SpaceShipOne

Another Step for Mankind

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All photos and drawings used are from the Scaled Composites, LLC website unless otherwise indicated.

Problem Statement

SpaceShipOne, winner of the 10 million dollar Ansari X-Prize, was designed, integrated, tested and flown by Scaled Composites, LLC after eight years of development. The rules of the contest were to launch three people to an altitude of 100km (62 miles), land safely, and repeat the launch in two weeks with a 90% reuse of the previous flight components. The X-Prize inspired 27 teams to participate and represent the NASA desire for a Commercial Orbital Transportation Services (COTS). Although it is truly remarkable that a private company was able to successfully breach the threshold of space and produce a new group of non-NASA astronauts; the underlying question for systems engineers is, how did they do it? In particular, how was SpaceShipOne's design integrated and tested as the first successful privately funded space ship? This paper will attempt to answer this and other related questions.

Overview

In 1996, Scaled Composites, LLC began the conceptualization of the design of SpaceShipOne. Funding for the project (development cost of $20 million) was secured from a private donor, Paul Allen of Microsoft. The SpaceShipOne System consists of the spaceship, SpaceShipOne, and a launch vehicle, the White Knight.

Figure 1 SpaceShipOne and White Knight

Figure 1 shown above is a picture of SpaceShipOne and White Knight. White knight is a fixed wing twin turbojet that had its first flight on August 1, 2002. The primary purpose of White Knight was to carry SpaceShipOne to an altitude of 50,000 feet. The secondary purpose was to allow for the training of the astronauts to fly SpaceShipOne via the use of common flight controls. SpaceShipOne is a high altitude research rocket that can carry three people to 100km (62 miles). The configuration of the spaceship changes during the phases of the flight. (See Appendix A for more information on flight configuration). SpaceShipOne uses a hybrid rocket motor that burns rubber fuel with pressurized liquid Nitrous Oxide.

SpaceShipOne requirements

In order to adequately understand the systems engineering and integration process used by Scaled Composites, LLC, we need to first understand the key requirements SpaceShipOne needed to meet in order to be successful. Detailed information on key requirements was difficult to come by due to the proprietary nature of the project; however, the key requirements were derived by in-depth research.

The following are key requirements that SpaceShipOne had to meet in order to comply and win the Ansari X-Prize:

1.) The spaceship shall reach a minimum altitude of 100km.
2.) The spaceship shall carry a minimum three people (a pilot and equivalent weight).
3.) The spacecraft shall repeat the flight within 2 weeks minimum.
4.) The spacecraft shall have a 90% minimum reuse.
5.) The spacecraft shall complete the second flight before 1 Jan 2005.

SpaceShipOne system design

SpaceShipOne is technically a glider. More specifically it is a "monocoque structure with fuselage skin made mostly of carbon fiber/epoxy honeycomb with a Nomex core." As is the case with many complex projects, SpaceShipOne consists of many subsystems. Its major subsystems include:

- Avionics - INS-GPS navigation, flight-director, flight test data (recording & T/M), air-data, vehicle health monitoring, backup flight instruments, & video system [developed by Fundamental Technology Systems in tandem with Scaled Composites]

- Environmental Control System - scrubs CO_2, removes humidity and defogs windows

- Cockpit - allows single-pilot operation (VMC - Visual Monitoring Camera -day conditions only)

- Electrical system - Electrical power comes from lithium batteries.

- Hybrid Rocket Engine - A new non-toxic liquid-nitrous-oxide / rubber-fuel hybrid propulsion system was developed specifically for SpaceShipOne [developed by SpaceDev and eAc]

- Landing Gear System – Springs extend the landing gear and are manually released. Independent wheel brakes activate at full extension of the rudder pedals. The nose has a skid with a maple tip. Wheel brakes are hydraulic.

- Flight Control System - Provide flight control in three modes: manual-subsonic, electric-supersonic and cold-gas RCS (Roll Control System). Elements in the Flight Control System include: manual controls, trim servos, pneumatic-actuated 'feather', 6,000 psi, dry air bottles and yaw, pitch and roll thrusters.

Figure 2 shows the internal systems view of SpaceShipOne and Figure 3 shows the SpaceShipOne cockpit.

