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X-37B Orbital Test Vehicle and Derivatives

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The advantages of a reusable spacecraft for technology demonstations in Low Earth Orbit (LEO) operations are discussed. Programs are able to realize cost savings and acceleration of technology developmental timelines by focusing on the payload. Non-recurring costs are substantially reduced by taking advantage of a mature spacecraft bus with well defined bus to payload interfaces and a ground station supported by seasoned mission operations staff using flight validated operational products. The return of experimental payloads enables post flight inspection, test, and analyses and reflight opportunities for more educated product improvements and shorter design cycle times. The X-37B recently completed its first test mission and demonstrated the viability of a small test platform that can return experiments for post flight inspection and analysis. Several key technologies for reusable spacecraft were successfully demonstrated in the areas of aerodynamics, aerothermodynamics, reusable solar arrays, Thermal Protection Systems (TPS) and autonomous Guidance, Navigation, and Control (GNC). The current system provides a demonstration platform for autonomous spacecraft technologies, on-orbit environments for material and microelectronic characterization and re-entry environments for advanced TPS materials and concepts. Automated Rendezvous and Docking for ISS operations or risk reduction for satellite servicing are discussed. Derivative vehicles supporting ISS cargo supply, crew transfer and soft return to runway landings are presented.

Nomenclature

AFRL = Air Force Research Laboratory
ALTV = Approach and Landing Test Vehicle
APAS = Androgynous Peripheral Attach System
BRI = Boeing Reusable Insulation
CADS = Calculated Air Data System
CBM = Common Berthing Mechanism
C/C = Carbon-Carbon
CCAFS = Cape Canaveral Air Force Station
CCDev = Commercial Crew Development
CFD = Computational Fluid Dynamics
CMC = Ceramic Matrix Composite
CMOS = Complementary metal–oxide–semiconductor
COTS = Commercial Orbital Transportation Services
CRI = Conformal Reusable Insulation
C/Sic = Carbon Silicon Carbide
dGPS = differential Global Positioning System
DFRC = Dryden Flight Research Center
EAFB = Edwards Air Force Base
EELV = Evolved Expendable Launch Vehicle
FPGA = Field Programmable Gate Array
fps = Feet per second
Gr/BMI = Graphite/Bismaleimide
GEO = Geosynchronous Orbit
HEO = High Earth Orbit
ISS = International Space Station
LDEF = Long Duration Exposure Facility

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LEO = Low Earth Orbit
LRU = Line Replaceable Unit
MEO = Mid Earth Orbit
NASA = National Aeronautics and Space Administration
NEO = Near Earth Objects
NEPP = NASA Electronic Parts and Packaging
OTV = Orbital Test Vehicle
PTI = Programmed Test Inputs
ReFLY = Reusable FLYback Satellite
SDRAM = Synchronous Dynamic Random Access Memory
SiGe = Silicon-Germanium
SLI = Space Launch Initiative
SRAM = Static Random Access Memory
SSRMS = Space Station Remote Manipulator System
TPS = Thermal Protection System
VAFB = Vandenberg Air Force Base

I. Advantages of a Reusable Spacecraft

THE concept of a reusable upper stage or spacecraft (Figure 1) was suggested by Cervisi et al.[1] in 1993 to address deficiencies in the international infrastructure for space transportation and utilization. No capability existed then for "placing small payloads in orbit in a timely, flexible, and cost effective manner, supporting the payloads while on-orbit and returning them and their data to earth with airplane-like utility." The Space Shuttle Orbiter flew infrequently, had a long backlog to its manifest of secondary payloads, the complexity of coordinating with the primary Orbiter mission objectives, and the cost of integrating on to a crewed vehicle and proving there were no safety concerns. In addition, the average Shuttle mission duration of 10 days on orbit, in 1993, severely limited what could be demonstrated, especially as a secondary payload. Today with the Shuttle fleet retired, access to the International Space Station (ISS) for conducting and returning on-orbit experiments is equally difficult. Integration of external experiments on the ISS continues to require the human safety and operational analysis to insure that other ongoing experiments are not impacted by new hardware and activities. The logistical competition for scarce upmass resources between restocking critical crew consumables and lower priority experiment hardware is intense. The return of experiment results and critical ISS items requiring service are also constrained with a growing backlog. No capability exists today to return payloads of more than a few tens of kg with the Shuttle retirement and the limited downmass capability of Soyuz. Once in service, the new generation of return capsules will only be able to return experiments that can survive the high re-entry acceleration loads and the shock of parachute deployment, ground or water landings.

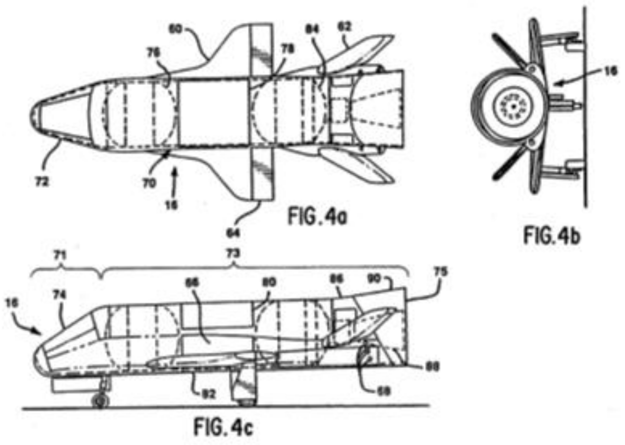


Figure 1. The concept of a reusable upper stage/spacecraft dates back to 1993.

Another deficiency in the way the community approaches technology development in space is the tendency to increase reliability and redundancy in order to minimize the prospect of mission failure to an expensive launch, expensive spacecraft, and the investment in a long development timeline. While this may make sense for a 15 year spacecraft using mature technologies and contractual performance guarantees, it does not make sense for technology that evolves over 2-4 year cycles. In a ground test product development, new technology items are tested, modified, and retested using reliable, overbuilt support hardware and software that is continually reused. Short cycle times iterate to the desired maturity state quickly. Inspection of the test article is a key guide in dermining success, failure, and new directions. Airborne flight testing of new technologies operates the same way. A common feature to the ground and airborne technology test programs are simple, single string electronics, support subsystems with only selective redundancy for flight safety, and post test inspections. The consequences of a failure are to return the unit for repair, redesign and reflight. Unfortunately, the consequences of failure in space for a single use, expendable system are loss of the bus, the experiment, and a huge impact to the technology maturation schedule. Even relatively simple on orbit experiment developments and demonstrations get trapped into the spiral of adding redundancy and complexity (both bus and experiment) to mitigate potential failure modes. Higher spacecraft costs imply that the mission should be longer or have additional objectives to justify the investment. Requirements for parts reliability increase creating lead time problems. Test programs stretch out to qualify for the longer mission duration. This spiral may take several years to evolve with continual cost and schedule growth ultimately killing the effort.

