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A Concept of Operations and Technology Implications for Operationally Responsive Space

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Background and Introduction

During the last couple of decades, the United States Air Force has dramatically changed the way it views space and has shifted its terminology from "air power" to "aerospace power" to "air and space power." Air Force leadership also discussed a future shift from an "air and space force" to a "space and air force." This evolution began with an increasing reliance on space assets to support the full spectrum of United States military operations. The nearly ubiquitous use of space capabilities during Operation Iraqi Freedom (OIF) clearly illustrates our military's dependence on space, as exemplified by an infantryman's routine use of the global positioning system (GPS) for navigation. Other high-leverage systems include GPS precision-guided munitions; global communications; and intelligence, surveillance, and reconnaissance (ISR) satellites. Our use of existing space capabilities not only allow us to envision future opportunities, but also points our potential adversaries to systems and capabilities that they must plan to defend against or attack. A Russian military assessment of OIF combat operations identified the coalition's reliance upon space assets, and included a recommendation for the Russian military to develop antisatellite weapons.[1] As more countries develop or acquire space access systems, the threat to US military and commercial space assets will increase. The capability to maintain and supplement space assets ensures our asymmetric advantage in space.

An operationally responsive space (ORS) system could be an integral part of national defense by providing operational capabilities, flexibility, and responsiveness that does not exist today. Current space assets provide communication, navigation, and ISR capabilities using satellites designed for long life and high reliability. Those life and reliability requirements are due in part to the high cost and limited availability of space launch. Current space systems require years to develop due to the complicated specialized design and manufacturing processes. The high cost of launching space assets, and competition with the commercial launch market, require launch scheduling years in advance. Moreover, once it has been scheduled on a launch vehicle, it may take several months to checkout and integrate into the launch vehicle, and several additional months to become operational once it's in space. This existing capability is not operationally responsive.

An operationally responsive space system needs the capability to transport space assets to, through, and from space. The responsive satellites need operational capability immediately upon deployment for contingency constellation sustainment or augmentation. The global strike capabilities provided by a common aero vehicle (CAV) address issues associated with limited regional access or sovereign nation overflight.

The US Air Force Space Command (AFSPC) is conducting an ORS analysis of alternatives (AoA) to determine the cost effectiveness of responsive space launch and payload systems. The AoA originally addressed only responsive space launch and determined "responsive spacelift is nothing without responsive payloads."[2] The preliminary conclusions from the military utility analysis indicate that "ORS can provide significant military utility at the campaign level," through the use of responsive space asset delivery.[3] The largest impact occurs when the enemy has offensive counterspace (OCS) capabilities, and responsive launch vehicles and satellite systems maintain on-orbit capabilities. Space force application (SFA) and OCS missions also provide significant military utility, with the SFA contribution increasing as a function of theater access.[4]

To understand if the desired capabilities are feasible within current or near-term technology, it is helpful to examine a concept of operations (CONOPS) for an operationally responsive space system. Many types of space launch systems are under consideration— ranging from fully expendable launch vehicles originally developed from intercontinental ballistic missiles (ICBM) to fully reusable single-stage-to-orbit hypersonic vehicles, with the technological implications increasing across that spectrum. The preliminary ORS AoA evaluated a wide range of launch vehicle architectures and determined that the system with the lowest life cycle cost was a partially reusable system— a reusable first-stage booster vehicle used in conjunction with expendable upper-stage vehicles. This paper develops a CONOPS for such a system and identifies the technology development that is needed to provide an initial operational capability in the 2015 timeframe.

Operationally Responsive Space Missions

Based upon the preliminary AoA results, a partially-reusable space launch vehicle and payload systems is postulated.[5] Examining how it supports each of the Air Force Space Command mission areas, shown in Figure 1, develops the concept of operations.

- **Space Force Enhancement (SFE)**
  – Capabilities that contribute to maximizing the effectiveness of military air, land, sea, and space operations
- **Counterspace (CS)**
  – Capabilities to attain and maintain a desired degree of space superiority by allowing friendly forces to exploit space capabilities while negating an adversary's ability to do the same
- **Space Force Application (SFA)**
  – Capabilities to execute missions with weapons systems operating from or through space which hold terrestrial targets at risk
- **Space Support (SS)**
  – Capabilities to provide critical launch and satellite control infrastructure, capabilities and technologies that enable the other mission areas to effectively perform their missions
- **Mission Support (MS)**
  – Functional areas that cut across all mission areas and provide the required infrastructure

Figure 1. Air Force Space Command Mission Areas and Mission Support
Courtsey of the AFSPC's Strategic Master Plan for FY06 and Beyond, 1 Oct 2003

The ORS system's communication, navigation, and ISR satellites are designed to replace or supplement existing systems to enhance to current space force. The system also includes new tactical satellites specifically designed to support contingency operations through rapid on-orbit checkout. These tactical satellites could provide increased communication bandwidth, increased ISR imagery, and additional GPS signal density over the theater for a limited period to support air, ground, and naval force missions. To achieve such capabilities, the launch vehicle needs the capability to deploy several satellites during each launch, requiring each satellite to be small, efficient, and available for launch on demand. Theater commanders need on-orbit assets to be capable of quickly becoming operational, performing tasks more reliably, operating at a lower cost, and exposing crew members to less risk than current or future alternative airborne systems.