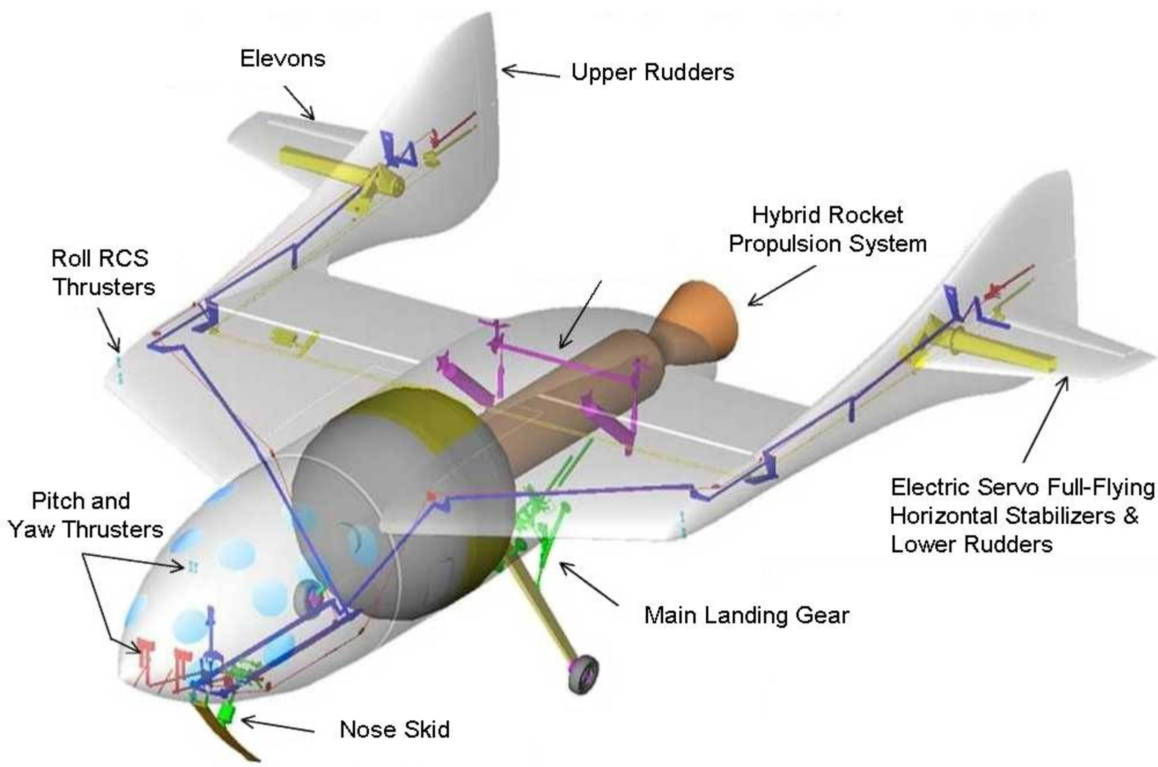

Figure 2 SpaceShipOne Internal Systems View

White Knight is also part of the SpaceShipOne system. Its purpose is to carry SpaceShipOne to an altitude of 50,000 feet. White Knight has the ability for carriage and launch payloads up to 8000 pounds.

Figure 3 SpaceShipOne Cockpit
http://www.nasm.si.edu/exhibitions/gal100/ss1.htm

SpaceShipOne Mature vs. Immature Technologies

SpaceShipOne utilizes a mixture of both mature and immature technologies in order to create a state-of-the-art commercial spacecraft. Some of the technologies utilized aboard SpaceShipOne as well as White Knight include the development of a simulator, avionics system, flight navigation unit, data reduction system, and hybrid motor.

The simulator developed for SpaceShipOne is "a full mission, 6 degree of freedom, non-linear, hardware-in-the-loop tool (www.scaled.com)." The simulator is equipped with a flight representative cockpit and an accurate pilot interface. The pilot interface is what drives the flight model and determines vehicle position as well as other inputs that are expected by the avionics. Once collected, the position and attitude of the vehicle are sent to a dozen display computers. These computers then use commercial graphic software to generate outside views. Those views are then displayed on monitors as well as a projection screen. The idea behind these technologies is that the pilots will be well trained and will already know what it is like to fly before even setting foot in the space ship.

Looking at the simulator technology, it is clear that Scaled used a combined approach of both mature and immature technologies to make the simulator successful. Specifically, all of the controls and displays for the simulator were developed in-house, and reflect many iterations and alterations in the simulator. Along with this, in-flight assessments of the controls and displays were performed during White Knight test flights where COTS software was used and integrated into the system to display position and attitude data.

The avionics systems for SpaceShipOne was contracted to a company called Fundamental Technology Systems (FTS). The function of the avionics system is to guide the astronauts on their mission. The hardware for the avionics system was primarily developed by FTS; the software was jointly developed by both Scaled and FTS.

SpaceShipOne is flown along an extremely precise trajectory in order to reach its maximum altitude. In order to accomplish this, the astronauts must depend on accurate flight path data that is provided by the Flight Navigation Unit (FNU). The FNU is a GPS inertial navigation system comprised of a System Navigation Unit (SNU) and a color LCD Flight Director Display (FDD). The FNU works when the SNU provides navigation and guidance information to the FDD and the ground. The transmission to the ground is via an RF telemetry downlink. Another job of the SNU is to acquire and store system health information for SpaceShipOne. The FNU was developed and performs similarly on both SpaceShipOne and White Knight. In addition to utilizing developing technology for both SpaceShipOne and White Knight, Scaled used a number of COTS software products in the development of the FDD that displays data such as warning messages to the pilots.

The Data Reduction System (DRS) commands a TM antenna in order to relay data from both White Knight and SpaceShipOne to Mission Control using a dual channel TM receiver on the ground.

SpaceShipOne uses a hybrid rocket motor consisting of a combination of both solid and liquid rocket motors, the composite nitrous oxidizer tank, and motor case/throat/nozzle (CTN). The motor components include controller, valve, injector, aft bulkhead, head insulation, ignition system and fuel. The propulsion system utilizes nitrous oxide (N_2O) gas and rubber fuels that are safe and provide enormous thrust of 88 kN to get the spaceship up to the desired altitude of 100km (~ 62 miles) within 87 seconds of burn, from the original 50,000 feet (~ 9.5 miles) above earth where SpaceShipOne is launched from the White Knight carrier. The Hybrid motor propulsion system was developed at Scaled Composites and manufactured by two (2) competitive subcontractors, SpaceDev and eAc companies. SpaceDev won the subcontract to build the rocket motor propulsion system.

While the concept of a hybrid motor is not new in and of itself, the configuration designed by Scaled for use on SpaceShipOne is a unique technology. What makes this technology unique is that the hybrid motor has its fuel case and nozzle cantilevered off the main oxidizer tank which forms part of its aft fuselage (www.scaled.com). A patent has been applied for this new configuration. Additionally, the oxidizer tank and fuel casing have a Scaled-designed composite structure.

In order to have good simulations you need to have good models. Interestingly, no wind tunnel testing was used for SpaceShipOne. All the design refinements and performance predictions were derived from computational fluid dynamic tools. This is very different from the standard methodology for testing air/space vehicles. Therefore, the designers at Scaled were relying solely on the validity of their software to confirm the durability of the space vehicle before flight. Significant software testing is imperative when relying so heavily on these results.

It seems that one of the strengths inherent to the design of SpaceShipOne is the amount of technology that is used by both SpaceShipOne and White Knight. Using identical technology allows the spaceship pilots to train using the carrier aircraft. Therefore, pilots can practice flying near-vertical profiles safely. Both aircraft also share the same avionics and environmental systems, along with the same stabilizer and the rudder trim actuators. Flying in the White Knight therefore allowed testing of these systems for both aircrafts. The actuators that retract the landing gear on White Knight, also feather the spaceship. Using this design strategy SpaceShipOne is equipped with all the necessary technology at a fraction of the cost employed by the government space program.