In contrast, the reusable spacecraft can operate more like the airborne test platform with more responsive and lower cost developments. The reusable spacecraft bus, like the aircraft, will have the subsystem and system level redundancy to tolerate failures and reliably return to Earth safely. X-37B operates this way. By designing for shorter missions, the reliability of simpler, single string experiments become palatable. Reliability and redundancy can be selectively designed in, but do not need to be comprehensive. Lower cost, Grade 3 EEE parts[2] become viable. Less complex hardware translates to simpler software. Both translate to shorter development schedules and lower cost per mission. The shorter mission also enables a planned insertion of improved technology items on a subsequent flight that can reuse the core payload hardware and software. Alternatively, a lagging technology development might be held back for a future flight without bringing the rest of the program to a standstill. Summarizing, a reusable spacecraft bus enables technology developmental opportunities analogous to the airborne platform with the ability to inspect payloads post flight and make more educated decisions on the next steps. The reusable spacecraft provides the environment to reduce technology development cost and schedule by taking advantage of shorter product cycle times.

A reusable spacecraft introduces the characteristic of bus and mission infrastructure stability across many unrelated programs that further reduces development schedules and total costs. Each flight of a reusable system is comparable to a new program for an expendable system. However, since the reusable bus is already complete, the payload design team has limited ability to drive customized features into the bus. The mechanical, electrical, thermal, command, telemetry, software interfaces and customization options are all well-defined. The ground station infrastructure is in place, the nominal and contingency mission procedures are defined, and a pool of trained operators exist. Even if the ground station is replicated, the cost of that replication is a small fraction of standing up a new environment from scratch. This long term stability has the effect of eliminating trade studies and reducing developmental timelines. Even if the reusable spacecraft bus has excess capability, no time or dollars will be spent attempting to negotiate the removal of those hardware or software services. Change traffic to a completed, flight ready bus only increases cost. The developmental effort is focused entirely on the new technology of the payload and the mission specific needs versus standing up an entire system.

The long term stability of the bus, interface configurations, and mission ground station architecture across many flights and users creates the situation where the investment in software to create a true “plug and play” integration environment can be justified. The benefits are a dramatic reduction in the system development timeline; the extensive reuse of software; the simplification of effort in integration and test; the additional robustness and resilience of interfaces; and the graceful accomodations of late requirement changes[3]. First time and repeat customers will be able to take advantage of engineering reuse, lessons learned, and traditional learning curve cost and schedule reductions.

II. X-40A Approach and Landing Demonstrations

The niche market objective was to fly small experiments into orbit, support them on orbit, and then return the experiments with aircraft-like utility. Though many were discussing fully reusable Two-Stage-To-Orbit (TSTO) concepts in the mid 1990's, the development costs for a reusable booster and a reusable orbiter were substantial. Instead, Boeing recommended the development of a small reusable spacecraft that could be launched using a variety of small to mid-sized expendable launch vehicles. Splitting the launch vehicle and the reusable spacecraft enabled independent development, cost efficiencies, and flight rates for the separate elements

Development of the X-40A began in 1996 (Figure 2). Sponsored by the Air Force Research Laboratories (AFRL), the X-40A demonstrated the capability to perform autonomous, precision landings of a low L/D lifting entry vehicle using differential Global Positioning System (dGPS) as a landing aid.   dGPS is a simple aid that enables landing on any runway of the required dimensions without extensive capital improvements. X-40A also provided early design information used in the development of the Calculated Air Data System (CADS)[4]. CADS processes surface pressure measurements with other vehicle information thru a Kalman filter to robustly derive angle of attack, angle of sideslip, airspeed, dynamic pressure and Mach number. One benefit of CADS is that it enables pressure measurements to be taken away from the re-entry stagnation heating zones that are difficult or impossible to instrument. Precision altitude for the landing flare was obtained from a radar altimeter. Eight autonomous flights were completed: one at Holloman Air Force Base in New Mexico sponsored by AFRL; and seven at Edwards Air Force Base (EAFB) in California sponsored by the NASA Dryden Research Center. Landing touchdown performance was excellent with sink rates averaging only 1.8 fps with a maximum of 2.7 fps. Runway dispersions averaged only 150 ft along the length of the runway and 16 ft from centerline. Videos of the flights[5] are easily found on the internet using the key search words "X-40" and "YouTube." X-40A provided excellent validation of Guidance, Navigation, and Control (GNC) design methods and provided critical wind tunnel to flight corrections for the aerodynamic database developed later for the X-37 vehicles. The X-40A ground test program also originated the concept of captive tow taxi and free release rollout testing for an unpowered autonomous vehicle as a replacement for the conventional manned or remotely piloted taxi test buildup to first flight (Figure 3).

Figure 2. The X-40A Flight Program validated GNC algorithms, subsystem math models, and the methods for autonomous vehicle test and flight operations. (Photos courtesy of The Boeing Company)

Figure 3. The concept of captive tow and free release was developed during the X-40A program since there wasn't a remote pilot capability with which to conduct dynamic taxi tests of the landing gear or GNC related subsystems. (Photo courtesy of The Boeing Company)

III. Early Development of the X-37

The X-37 program started in the age of the NASA Future-X (1998-2001) and Space Launch Initiatives (2001-2006). The primary objective of these programs was to develop technologies that would reduce the cost of getting to and from LEO for Shuttle and EELV replacements. One of the key shortfalls identified was the inability of ground test facilities to properly simulate the hypersonic physics or durations of atmospheric entry necessary for advanced TPS verification. Conducting material or attachment experiments in flight critical regions of the space shuttle orbiter was considered too risky to the astronauts and the high value national asset. The X-37 was designed as a small unmanned lifting entry vehicle that could be carried aloft by the Space Shuttle or an expendable launch vehicle. Released on orbit, the X-37 would then fly a typical lifting entry trajectory to test next generation TPS system materials and attachment concepts. The entry trajectory could be adjusted to tailor the hypersonic, chemically reacting environments, heating rates and heat loads required for specific test objectives.