An ORS system can provide enabling capabilities to support offensive and defensive counterspace operations. The predictable nature of satellites in earth orbit makes them relatively easy targets for an adversary. While some OCS operations can be conducted from the ground, as demonstrated by Cuba jamming satellite broadcasts into Iran from America or anti-satellite missiles launched from fighter aircraft, systems can be envisioned that would be launched at the beginning of a conflict to blind or mute an adversary's satellite. Such OCS systems could do so either benignly or destructively. A highly maneuverable orbital spacecraft might approach another satellite and deploy an umbrella to "shadow" its solar panels, causing it to shut down; another might maneuver to block a satellite's signal or optical view. Defensive counterspace systems could include the deployment of decoys, attack detection, and possibly defensive maneuver.

Affordable, responsive spacelift enables force application from or through space for the appropriate target set. However, launching ICBMs with conventional munitions is not a practical solution for the broad range of operational targets. Not withstanding the significant international political ramifications; the costs associated with acquiring and storing the vast quantities of conventionally armed ICBMs needed to replace air delivered conventional weapons, in even a small conflict, would be prohibitive. That said, the common aero vehicle could protect and guide an appropriate payload through atmospheric reentry heating— after launch from a reusable or expendable launch vehicle— to attack those appropriate high-value targets. Wide varieties of CAV payloads are postulated; from kinetic energy deep penetrating munitions, to high explosive munitions, to the deployment of micro-unmanned aerial vehicles (UAV) for specialized ISR.

The operationally responsive *spacelift* portion of ORS is the definition of the space support mission area. The small size of ORS payloads leads to the development of a spacelift capacity that will be to small to replace the evolved expendable launch vehicle (EELV) fleet. However, many low earth orbit communication, navigation, or ISR constellation satellites could still use the ORS launch vehicle.

ORS System Details

An operationally responsive space system consists of three primary elements: the reusable first-stage boosters, expendable upper-stage vehicles, and responsive payloads. Detailed systems engineering and preliminary design studies are not complete, so the description provided in this paper is the author's, and only provides a sense of perspective; a future system would emerge different than presented here. However, the concept of operation and technology implication discussions should remain relevant.

The launch vehicle's delivery capability is approximately 10,000 pounds of payload to low earth orbit— a reference orbit of 100 nautical miles and 28.5 degree inclination from the Eastern Test Range at Cape Canaveral, Florida— making it a medium-lift launcher in a similar class with the Delta-II or Atlas-II launch vehicles, with slightly less capability than the smallest EELV.[6] The launch vehicle architecture is a vertical takeoff, horizontal landing (VTHL) system, similar to the space shuttle, and is represented in Figure 2. The first stage is a fully reusable booster vehicle that lifts off vertically, accelerates to an approximate speed of Mach 5, achieves an altitude of 150,000 feet, and travels about 350 nautical miles downrange. The upper stage separates, starts its engine, and accelerates to deploy its payload. Payloads can be deployed either to orbit or into a trajectory for a CAV mission. The booster vehicle coasts to apogee and begins its return to the launch site. When the booster has descended to an altitude with sufficient air for jet engine propulsion, its gas turbine engines provide powered flight back to the runway. Autonomous vehicle operation requires minimal input or control from the launch control center.