Systems Integration and Test of SpaceShipOne

Integration Testing for SpaceShipOne was completed in several phases. First, rocket motor ground tests were conducted, followed by SpaceShipOne ground tests, White Knight solo flight tests, and finally White Knight and SS1 combined flight tests. The combined flight test culminated with the record-breaking flight that won the X-prize on October 4, 2004, which also happened to be the 47th anniversary of the Sputnik flight.

Rocket Motor Ground Tests

The main components of the rocket motor were developed at Scaled. These components passed qualification tests by late 2002. However, the other motor components were outsourced and developed by two competing contractors: eAc and SpaceDev. The rocket motor tests took place periodically from November 2002 to November 2003 and consisted of full-scale motor firing events. All tests used full-scale, flight-article components mounted on a mobile rocket motor test stand and the same tank, CTN and adjacent structure as SpaceShipOne.

A mobile thrust Test Stand Trailer (TST) was to be used to measure the performance of the rocket and its flight motor. The rocket was mounted on the trailer the same way as it is mounted on the SpaceShipOne vehicle, using the same forward-center-fuselage and aft-fuselage of the rocket mounting positions. Actual flight components were used to test the structure and its system for the same vibration, temperature, and stress as experienced in flight. A series of load cells on the trailer were used to measure the thrust asserted by the rocket, its side force, and weight. For accurate thrust determination on the ground, a shortened 10 to 1 expansion ratio nozzle was used rather than the 25 to 1 expansion ratio nozzle on flight. Data acquisition was accomplished through a signal conditioning unit and a computer at the test site.

The trailer together with the rocket was rolled to an open field to prepare for testing. A filling system (MONODS) fills up the oxidizer tank of the rocket with Nitrous Oxide. A mission control unit was connected to the rocket system. A final check for safety was performed before the rocket was ignited for testing. The oxidizer tank was refilled many times for these repetitive tests. Thrust data was then collected for analysis and minimum/maximum thrust boundary conditions defined the pass/fail criteria of the test. A timing device was used to determine the elapsed time for a full tank burn and is used to determine the time and distance of an actual flight. Figure 4 below shows a SpaceShipOne rocket test at the Northrop Grumman Capistrano Test Facility.

Figure 4 Northrop Grumman Capistrano Test Facility
http://www.spacedev.com/hybrid_detail.php?id=1

SpaceShipOne Ground Test

The ground testing for SpaceShipOne started in the summer of 2002. By May 2003, SpaceShipOne had completed most structural and systems qualification tests. Remaining tests for glide qualification were cabin pressure, control systems, landing gear functionality and ground vibration tests.

- 21 May 03 – 23 May 03 Ground Vibration Testing (Flutter Qualification)
The objective was to collect vibration data to update the stiffness and mass distribution of the SpaceShipOne structural model.

- 24 Jun 03 – 09 Jul 03 System Tests

The objective of this test was to verify the as-built vehicle design requirements. Landing gear functional tests were completed. Flight control system and structural qualification tests completed as well. Flight test data calibrations completed.

- 14 Jul 03 – 24 Jul 03 System Tests

The objective of these tests was system level qualification for the various subsystems. Landing gear qualification, brake and low speed taxi tests were completed. Cabin proof pressure tests and leak rate tests were finalized. Structural load tests of the horizontal stabilizer, flight control system and feather mechanism were completed. The nose skid material needed change to prevent excessive wear.

- 8 Oct 03 – 21 Oct 03 Horizontal tail Modification Aerodynamics Test

The objective of these tests was to examine various changes to SpaceShipOne's tail assembly to provide better horizontal tail lift and tail lift-slope characteristics. These tests validated several aerodynamic fixes to solve the tail stall program.

White Knight and SpaceShipOne Flight Test

The White Knight was equipped with the same system components as the SpaceShipOne and therefore many tests could be run to focus on SpaceShipOne systems verification and validation. Intertwined with the solo White Knight flight tests were combined flight tests with SpaceShipOne. This allowed troubleshooting of any problems that arose with the dual ship configuration with a just the White Knight. The first combined flight occurred after 23 White Knight test flights. After four more White Knight flights, four consecutive combined flight tests were conducted. Many rehearsal and practice flights were performed utilizing just the White Knight. These test flights set the stage for the glide and powered flights. (See Appendix D for more details on all the flight and test data.)

Much of what was accomplished during the flight test phase was successful on the first attempt. Setbacks were minor at most, usually requiring a fix that was tested and verified thoroughly prior to re-qualification. In addition, multiple pilots were involved in flight-testing allowing for a larger sample of user tendencies to be evaluated. The test results indicate that the design was excellent and this allowed for a smooth integration. (Additional information on the successfulness of the test flights can be found in the Test and Integration Analysis Section). The smooth integration was the result of hard work, experience in the field, and adequate funding.

The following exemplifies the excellent design that facilitated a smooth integration. On June 21, 2004, the test objective was to launch up to 100 km. During the launch, there was a flight control malfunction. More specifically, the primary pitch trim control was lost. The design however, has redundant controls to provide robustness in such an occasion. The secondary pitch trim was used. Due to the anomaly, the climb was lower and re-entry was mapped farther south than planned. The glide capability compensated for the erroneous re-entry. This example shows the robustness of the design. Errors can (and most likely will) occur during a mission. A system that can still perform to spec in spite of this shows robustness.

One critique of the integration and test approach is one anomaly that occurred during a combined flight. On September 29, 2004, the first of the X-Prize flights, rolls occurred during the end of the rocket motor burn that was due to mid-thrust asymmetry. The results documented that this condition was not tested for on previous flights. Being that this was one of the X-Prize flights, this was very risky. Corner cases and anomalies need to be evaluated and accounted for early in the test phase to mitigate the risk that they might pose to the integration. Again, this did not adversely affect the results of this particular flight, because the objective was met. It is also difficult to isolate certain anomalies that may only occur after a test has been repeated numerous times. Due to the nature of testing in this case, where test runs are seldom, it may be difficult to find and correct all anomalies prior to final testing. Once again, an excellent design will mitigate this.