The X-37 concept also provided a natural platform for testing a broad range of other technologies relevant to next generation launch and reusable vehicles:

- Autonomous deorbit, entry, and landing GNC
- Fault tolerant architecture for autonomous on orbit and entry flight
- GPS and dGPS for landing with minimal airfield infrastructure
- Electro-mechanical flight actuation and brakes
- Li-Ion batteries for high cycle life and high current capabilities
- Reusable, deployable and stowable solar array
- Advanced Gr/BMI composite airframe
- Complex Carbon-Carbon control surfaces
- Advanced high temperature wing leading edge tiles
- Flight data to validate hypersonic aeroheating prediction methods
- Integrated system designed for aircraft like turnaround operations

The X-37 program evolved in two phases, the X-37 ALTV (Approach and Landing Test Vehicle) and the X-37B OTV (Orbital Test Vehicle). Even though the first phase was limited to the approach and landing portion of the entry profile, the engineering activities laid the fundamental ground work for the orbital vehicle. This phase developed the vehicle external aerodynamic mold line, TPS material distribution, and control surface configuration. A V-tail configuration is used to better balance a high tail with a low wing within the circular constraints of a launch vehicle fairing or the Shuttle payload bay. A single vertical tail would be too tall. Circular fuselage cross sections are used with lower chines for structural and packaging efficiencies. The small, but efficient wing and the large fuselage planform area each produce equal amounts of lift. Good performance, trim, and control characteristics were achieved for hypersonic maneuvering with and without RCS, supersonic pitch transitions, transonic and subsonic maneuvering, landing L/D, landing speeds, touchdown attitude, and cross wind capabilities. A wind tunnel test program totaling 6,000 wind tunnel hours and 1500 CFD computations were used to develop the vehicle configuration. This was approximately 19 percent of the comparable testing performed to develop the shuttle orbiter design and create the flight aerodynamic database used for entry. The metrics do not include Shuttle testing in the launch configuration. The substantial reduction is attributed to taking advantage of Shuttle lessons learned and using CFD to pre-screen model configurations prior to committing to expensive test programs.

The X-37 ALTV prototyped the airframe structural concept, the Gr/BMI composite manufacturing processes, and the internal subsystem arrangement. It prototyped the fault tolerant avionics architecture for the flight management system (flight control computers, sensors and effector controllers); the vehicle management system (power, thermal, communication, and instrumentation); and the associated system services and GNC software. The long lead development for the OTV of the high temperature carbon-carbon ruddervator and flaperon control surfaces and TUFROC wing leading edge tiles proceeded in parallel with the ALTV build and flight test activities.

IV. X-37 Approach and Landing Test Vehicle (ALTV)

X-37 ALTV flight test activities retired many risks for the OTV. A total of five captive flights and three free flights were made from the Scaled Composite's White Knight (Figure 4). For a free flight, the vehicle was released at 35 kft AGL, accelerated to approximately Mach 0.7, turned through 135 degrees of a representative entry Heading Alignment Cone (HAC) and landed on EAFB's hard surface runway 22L. The first flight used a conventional air data system using a nose mounted boom and flew CADS in a data acquisition mode. In spite of all of the taxi test risk reduction, the redundant electromechanical brakes failed at high speed. The resulting runway over run generated only minor damage. The second flight flew CADS in the control loop with the air data boom system in backup. The third flight removed the air data boom and completed the validation of the CADS air data system for the OTV. Each flight included Programmed Test Inputs (PTI's) and flight instrumentation to collect data later used to verify key elements of the aerodynamic data base. Extensive pre- and post-flight GNC simulations were performed to characterize the subsystem model and vehicle level behaviors with actual flight data. Verifying the electro-mechanical flight actuator loads, currents, and responses to the maneuvering flight, touchdown, and rollout environments were of particular interest because they were difficult to comprehensively simulate in ground testing. These flights proved that the basic vehicle configuration, avionics architecture, software, and supporting subsystems could achieve safe, repeatable, precise, and gentle runway landings from a high altitude initial point. A summary video[6] of the three flights can be found by searching on the internet using the key words "YouTube Boeing X-37 Test Flight B-Roll."

Figure 4. Two of three X-37ALTV flights used an air data boom; The third flight flew without an air data boom using CADS to support both primary and redundant air data requirements. (Photos courtesy of The Boeing Company)

V. X-37B Orbital Test Vehicle (OTV)

The Air Force Rapid Capabilities Office sponsored the Boeing development of the OTV in parallel with DARPA's ALTV program. Lessons learned from the ALTV airframe and subsystem integration, test, and serviceability were folded back into the OTV design to reduce weight and manufacturing cost. Subsystems were optimized for the on-orbit and hypersonic entry environments. Comprehensive mechanical, electrical, thermal, and software interfaces were developed to support fast and flexible experiment integration. Results from the ALTV flight test events were incorporated into the aerodynamic database, the electromechanical brakes, the flight controls, and the GNC subsystem models. The team that designed, built, and flew the OTV drew on experience from the X-planes, the Space Shuttle, ISS, EELV, commercial and government satellites, and commercial and military aircraft.

OTV-1 launched successfully on April 22, 2010 using an Atlas V 501 booster. The spacecraft autonomously opened payload bay doors, deployed thermal radiators, deployed the solar array, and initialized itself for a variety of experiments and technology demonstration activities. After 224 days on orbit, the spacecraft was commanded to deorbit on Dec 3, 2010. A night time landing was selected to minimize surface winds for this first landing attempt from orbit. At the appropriate time, the OTV-1 autonomously stowed the solar array, radiators, payload bay doors, and executed a deorbit burn. Without ground intervention, the spacecraft flew a shuttle like entry trajectory and managed its position, altitude, and energy across 5,500 nm using bank angle, pitch angle, and S-turns. Flying like a conventional aircraft approaching VAFB, the OTV-1 assessed its energy to go and moved the HAC away from the runway threshold to adjust for high altitude tailwinds. The capability to autonomously adjust for winds and energy by moving the HAC is just one of the guidance algorithm advancements over the Shuttle Orbiter approach and landing methods. The OTV-1 used dGPS for position corrections and a radar altimeter for precision altitude. Touchdown was 9 ft off centerline with a sink rate of less than 2 fps. Although the left main tire was punctured half way through the landing rollout due to a runway obstacle, the autonomous GNC system maintained robust control, and brought the vehicle to a safe stop only 6 ft off of centerline. The condition of OTV-1 at landing was excellent across all subsystems including TPS (Figure 5). The X-37B demonstrated a number of technologies and capabilities for the first time:

