confirmed by the launch vehicle release operator. The launch vehicle was cleared to proceed to launch speed. The Dominator vehicle appeared to launch normally from truck carriage. Eyewitness state the air vehicle failed to climb above ~80' AGL. Reported winds were within limits at launch. Air vehicle estimated winds recorded speed was approximately 20kts, which became a tailwind on the first commanded turn and caused a reduction in the relative airspeed over the wing resulting in a loss of altitude due to decreased lift. The test team switched mission plans to attempt to arrest the decent, but the vehicle kept descending and impacted terrain while still in a tailwind.

Investigation #2

No one causal factor found after a deep dive. However, the following were determined to be contributory factors:

- The engine was operating at the lower end of its expected performance envelope.
- The air vehicle was being operated at the highest weight to date. (~ 8% heavier)
- Control laws for commanded throttle were not optimized for best rate of climb performance (not a Dominator requirement based on air launch design).
- Electrical loads were within limits but were higher than prior flights, resulting in additional load on engine.
- The sustained winds were near limits with gusts and variability.
- Flight Operations Team included several new, inexperienced members, missing key experienced personnel (CRM).
- There was cost, schedule, and management pressure to execute on plan.
- The engine was near temperature limits at takeoff.
- The propeller was not optimized for climb performance (this was not a requirement based on air launch design).
- There were questions about fuel storage/handling conditions and duration (i.e. 1 yr. old, temp/humidity unknown).

For this flight attempt, the mission objectives were not met since the air vehicle was airborne for such a short duration. Lessons learned from this mission included all the causal factors listed above with special focus on the wind conditions and inexperienced team members. These lessons learned were passed onto other UAS programs to which has helped prevent mishaps since this last Dominator flight attempt.

Overview of Phantom Ice

The Phantom Ice air vehicle is one of the smaller UAS systems Boeing has developed to date. The vehicle meant to be hand launched and easily assembled/disassembled, fitting into a "rucksack." Powered by lithium battery, the proposed mission is Tactical - Intelligence, Surveillance, and Reconnaissance (ISR). Noise output is extremely low and the vehicle was fully autonomous with the capability of the Pilot in Charge (PIC) to intervene as needed. All tests of the vehicle included being truck top launched similar to the Dominator platform previously mentioned. The objective for this test was comparable to the previous dominator tests as it was testing a new payload at a different range location for a much smaller and possible future hand launched air vehicle.

Phantom Ice Incident

Phantom Ice had two previous successful flights. For flight test 3 of this platform, the objective was to carry a payload for a customer located in restricted airspace in California, Similar to the Dominator tests, the test team was in place, dry runs had been conducted with the strap over the vehicle on the truck top launch. Wind and moisture were within the test plan operating limits (where measured). However, the trees on some of the surrounding hills looked like they were moving due to more than a slight wind, which was measured at the runway near the TM trailer. The strap was removed and the flight test roll commenced. The "carriage operator" pulled the rope attached to the pin, the vehicle climbed at a lower rate of ascent than previous successful tests. The air vehicle continued to follow the mission profile for a few minutes when it suddenly appeared to descend. The operator barely recovered it before it then went straight up again climbing to around 100’ AGL, followed by an immediate nose down accelerating in a dive until it impacted the ground.

Investigation:

- A review of telemetry and the flight data recorder showed the following: winds were much higher at 100’AGL than at the surface where the winds were measured and determined to be within the air vehicle’s operating limits.
- Vehicle performance did not match predictions; autopilot was not robust for the actual winds at altitude.
- Propulsion was reduced, due to a voltage drop in diode wiring.

Clearly, the objective of this mission was not met, but the lessons learned including ensuring winds are within limits throughout the proposed flight profile and some hardware and software upgrades were passed on to other programs to help prevent reoccurrence of these issues in future testing.

Overview of HYPRC

The HYPRC is 5.5% scale model of a potential hypersonic air vehicle. Constructed of carbon fiber tubes, 3D-printed mounts, foamboard frames and skin and powered by an electric ducted fan. It is fully instrumented and remotely-controlled using high-quality COTS RC-model equipment. The instruments include: 6-axis acceleration, GPS position and alt., baro alt., pitot static airspeed, current draw and battery voltage. The purpose of this vehicle is to explore and understand Takeoff/Landing Feasibility, along with gathering data on low-medium speed stability and control. Lastly to learn and prove how to make low-cost but useful flying models for future concept development.

HYPRC Incident

The initial flight occurred on 07 May 2020. After a successful controlled take-off, the aircraft climbed steadily to about 200 feet altitude before gradually banking to the right as planned. The aircraft appeared stable during the initial portion of the bank in a right-hand traffic pattern and was maintaining altitude. Before the first full 180 degree turn of the pattern was completed, at approximately 5 to 10 seconds into the bank at or near where the aircraft was planned to enter a straight run, the aircraft began to lose altitude and was not flying in a controlled manner. At this point the aircraft started to lose altitude and level flight. The aircraft then banked hard left on its side and nose down, eventually experiencing surface impact. The aircraft was located at approximately 12 noon Pacific Daylight Time (PDT) in a vacant field several thousand feet away from the take off point in a vacant desert lot.