Test and Integration Analysis

The analysis of the integration and test of the SpaceShipOne System is divided into two parts. The first part simply evaluates the successfulness of each "test" in terms of meeting the desired test objectives. A relative "success score" was given to each test

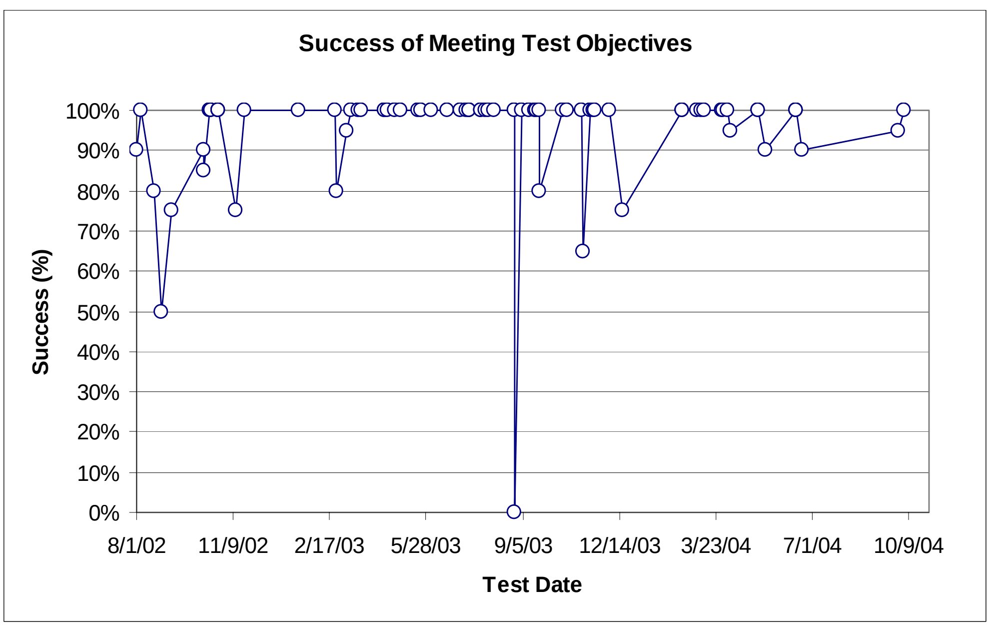

Figure 5 Successfulness of Test Result to Meet Test Objectives

which would rate the success from 100% to 0% (see Figure 5 for the Successfulness Ratings). This is a subjective measure of the quality of the design and the ability to meet the test objectives. In some places where there is no data we assume that the test was successful.

The average "successfulness" to meet the test objectives is 95% for all tests evaluated. This figure of merit seems high for the development of a new space ship design using many new design elements and not using some of the more traditional design techniques. One test (flight 31L/04GC) out of the 78 tests performed was aborted and resulted in a 0% score of meeting the test objectives. However, even this failure produced values test data that helped to move the program forward. All in all the design, integration and test of the SpaceShipOne system was quite amazing.

Part two of the evaluation of the integration and test address the question, "did the tests occur at the correct time for the development of SpaceShipOne?" For example, reviewing the GT4, (Horizontal Tail Modification Aerodynamic Tests), which began on 21 Oct 03, ground tested a potential issue with the tail design. This test had to be conducted because the computer model was not ready. Thus, a pseudo wind-tunnel test had to be performed to evaluate the performance of the tail section. It is believed that this was an unplanned test and was needed to support the design activity. To measure the timing of the integration and testing, a calculation that shows the spacing between tests is graphed in Figure 2. Long gaps in integration could potentially be caused by design problems, weather, holidays, etc. These gaps could be considered as abnormal based on the tight schedule that SpaceShipOne was under.

There are three distinct gaps in the test and integration schedule time. These gaps can be seen in Figure 6. The First gap appears during the start of the initial rocket motor tests for both eAc and SpaceDev. Clearly the need for a rocket engine was critical for