- First autonomous deorbit, entry, and runway landing of a spacecraft by the United States. Russian Buran was first in the world
- Longest duration on orbit mission for fully reusable vehicle returned to Earth. 224 days versus 17 days for the Shuttle Orbiter Columbia. This duration in LEO is second only to NASA's Long Duration Exposure Facility (LDEF)
- First re-entry vehicle to use all electric flight control and braking system from deorbit through runway landing. No hydraulic systems were used.
- First solar array that was deployed, stowed, and then returned from orbit
- First use in re-entry from orbit of tile system for reusable nose cap thermal protection - BRI
- First use in re-entry from orbit of tile system for wing leading edge thermal protection - TUFROC
- First use in re-entry from orbit of blanket system using CMC facesheets - CRI
- First use in re-entry from orbit of complex Carbon-Carbon assemblies for hot, aerodynamically shaped control surfaces. Shuttle leading edge segments are mechanically supported by the wing. The cantilevered X-37B ruddervator carries all primary loads internally.

Figure 5. The X-37B demonstrated many technologies by successfully completing the first fully autonomous deorbit, re-entry, and runway landing at VAFB, December 3, 2010. (Photo courtesy of The Boeing Company)

OTV-2 was successfully launched on March 5, 2011, just 3 months after the return of OTV-1. At the time of this writing, it is operating well on orbit. Turnaround of the first vehicle for its next flight has required less time and hours than expected supporting the concept of an affordable, reusable system.

VI. Orbital Test Vehicle Missions

With the successes of the first two X-37B OTV's, there are many opportunities for demonstrations with these spacecraft and derivatives. Primary or secondary experiments can be flown to characterize new TPS technologies, expose materials to extended LEO environments or characterize new generation EEE parts for radiation and SEU tolerance. Autonomous rendezvous, proximity operations, docking, and 3-D mapping support International Space Station (ISS) servicing and space exploration to Near Earth Objects (NEO) initiatives. GNC strategies and performance for aerobraking and atmospheric maneuvering can be demonstrated. The X-37B can be used as the upper stage paired with a reusable booster prototype to mature Two Stage To Orbit (TSTO) architectures and technologies. Larger derivatives of the X-37B can support large cargo and crew transport to and from the ISS.

The OTV is perfectly suited to testing new TPS material systems. Opportunities exist to test new tiles, blanket, seals, C-C, C-SiC, or other CMC materials, and attachment concepts. TPS testing on the Space Shuttle was highly restricted, reviewed in the context of manned space flight safety, and relegated to benign, non-flight critical regions. A more aggressive testing approach can be taken with the unmanned X-37B. For instance, X-37 B flew wing leading edge tiles and Carbon-Carbon materials in applications never flown before (Figure 6). An appropriate level of technology readiness and rigor is still necessary to minimize the risk of losing a vehicle. The X-37B also provides an excellent material test platform for atomic Oxygen, radiation, and other LEO environments during its many month mission durations.

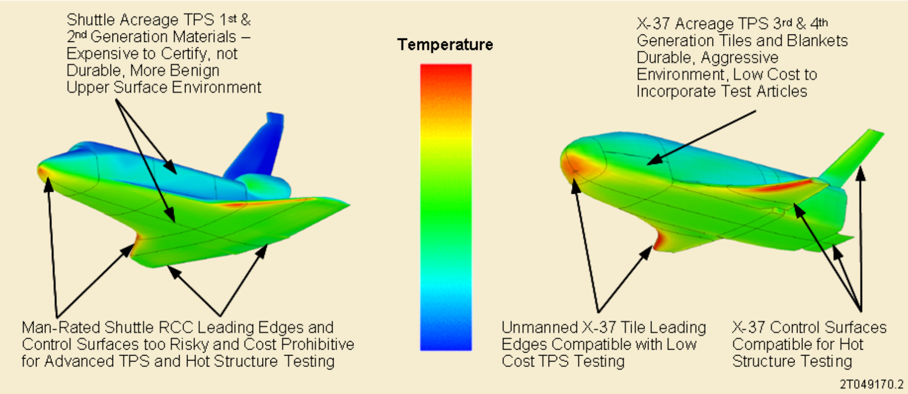


Figure 6. X-37B OTV provides an excellent TPS test bed with the proper temperature environments.

With the industry reluctance to fly anything in space that does not have space heritage, the OTV provides an excellent risk reduction platform. For example, the X-37 program discussed at length which solar cell technology to select. Solar cell technology is advancing several percent in efficiency with each generation. There are advocates for flying the technology that has several years of life demonstrated with thousands of on orbit cycles and successful exposure to space environments. There are advocates arguing that the qualification testing of the next generation is almost done and the extra few percent provides a meaningful increase in power to experiment users. The beauty of a reusable spacecraft with a reusable solar array is that the array can be populated with a mix of technologies, characterized on orbit, and then returned for inspection and performance testing on the ground. Flying the next one to two generations of solar cells in test and evaluation strings on the OTV arrays has the potential to speed up the product development cycle. Real space flight data versus or in parallel to simulated chamber environments would encourage more rapid acceptance

The advance of microelectronics technologies, such as FPGA's, CMOS, SDRAMs, SRAMs, and SiGe, creates a continual need for evaluating part suitability in the natural space radiation environment[7]. Ground testing tends to be conservative and can only focus on a single phenomenology at a time. The capability to return microelectronic parts from orbit is critical to determining failure mechanisms and anchoring ground test methodologies. These parts can be assembled into small secondary payloads that can ride in parallel to other mission activities and then evaluated at the conclusion of the flight. A more ambitious approach would be to launch a free flying satellite hosting several experiments directly into a MEO, HEO, or even a GEO orbit. At the conclusion of the experiment, the free flyer would lower its orbit and re-circularize where the X-37 could rendezvous with it. X-37 would collect the experiment portion of the free flyer and then return it to Earth for inspection and destructive analysis.

The NASA ISS COTS cargo and CCDev crew transport developments have a need to qualify a new generation of autonomous rendezvous, proximity operations, and docking sensors and software. When coupled with the ability to three-dimensionally map an object, this same technology is also required for satellite servicing and asteroid exploration objectives[8]. The X-37B OTV has the capability for 6 DOF attitude control and adequate subsystem fault tolerance for autonomous aborts. It provides an excellent spacecraft test platform to demonstrate, refine, and validate competing technologies and operational concepts without having to build a unique demonstration spacecraft. A valuable benefit of a test platform is that multiple competing technologies can be integrated onto a single OTV as independent subsystems. Once on orbit, the OTV conducts the rendezvous approach and other test points with each subsystem and completes a competitive fly off over the course of a single mission.