Investigation

The safety investigation was accomplished in two phases. The first being performed by the onsite flight test team involving vehicle recovery, physical evidence collection, securing of data and witness statement preparation and collection. The second phase involved a formal Investigation Review Board (IRB) chaired by independent members and supported by program development and flight test team personnel. The IRB adopted use of the KNOT (**K**now, **N**eed to Know, **O**pinion, **T**hink We Know) investigative tool. The KNOT tool was initiated with development of the following problem statement: “What led to the vehicle loss of control”. Three main causal branches were identified, developed, and analyzed. These branches were:

- Architecture / Design Flaws,

- Hardware / Install Flaws / Errors
- Operations

Each branch was developed with findings categorized into either an Undesirable Condition, Eliminated, or Contributing Factor determination with the latter category representing significant findings. Five Contributing Factors were identified, each leading to lessons learned for future applications. The 5 Contributing Factors (CFs) were:

- The pilot lost orientation,
- The visual observer also lost orientation,
- The sun reflecting off the tape potentially contributing to visual observer orientation loss,
- Was the vehicle unstable?
- Was the vehicle untrimmed?

The corresponding Lessons Learned associated with these CFs were further sub-categorized into either Actual Test, Pre-Test Readiness, Test Set Up, or Vehicle Readiness. The following is a bulletized listing of the Lesson Learned by sub-category:

<u>Actual Test</u>

- Have spotter/safety stationed as an additional observer for better safety containment of vehicle in the event of an issue and for SA, with a fire extinguisher for quick access to any fire in the southern fields.
- Communicate real-time on all test abort or test card changes to all test team members
- The Pilot should not be the Test Conductor: Test Conductor and Pilot need to be focused on different things at the same time, and that is not a workable situation.

- Vehicle should be equipped with real-time flight tracking, and the Ground Station Operator should monitor and relay the vehicle's orientation to the Pilot, to aid him/her in keeping the vehicle within the planned flight path.
- Add mission planner or other companion computer that does not interfere with com and/or telemetry.
- Add clarification of Go / No Go criteria. Re-brief team on the communication plan that was developed for this flight test effort. Update as appropriate.
- Review vehicle paint scheme for ease of orientation determinations.

Pre-Test Readiness

- Make sure all test assignments are clearly defined and practiced pre-test
- Assign a test team member to record test day key activities, timeline and initial completed activities. Use new test card for any repeat tests after activity hardware/SW breaks, equipment breakage/repair or repeats on alt. days. Call out any recheck requirements or open steps that need to be completed and/or repeated before subsequent card steps.
- Develop/train/use for test a vetted set of Go / No Go criteria. Include in detail Test Cards and/or checklists.
- Site selection: RC usage, cost, schedule, obscurity, line of site and accepted risk. Review best practices for site selection with Flight Team.
- Need to review and perform program planning against existing test readiness review process documentation. Right size as appropriate with appropriate reviews and approvals.
- Compare and confirm flight test data to existing analysis, weight assessments, build details and wind tunnel data that can be compared. Make changes as appropriate.

Test Set Up

- Reduce the pilot work load during the preflight readiness.

Vehicle Readiness

- Acquire real-time flight data (GPS position, altitude, airspeed, aircraft orientation) for ground station operator to relay to pilot.
- Paint vehicle to better assist orientation.
- Add structural alignment fixtures/tooling and/or checks to build and repair process. Include checks of engine alignment and/or variable thrust of engines

Reoccurring Themes or Patterns

These four incidents were reviewed for common causal factors and any other notable themes. Schedule Pressure (or perceived schedule pressure) was the number one theme in all of the incidents. Teams did not follow exactly every step for both preparation of the aircraft and the supporting team for the test events. Related to succumbing to schedule pressure was the trend of inexperienced test teams. Inexperience can lead to lack of resistance to real or perceived schedule pressure, lack of ability to self-detect missing steps in preparation for a test flight along with addressing challenges of new and unique test ranges and environments. The lack of experience can also come to play when addressing meteorological assessments. The final common thread between several of these incidents was wind speed sensitivity for vehicles of this scale. Specifically, wind speeds at the surface versus wind speeds starting at 70' AGL and above. The difference could possibly be out of the vehicle's limits, with rising terrain also adding to the potential of these wind speeds to deviate significantly from those measure previously on the ground. Albeit, not necessarily a common cause, in each mishap the organization's these products were developed and tested under separate organizational structures.

Recommendations

- Ensure accurate and thorough training of test team members on UAS programs.
- Level set expectations, large airplane test programs don't precisely scale to UAS testing.
- Emphasize test team focus on resisting schedule pressures.
- Ensure team personnel review site(s) environmental / meteorological considerations.
- The most impactful recommendation is for all small UAS products to be tested under the same organization. A unified testing organization focused on a small unmanned systems approach would ensure centralization of team documentation enabling consistent learning applications. The hypothesis being leveraging a single missionized organization would increase success rates in the already successful small scale UAS test programs.

Benefits of Fly Fix Fly

Even though the test teams were highly disappointed in each of these test results, the test investigations yielded powerful learnings. Each incident was investigated in a timely manner and lessons learned passed on to other UAS programs. The lessons learned have improved design and test protocols for follow on new air vehicles, along with reduced mishap rates of rapid prototype test vehicles. The time and cost savings from performing months and months of predictive analysis exponentially offset the expense of damaged parts and in some cases the loss of the whole rapid prototype vehicle. Test schedule reductions of follow on UAS programs have also been able to be accelerated due to lessons learned from the incident data gathered. Moral of the story – "Don't be afraid to fail (safely)".

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