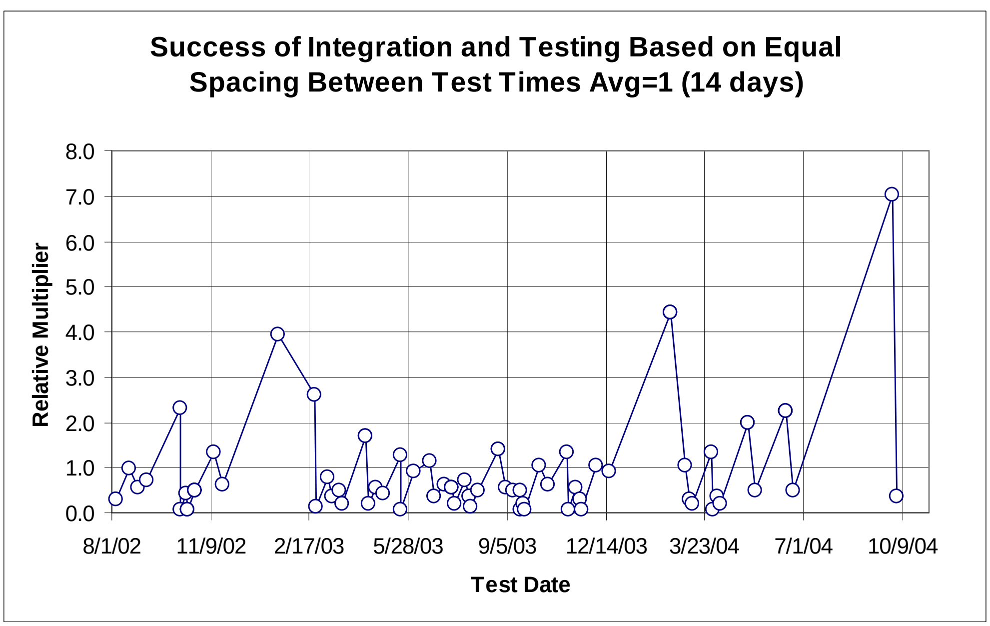

Figure 6 Equal Spacing Analysis Between Tests

SpaceShipOne. This key element was outsourced to eAc (which started late but finished in 7.7 months) and SpaceDev (which started first but took nearly a year to produce the final product) as a competition. SpaceDev won the competition for the hybrid motor but it does appear that both competitors produced viable hybrid motor behind schedule and this affected the test and integration of the system. It should also be pointed out that testing of the hybrid motors began at the end of the year near the holidays. This may have been a contributing factor to the time gap. The second major gap appears after Flight 43L/11P, the first power flight for SpaceShipOne. A number of problems occurred during this test; flight control flutter, feather recovery exhibited a ±30 roll, upon landing, the left main gear collapsed which caused minor damage to SpaceShipOne. Clearly, there was a need for some redesign and repair during this two-month gap. The next was Flight 44 (White Knight only) and its objective was pilot practice and new software testing. SpaceShipOne didn't fly another powered flight for almost 4 months. The third major gap appears to have occurred between 60L/15P and 65L/16P. No additional flight test information is available to fill the three-month gap between flights. Flight 60L/15P had a problem with the primary pitch trim control which resulted in a change in the desired rocket trajectory. SpaceShipOne broke the 100km space barrier but only barely. A shorter rocket burn on the next flight would insure that they would fail to claim the X-Prize. Thus, the design and test team could have decided to make some improvements on SpaceShipOne during the three-month gap. The conclusion here is that there was very little margin in the schedule because the X-Prize required two flights within a two-week window before Jan 1, 2005. Any more schedule slips could have cost the team the X-Prize, but in the end they were successful and won.

Conclusion

Scaled Composites stated at the successful completion of the final flight **“**The 13 month, 17-flight SpaceShipOne flight test program included just six rocket powered flights, three of which flew to space (above 100 Km). In comparison, the X-15 program (which included 3 test aircraft) took 3 years 4 months, and 110 flights to reach 50 miles altitude (80.5 Km), and 4 years 4 months to reach Space (100 Km altitude).”

SpaceShipOne proved to be a very successful systems integration project. Through significant research, our team found that Scaled Composites and its contractors used a variety of new technologies, coupled with COTS technologies to design a low-cost, state-of-the-art commercial spacecraft and win the Ansari X-Prize. By coupling technologies used between SpaceShipOne and White Knight, Scaled was able to perform testing for both aircraft on only one. Also, simulation allowed its pilots obtain accurate training on the system safely and effectively. A variety of system tests were conducted in order to ensure proper system function and the safety and success of the SpaceShipOne program and all stakeholders involved.

Modeling and simulation were used in place of wind tunnel testing for both SpaceShipOne and White Knight. Scaled developed and integrated a variety of new hardware designs such as the hybrid rocket motor, the oxider tank and fuel casing with necessary COTS products. Rigorous testing was completed and test logs were kept in order to ensure proper results and crew safety. All things considered, SpaceShipOne was a successful and well-managed example of excellent systems integration and should be considered a great accomplishment to the commercial space industry and to the world.

Recommendations

SpaceShipOne was very successful but there was a potential for failure because of the very short window that existed between the final flight and end of the X-Prize. Schedule improvements could have helped the program. Less schedule pressure would have existed if the rocket engine had been completed sooner. The use of simulation models for SpaceShipOne may also have caused some schedule problems.

Because SpaceShipOne seemed to be very well done, recommendations to this project were relatively hard to determine. As we know, there is risk associated with any opportunity and we would recommend that Scaled perform significant risk analysis and practice extreme safety measures when testing its hardware and software components. In August 2007, there was an accident at the Mojave Airport during the testing of hardware for Spaceship Two. Three Scaled employees were killed and 3 more injured in a nitrous oxide explosion. In dealing with these new technologies, there needs to be strict safety guidelines to ensure the safety of those involved on the project.

Lessons Learned on Team Project

Through completing this project our team learned that it is sometimes necessary to redesign your approach in order to organize a successful project in a given time frame. Originally when deriving our project plan, our team assumed that we would be able to acquire more technical information from Scaled Composites, LLC on SpaceShipOne than was actually given. Due to protection of proprietary information, Scaled refused to give us any further technical information than was already listed on their open source website. Therefore, we needed to restructure our tasking and project approach in order to accommodate the information we were able to acquire and create a successful project out of what we had to work with. Our team also learned that verbal communication using Interwise sessions helped us communicate more effectively. Previously, our team was using Skype Instant messaging and found that communicating in this manner was very time consuming and difficult to understand. As a result, we knew that we needed to employ a different method of communication in order to complete our project as a team and with team unity. Our team learned a variety of lessons during the completion of this course and our final team project, and look forward to finishing up the semester strong and as a team.

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Appendix A – Flight Configuration for SpaceShipOne

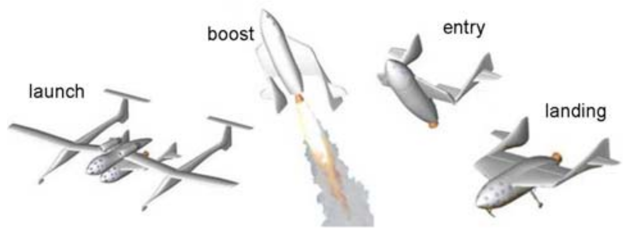

Figure 7 SpaceShipOne Flight Configurations

There are four phases to the flight of SpaceShipOne; the launch, boost, entry and landing phases (shown in Figure 7). During the launch phase SpaceShipOne is carry to 50,000 feet by White Knight. After the release from White Knight, SpaceShipOne enters the boost phase which is approximately a 60 second burn of the rocket motor. The spaceship reaches an altitude in excess of 62 miles (100km). SpaceShipOne is effectively a glider but during the entry phase its must slow using a "feathering" technique where the wings tilt to produce a shuttlecock configuration which creates high drag and slows the decent of the spaceship. This phase of the flight can last down to approximately 80,000 feet. The last phase of the flight is the landing to include the glide phase of the flight. The glide or landing phase is not powered and includes the extension of the landing gear.