VII. Future Derivatives of the X-37

With the retirement of the Space Shuttle Orbiter, the X-37B represents the only vehicle flying in the world today that can provide a soft 1.5g class return of sensitive cargo from the ISS. For example, this unique capability can support the return of biological samples or material science crystals that are at the core of the ISS microgravity experiments and unsupported by high acceleration capsules. Time sensitive cargo can be quickly extracted from the payload bay after a runway landing.

At the X-37B's current size, upmass cargo would be carried internally and externally while downmass cargo would be entirely within the payload bay (Figure 7). The considerable excess launch capability of the EELV class launch vehicles and unused volume within the 5m fairing enable the X-37 to carry several large ISS LRU's or other items externally on the service module (Figure 8). Cargo intended for the payload bay would be containerized to simplify unloading and loading by the astronauts or robotically. The operational concept would be to rendezvous in the berthing box of the ISS Space Station Remote Manipulator System (SSRMS) and have the ISS position the X-37 on the Common Berthing Mechanism (CBM) (Figure 9). The X-37B requires no services from the ISS except for the mechanical support provided by the CBM. Departure from the ISS would be initiated by the SSRMS. During preparation for deorbit, the service module would be jettisoned to provide a clean configuration for entry. After a conventional runway landing, the spacecraft would be towed into a hangar where the payload container would be removed.

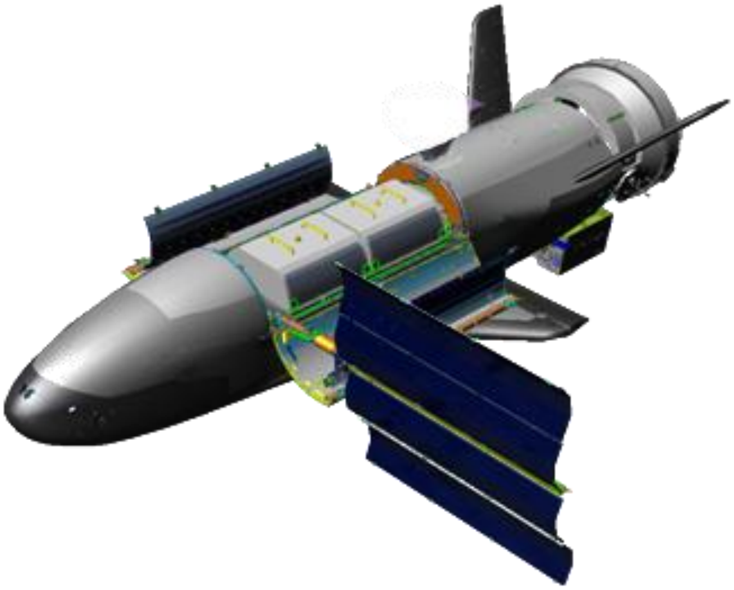


Figure 7. The X-37B, as currently designed, is able to support high value payload delivery and return.

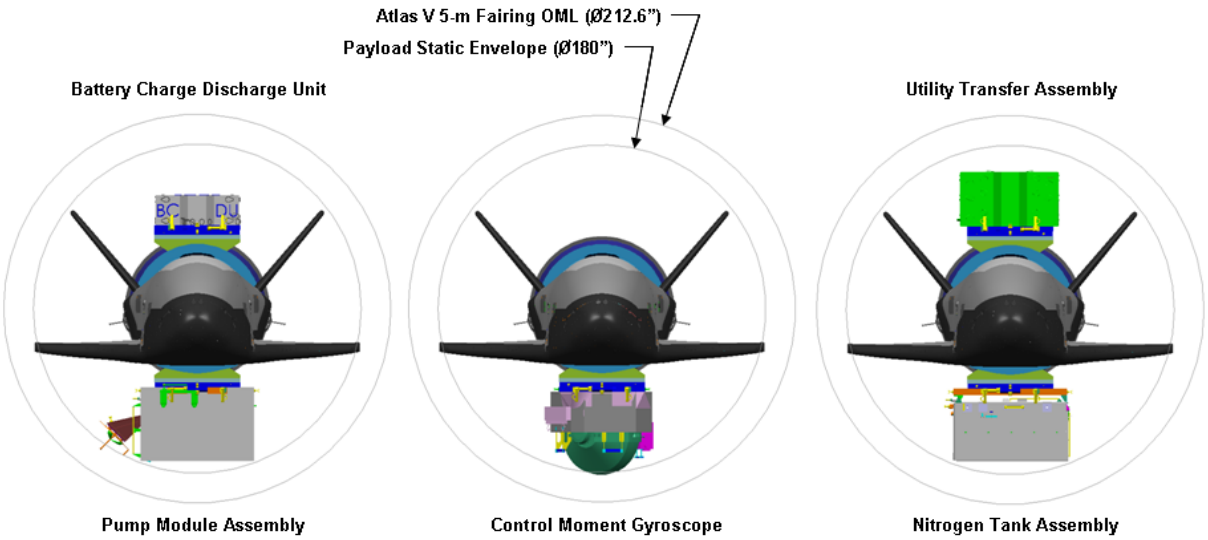
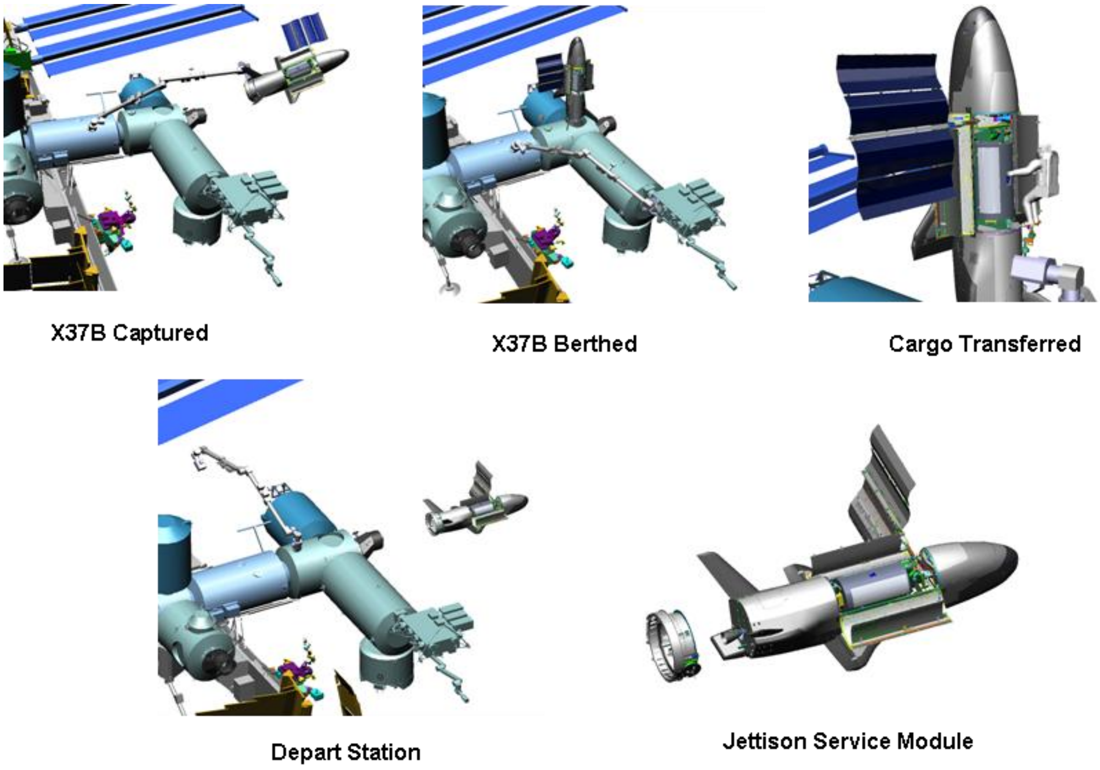