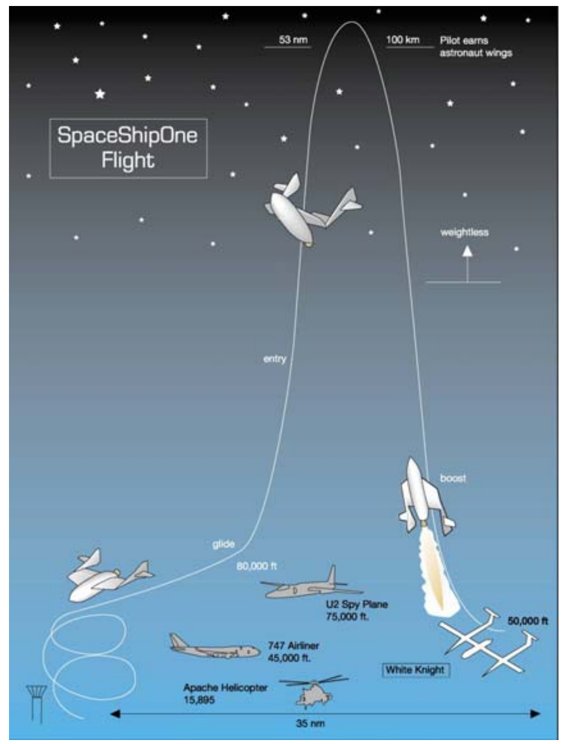

Figure 8 SpaceShipOne Flight Profile

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Appendix B – Table of System Tests Performed for SpaceShipOne

Date	Objectives	Results
05/20/03	Mated ship configuration vibration/aerodynamic assessment.	Excellent control w/ mated configuration
07/29/03	Mated ship w/ SS1 Passenger, Glide rehearsal.	SS1 system checkout successful, all system passed.
08/07/03	First glide from 47,000 feet.	Separation was clean Handling supported close correlation w/ simulator
08/27/03	Second glide flight, performance of SS1 in feather mode	Aborted before launch, GPS malfunction
08/27/03	Second attempt at glide flight. Assessment of pilot workload and situational awareness during transition	Positive Results
09/23/03	Third glide flight. Aft CG flying qualities and performance evaluation in glide and feather modes. More aggressive post stall maneuvering and spin control.	Clean separation Aft-CG stall characteristics WORSE than predicted. Needs modification.
10/17/03	Fourth glide. Examine effects of horizontal tail modifications Functional check of rocket motor controller. Maneuvering, more aggressive nose pointing in feather mode	Tail performance showed considerable improvement. Rocket motor tests satisfactory. Results show that the pilot could readily point nose where desired.
11/14/03	Fifth glide. New pilot. Stability/Control Testing w/ new extended horizontal tails. Stall performance at aft limit CG. Evaluation of increased pitch and roll control. Additional motor control and handling in feather mode.	Satisfactory stability and control. Handling qualities into and out of feather mode remained excellent with good nose pointing ability.
11/19/03	Sixth glide. Emergency CG handling qualities evaluation. Simulated landing exercise with new tail configuration Airspeed and G envelop expansion and dynamic feather evaluation	Satisfactory handling at emergency CG limit. Improved stability/ control due to new configuration Landing pattern flown at higher airspeed which allowed for more controlled flare and landing.
12/04/03	Seventh glide. New Pilot. Functional check of propulsion system. Completed airspeed and positive and negative G-envelope expansion	All propulsion components, displays and functionality performed as designed. Vehicle recovered to a stable attitude/descent after only a single oscillation.
12/17/03	First powered flight. 15 second burn of rocket motor. Vehicle handling through transonics and feather performance from altitude.	No flight control flutter or buzz during climb. Feather recovery exhibited a +/- 30 roll before settling. Left main landing gear collapse during landing. Damage to system minor.
03/11/04	Pilot proficiency, reaction control system functionality	All systems performed as expected.

	Stability, control and performance w/ thermal protection system installed.	Successful landing.
04/08/04	Second powered flight. 40 seconds motor burn time. Handling qualities during boost, through trans and super sonic. Reaction control system functionality in-flight and in feather mode stability during transonic re-entry. Radar tracking capability evaluation. Handling qualities during boost and performance verification. Reaction control system use for reorientation to entry altitude. Supersonic feather stability and control.	Rocket boost smooth w/ good control. No flight control flutter or buzz during climb. Feather recovery was nominal. Satisfactory handling quality during descent. Reaction control authority functioned as predicted. On-board avionics was re-booted for a smooth landing.
06/21/04	First commercial astronaut flight exceeding 100 km	76 seconds rocket motor burn. Successful landing. Anomaly: Flight control malfunction Primary pitch trim control lost. (redundancy designed) Two consequences of anomaly: Climb was lower than planned and re-entry was south. Glide capability compensated for south re-entry.
09/29/04	First X-prize flight	Rolls occurred during end of motor burn due to mild thrust asymmetry. This condition was not tested on previous flights.
10/04/04	Second X-prize flight (Attempt to break X-15 record)	Broke X-15 record. No anomalies.

Appendix C – Rocket Burn and Apogee Calculations

Based on the measured test data from the six powered flight of SpaceShipOne a rocket - "burn time" estimated can be made to show just how close SpaceShipOne was to the 328,000 feet space threshold. Three of the flight broke the barrier but as can be seen a burn time of less that 75 seconds could have prevented the spaceship from breaking the threshold. In addition, a lower launch altitude form Whit Knight could have caused the flight to be unsuccessful. Rocket burn times for Flights 56L/14P and 43L/11P were linearly extrapolated from the other test flight data.