Figure 8. The X-37B design permits versatility in supporting up and down mass requirements.


X37B Captured

X37B Berthed

Cargo Transferred

Depart Station

Jettison Service Module

Figure 9. Sequence of events illustrating cargo transfer at the ISS.

At a larger vehicle size, derivatives of the X-37 can provide both cargo and crew transport to and from the ISS, Bigelow Space Habitats, or other forms of space tourism in LEO. The preferred size is approximately 160-180% of the current X-37B (Figure 10). At this fuselage diameter, a common airframe can support the internal return of ISS LRU's and provide pressurized crew accomodations. Analysis indicates these vehicles can be flown comfortably on a medium class EELV.

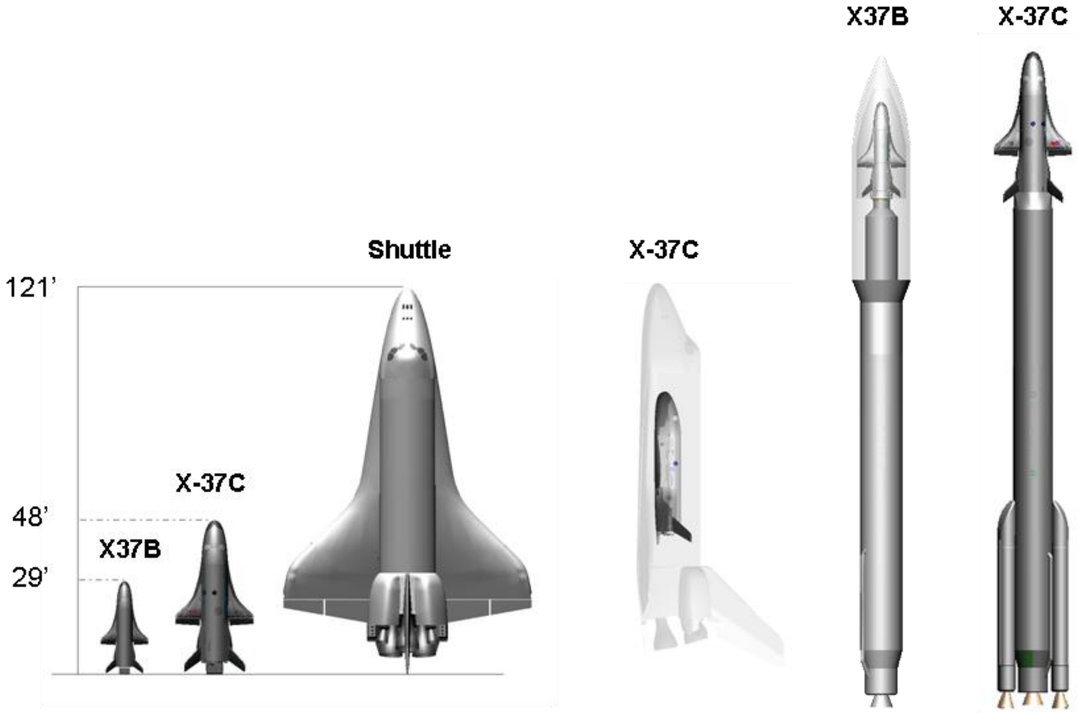


Figure 10. Size comparison of the X-37B, X-37C, Shuttle, and Atlas V EELV.

A cargo derivative can be configured several ways depending on the logistics needs of the destination: completely unpressurized, mix of pressurized and unpressurized spaces (Figure 11), or a large pressurized volume. (Figure 12) Unpressurized volume in the mid payload bay provides the capability for the largest and heaviest items. A mixed configuration has pressurized volume aft for perishable foods, water, supplies, and experiments. The ratio of pressurized versus unpressurized volumes could be modular and extended into the payload bay if there were no requirement for large cargo on a particular mission.

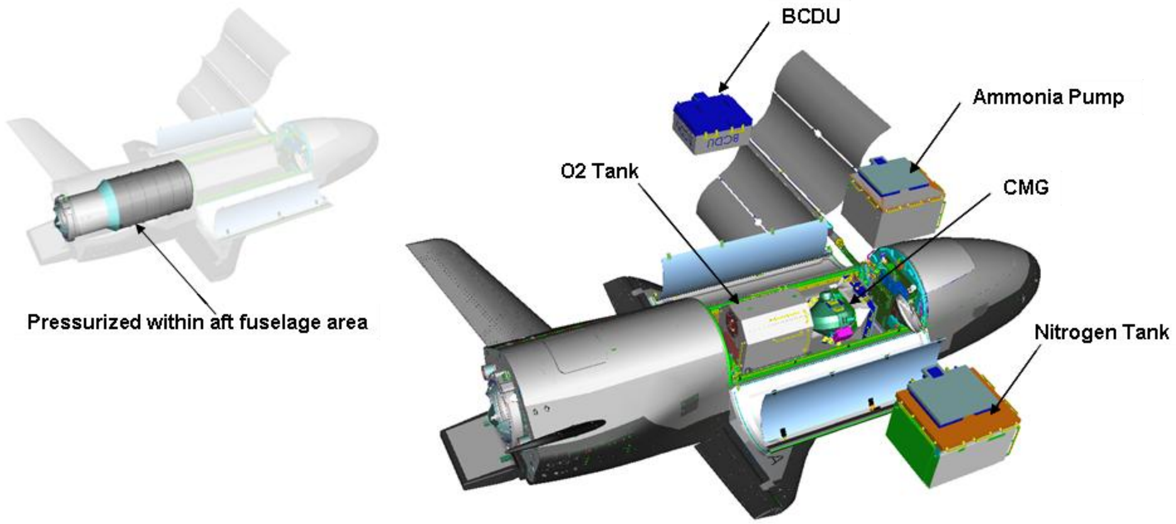


Figure 11. Larger X-37C provides flexibility for up and down mass – pressurized or unpressuirzed.

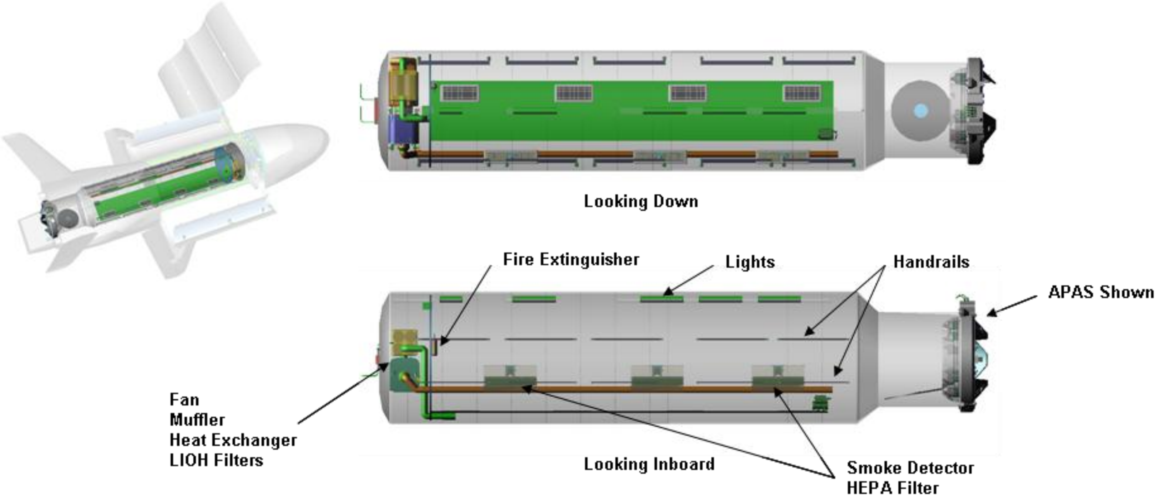


Figure 12. Maximum pressurized volume uses the full payload bay and aft fuselage.

The design for crew transportion derivatives is sized around 5-6 astronauts with provisions for one that is injured and requires a stretcher. There are two configuration types: 1) Aft APAS (Figure 13) and 2) mid APAS (Figure 14). Common features are that the crew is seated on one side so that there is a free corridor for both zero g access and vertical climbing on the launch pad. A secondary hatch is provided on the top surface for launch pad access and emergency egress. A pusher style abort system between the Centaur and the spacecraft can provide the appropriate acceleration and delta-v for the required abort scenarios. The spacecraft would be capable of rendezvous, docking, deorbiting, re-entering, and landing autonomously. Cross range capabilities yield several opportunities a day into Kennedy Space Center from the ISS. For the aft APAS configuration, an astronaut pilot flying a backup shadow mode would be provided a virtual wind screen view and direct optical periscope views, if required. Cargo and crew ingress and egress have less turns to negotiate and more flexibility with the aft APAS configuration. The primary advantage of a mid APAS is the ability to provide a pilot with direct forward view sightlines as a backup to a virtual wind screen view. A mixture of cameras and windows would cover other desired view angles.

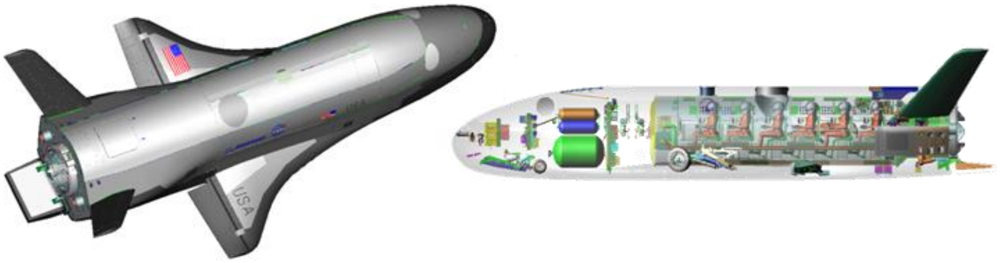


Figure 13. Aft APAS with 6 astronauts, forward and aft cameras, side windows.