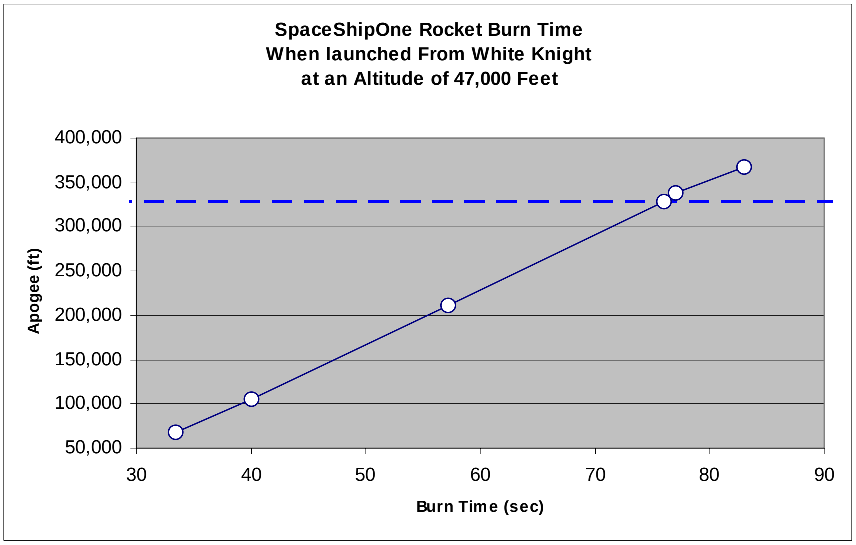

Figure 9 Rocket Apogee versus Rocket Engine Burn Time

Flight	Date	Apogee	Threshold	Rocket Burn Time (sec)	Launch Altitude
66L/17P	10/4/04	367,500	328,000	83	47,100
65L/16P	9/29/04	337,700	328,000	77	46,500
60L/15P	6/21/04	328,491	328,000	76	47,000
56L/14P	5/13/04	211,400	328,000	57	46,000
53L/13P	4/8/04	105,000	328,000	40	45,600
43L/11P	12/17/03	67,800	328,000	33	47,900

Appendix D – Table of System Tests Performed for SpaceShipOne

Date	Test	Objective	Success Score
08/01/02	1	First flight. Handling qualities assessment and basic performance evaluation. Systems evaluation. Cabin un-pressurized.	90%
08/05/02	2	First flight test card repeat. Flying qualities assessment and basic performance evaluation. Avionics and pneumatic systems evaluation. Cabin un-pressurized.	100%
08/19/02	3	New pilot qual eval. Envelope expansion out to 25,000 feet and 150 knots. First flight with the cabin pressurized for environmental control system tests .	80%
08/27/02	4	New pilot qual eval. Envelope expansion out to 35,000 feet and 150 knots / 0.4M and 3 G's. Engine relight performance. Avionics software upgrade.	50%
09/06/02	5	New pilot qual eval. Envelope expansion out to 45,000 feet and 160 knots / 0.5M. Practice SpaceShipOne glide approaches. Effectiveness of new tail vortex generators and clipped outboard speed brakes.	75%
10/09/02	6	Evaluate rudder mass balance modifications. Effectiveness of engine bleed air heating of the fuselage aft of the cabin (first test of SpaceShipOne Nitrous heating system).	90%
10/10/02	7	Completion of Flight 6 objectives. Airspeed and altitude envelope expansion, 45,000 feet / 160 knots / 0.5M	85%
10/16/02	8	Envelope expansion above 50,000 feet and 0.55M. Avionics software upgrade. Practice SpaceShipOne glide approaches	100%
10/17/02	10	SpaceshipOne boost profile and steering capture practice. Simulated SS1 glide approaches.	100%
10/17/02	9	Boost phase pilot training. Formation flying and air-to-air photography with the Proteus aircraft.	100%
10/24/02	14	FAA-monitored flight for pilot "Type Rating".	100%
10/24/02	13	FAA-monitored flight for pilot "Type Rating".	100%
10/24/02	12	FAA-monitored flight for pilot "Type Rating".	100%
10/24/02	11	FAA-monitored flight for pilot "Type Rating".	100%
11/12/02	16	Continued engine, ECS and avionics evaluation. Simulated wheel brake failure landing rollout.	75%
11/21/02	SpaceDev1	test motor	100%
01/16/03	eAc1	test motor	100%
02/22/03	eAc2	test motor	100%
02/24/03	17	Evaluate performance of updated engines. Measure effect of new canted wingtips. Test new landing gear doors and upgraded INS hardware.	80%
03/07/03	18	Revised ECS configuration evaluation. Multiple SFO (simulated flame out) approaches to assess updated flight director steering cues.	95%
03/12/03	SpaceDev2	test motor	100%
03/19/03	SpaceDev3	test motor	100%
03/22/03	eAc3	test motor	100%
04/15/03	20	Repeat airshow maneuver practice	100%
04/15/03	19	Airshow maneuver practice. First flight with Spaceship launch system installed.	100%
04/18/03	21	Formal media rollout	100%
04/26/03	22	Airshow for the 'friends and family' unveiling	100%
05/02/03	23	Engine performance at altitude. New pilot masks and ECS airflow routing. Regulated bleed air control of the aft cabin temperature (to test the capability to heat SpaceShipOne's nitrous oxidizer. Appraisal of new traffic alert system.	100%
05/20/03	24C/01C	First captive carry flight with mated White Knight and SpaceShipOne. Vibration and aerodynamic interface assessment. Mated handling qualities evaluation. Envelope expansion to 130 knots / Mach 0.5 above 45,000 feet. Stalls and 2/3-rudder sideslips. SpaceS	100%

05/23/03	GT1	To update the stiffness and mass distributions of the SpaceShipOne structural model so the analytical predictions match the actual vehicle frequency and modal response to a series of different forced vibrations. Since most flutter issues are critical for	100%
06/03/03	SpaceDev4	test motor	100%
06/19/03	eAc4	test motor	100%
07/03/03	25	First glide flight profile rehearsal / two ship checklist flow / airspace coordination / Command and Control responsibilities and handoffs.	100%
07/09/03	GT2	To ensure the as-built systems meet the vehicle design requirements	100%
07/11/03	28	Pilot proficiency. First flight for SpaceShipOne crew chief.	100%
07/11/03	27	Pilot proficiency. First flight for SpaceShipOne lead engineer.	100%
07/11/03	26	First glide flight profile rehearsal / two ship checklist flow / airspace coordination / Command and Control responsibilities and handoffs. First flight for Burt in the White Knight.	100%
07/24/03	eAc5	full-duration motor test	100%
07/24/03	GT3	System level qualification tests for several subsystems	100%
07/29/03	29L/02C	First manned captive carry flight of SpaceShipOne. A man-in-loop launch rehearsal and inflight checkout of all ship systems including flight controls and propulsion sytem plumbing.	100%
07/31/03	SpaceDev5	full-duration motor test	100%
08/07/03	30L/03G	First glide flight of SpaceShipOne.	100%
08/27/03	32L/05G	Same objectives as the aborted flight 31LC/04GC earlier today. Second glide flight of SpaceShipOne. Flying qualities and performance in the space ship re-entry or "feather" mode. Pilot workload and situational awareness while transitioning and handling qu	100%
08/27/03	31L/04GC	Second glide flight of SpaceShipOne. Flying qualities and performance in the space ship feather mode. Pilot workload and situational awareness while transitioning and handling qualities assessment when reconfigured. As a glider, deep stall investigation b	0%
09/04/03	eAc6	full-duration motor test	100%
09/11/03	33	SpaceShipOne approach and landing profile review	100%
09/18/03	34	SpaceShipOne approach and landing profile review	100%
09/19/03	35	SpaceShipOne approach and landing profile review	100%
09/22/03	36	Avionics upgrade evaluation	100%
09/23/03	37L/06G	Third glide flight of SpaceShipOne. Aft CG flying qualities and performance evaluation of the space ship in both the glide and re-entry or "feather" mode. Glide envelope expansion to 95% airspeed, 100% alpha and beta and 70% loadfactor. More aggressive po	80%

10/17/03	38L/07G	Fourth glide flight of SpaceShipOne. Primary purpose was to examine the effects of horizontal tail modifications at both forward and mid-range CG locations (obtained by dumping water from an aft ballast tank between test points). The tail modifications in	100%
10/21/03	GT4	The purpose of these tests was to examine various changes to SpaceShipOne's tail assembly to provide for better horizontal tail lift and tail lift-slope characteristics.	100%
11/05/03	39	Avionics upgrade evaluation and landing pattern practice.	100%
11/06/03	15	Continued engine, ECS and avionics evaluation. High-rate nose wheel steering assessment.	65%
11/14/03	40L/08G	The fifth glide flight of SpaceShipOne. New pilot checkout flight. Stability and control testing with the new extended horizontal tails. Tests included stall performance at aft limit CG and evaluation of the increased pitch and roll control authority. Oth	100%
11/18/03	SpaceDev6	Flight motor qualification run. A ground test to validate the first two planned powered flights of SpaceShipOne.	100%
11/19/03	41L/09G	The sixth glide flight of SpaceShipOne. Test pilot Mike Melvill's first flight with the enlarged tails. Emergency aft CG handling qualities eval and simulated landing exercise with the new tail configuration. Airspeed and G envelop expansion and dynamic f	100%
12/04/03	42L/10G	The seventh glide flight of SpaceShipOne and new pilot check out. Full functional check of the propulsion system by cold flowing nitrous oxide. Completed airspeed and positive and negative G-envelope expansion.	100%
12/17/03	43L/11P	The eighth flight of SpaceShipOne and first powered flight. 15 second burn of the rocket motor and supersonic flight. Motor light off at altitude and inflight engine performance. Vehicle handling qualities through transonics and feather performance from a	75%
02/18/04	46	Pilot proficiency, new software build checkout and landing practice	100%
02/18/04	45	Pilot proficiency, new software build checkout and landing practice	100%
02/18/04	44	Pilot proficiency, new software build checkout and landing practice	100%
03/04/04	47	SpaceShipOne flight 12G launch release rehearsal and avionics software evaluation	100%
03/08/04	48	SpaceShipOne flight 12G launch release rehearsal and avionics software evaluation	100%
03/11/04	49L/12G	The twelfth flight of SpaceShipOne. Objectives included: pilot proficiency, reaction control system functionality check and stability and control and performance of the vehicle with the airframe thermal protection system installed. This was an unpowered g	100%
03/30/04	50	Avionics software evaluation, launch release rehearsal and landing pattern practice.	100%
03/31/04	51	SpaceShipOne Flight 13P launch rehearsal, avionics checkout and landing practice	100%
04/05/04	52	Avionics checkout flight, pilot proficiency and landing practice.	100%

04/08/04	53L/13P	The second powered flight of SpaceShipOne. 40 seconds motor burn time. Handling qualities during boost, through transonic and supersonic. Reaction control system functionality in-flight and feather configuration stability during transonic re-entry. Evalua	95%
05/06/04	55	Flight 14P rehearsal, avionics checkout, pilot proficiency and landing practice.	100%
05/06/04	54	Flight 14P rehearsal, avionics checkout, pilot proficiency and landing practice.	100%
05/13/04	56L/14P	The third powered flight of SpaceShipOne. 55 seconds motor burn time. Handling qualities during boost and performance verification. Reaction control system use for reorientation to entry attitude. Supersonic feather stability and control.	90%
06/14/04	59	Avionics checkout flight, pilot proficiency and landing practice.	100%
06/14/04	58	Avionics checkout flight, pilot proficiency and landing practice.	100%
06/14/04	57	Flight 15P rehearsal, avionics checkout, pilot proficiency and landing practice.	100%
06/21/04	60L/15P	First commercial astronaut flight by exceeding 100 kilometers (328,000 ft)	90%
09/29/04	65L/16P	First X-prize flight: ballasted to simulate 3 place, & to exceed 100 kilometers (328,000 ft)	95%
10/04/04	66L/17P	Second X-prize flight: again ballasted for 3 place & 100 kilometer goal (328,000 ft)	100%