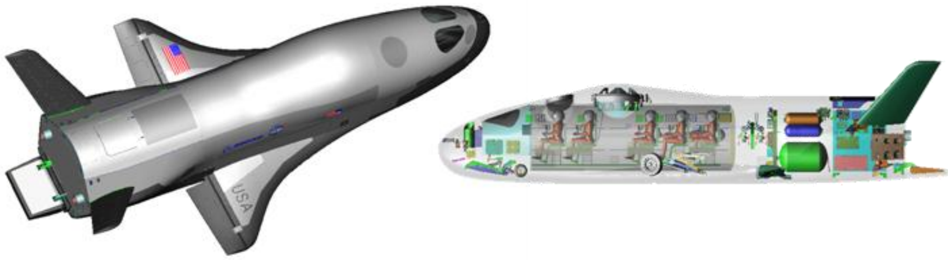
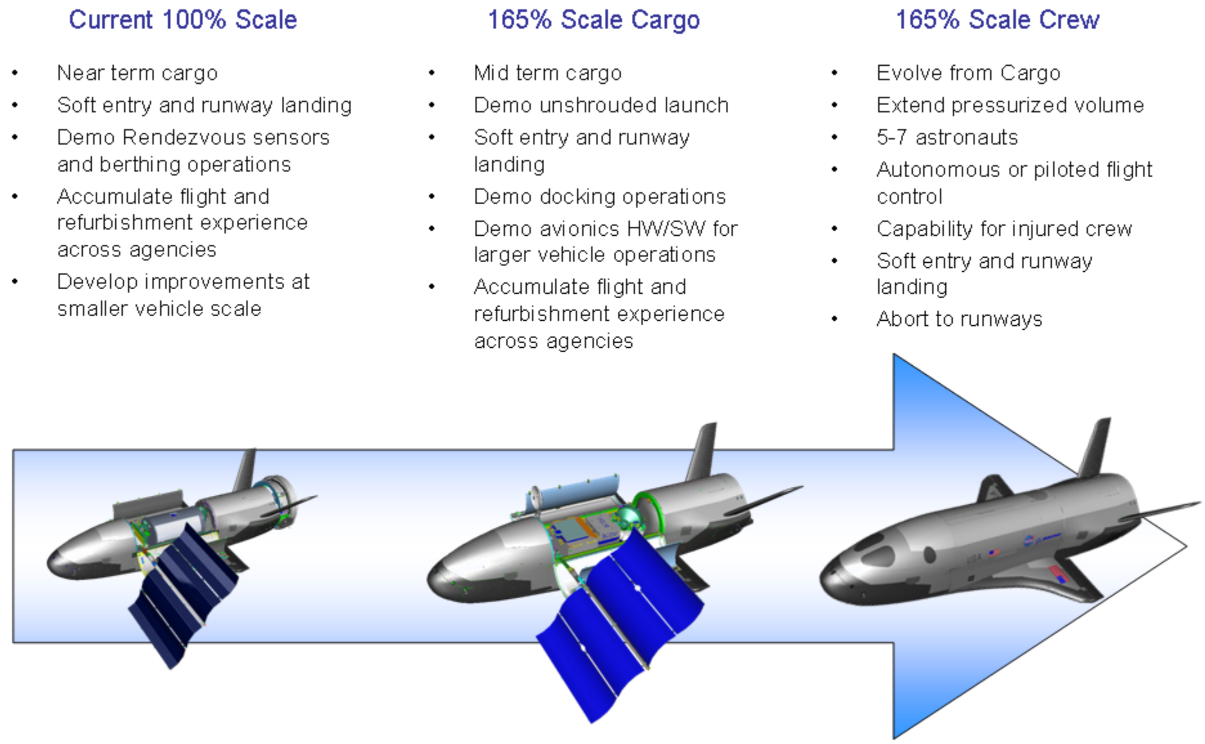


Figure 14. Mid APAS with 6 astronauts, forward and side windows, aft cameras.

The successful orbital and entry flight of the X-37B has retired many of the significant risks associated with a new, smaller and more affordable Orbiter replacement. The ongoing flights of the OTV will increase confidence in the configuration aerodynamics, aeroheating, and TPS design, the fault tolerant avionics and subsystem architecture, and the autonomous GNC operations (Figure 15). No new technology is required to build an X-37B customized to the ISS cargo mission and prototype the ISS operations and logistics. The next step would be a larger cargo vehicle with significant cargo return capabilities for ISS LRU's and experiments requiring a low acceleration return to Earth. At the same time the cargo vehicle is transporting supplies, it would be flying the demonstration missions necessary for a crewed spacecraft. It would retire any percieved risks of an autonomous system transporting astronauts through the launch, rendezvous, docking, entry, and landing phases of flight. Once qualified for human flight, these vehicles could transport a mix of astronauts and cargo to the ISS and offer a much gentler return to a runway landing for the space tourism industry.



Current 100% Scale

- Near term cargo
- Soft entry and runway landing
- Demo Rendezvous sensors and berthing operations
- Accumulate flight and refurbishment experience across agencies
- Develop improvements at smaller vehicle scale

165% Scale Cargo

- Mid term cargo
- Demo unshrouded launch
- Soft entry and runway landing
- Demo docking operations
- Demo avionics HW/SW for larger vehicle operations
- Accumulate flight and refurbishment experience across agencies

165% Scale Crew

- Evolve from Cargo
- Extend pressurized volume
- 5-7 astronauts
- Autonomous or piloted flight control
- Capability for injured crew
- Soft entry and runway landing
- Abort to runways

Figure 15. Development of X-37B derivatives incrementally retires risk as capabilities increase.

VIII. Summary

Reusable spacecraft for technology demonstations in LEO enable cost savings and acceleration of technology timelines by focusing customers on their experiments and not the rest of the system. Non-recurring costs are substantially reduced by taking advantage of a mature spacecraft bus with well defined bus to payload interfaces and a ground station supported by seasoned mission operations staff using flight validated operational products. The return of experimental payloads enables post flight inspection, test, and analyses and reflight opportunities for more educated product improvements and shorter design cycle times.

The X-37B recently completed its first test mission, has started its second, and has demonstrated the viability of a small test platform that can return experiments for post flight inspection and analysis. Several key technologies for reusable spacecraft were successfully demonstrated in the areas of aerodynamics, aerothermodynamics, reusable solar arrays, Thermal Protection Systems (TPS) and autonomous Guidance, Navigation, and Control (GNC). The current system provides a demonstration platform for autonomous spacecraft technologies, rendezvous sensors, spacecraft servicing, on-orbit environments for material and microelectronic characterization, and re-entry environments for advanced TPS materials and concepts.

The X-37B spacecraft represents the only vehicle flying in the world today that can provide a soft 1.5g class return of sensitive cargo from the ISS. The ongoing flights of the OTV will increase confidence in the configuration aerodynamics, aeroheating, and TPS design, the fault tolerant avionics and subsystem architecture, and the autonomous GNC operations. No new technology is required to build an X-37B customized to the ISS cargo mission and prototype the ISS operations and logistics. The next step is a larger cargo vehicle with significant cargo return capabilities for ISS LRU's and experiments requiring a low acceleration return to Earth. At the same time the cargo vehicle is transporting supplies, it would be flying the demonstration missions necessary for a crewed spacecraft. It would retire any percieved risks of an autonomous system transporting astronauts through the launch, rendezvous, docking, entry, and landing phases of flight. Once qualified for human flight, these vehicles could transport a mix of astronauts and cargo to the ISS and offer a much gentler return to a runway landing for the space tourism industry.

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