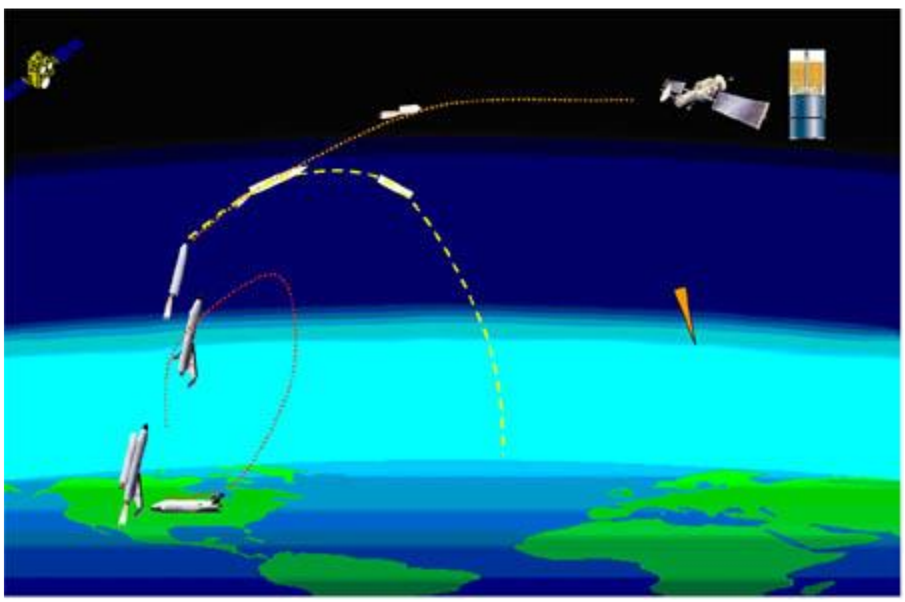

Figure 2. Notional ORS Mission Architecture

The booster vehicle utilizes rocket engine propulsion with liquid oxygen and kerosene propellants, and is slightly smaller and more elongated than the space shuttle orbiter. While the space shuttle orbiter contains a crew cabin, payload bay, main and auxiliary propulsion systems, and landing systems, the ORS booster does not have a crew compartment or payload bay. The ORS booster includes only the propellant tanks, main propulsion system, and landing system. The primary purpose of the first-stage vehicle is to lift the upper-stages and payload through the dense atmosphere near the surface of the earth and accelerate them to the first 30– 40 percent of orbital velocity. Since the booster vehicle does not encounter the severe atmospheric reentry heating that the space shuttle orbiter does, it does not require a complicated thermal protection system.

The upper stage vehicles sit on top of the booster vehicle, piggyback style, to simplify the vehicle interface and avoid aerodynamic and structural issues of an inline configuration. The second-stage vehicle provides the final acceleration to reach orbital velocity or enter a ballistic trajectory, reflecting the specific mission's requirement. After deploying the payload, the second-stage reenters the earth's atmosphere and mostly burns up during reentry. An orbital mission payload includes a mission insertion stage to provide the final acceleration necessary to place the payload in its destination orbit.

The ORS architecture envisioned in this paper supports spiral acquisition— an evolutionary approach with incremental instead of one long, large acquisition. It will begin operation with a multi-purpose vehicle and its evolutionary development of alternative upper-stages will increase the mission efficiency through lower cost or higher mass payload delivery. The initial upper-stage vehicle also uses a liquid propellant (liquid oxygen and kerosene) propulsion system to maintain operational simplicity. During evolutionary development, solid rocket propulsion stages customized for the CAV delivery mission could be developed to decrease call-up and turn-around time.[7] A liquid hydrogen fueled upper stage alternative could substantially increase the delivered payload to orbit, but would reduce responsiveness and increase launch operation complexity and cost.

The final part of the ORS architecture is responsive payloads, which are primarily categorized into three areas: satellites for communication, navigation, and ISR, common aero vehicles, and new systems for defensive and offensive counterspace capabilities. Currently, most state of the art military satellite system designs require long operational life, high reliability, and radiation hardening to withstand a nuclear detonation in space. The life requirement directly increases the size and mass of the satellite by increasing the station-keeping propellant quantity. Often, designs use redundant electronic systems, components, and software to meet the reliability requirements. These solutions to system requirements significantly increase the design complexity, and thus the cost, of a satellite system. Since these solutions reflect the assumption of an infrequent and expensive launch capability, a responsive launch capability enables a paradigm shift in design requirements.

Responsive payload requirement changes and the continued increase in electronic capability and miniaturization will reduce payload size, complexity, and cost. The ability to launch a satellite on-demand allows for shorter life requirements and proportionally smaller propellant quantities. Satellite reliability can be met using robust design practices instead of redundancy, which decreases the amount of hardware and results in an even larger decrease in software development and testing. The ability to rapidly replace the assets that provide space capabilities reduces the number of systems that need nuclear detonation radiation hardening— however, a detailed risk-benefit analysis would be needed on a case-by-case basis.

Common aero vehicles provide global access to payloads launched from the CONUS, primarily for precision strike missions and secondarily to deploy small UAVs for low altitude ISR missions. The CAV precision strike mission is particularly attractive for targets with limited regional access using conventional aircraft or ship launched cruise missiles. As enemy air defenses gain the ability to detect stealth aircraft, the risk of aircrew loss will go up significantly.

CAVs could play a critical role in the attack of high-value and time-critical targets as well as helping to open the air-breathing door by assisting in the suppression of enemy air defenses.

Infrastructure

The site selection process for a responsive space system must trade off a number of competing issues, including payload trajectories, operational security, public safety, environmental impact, and weather. An ORS needs the capability to launch satellites into orbits ranging from low-inclination easterly orbits— the majority of the missions— to polar orbits. A launch site located at a southern latitude is most efficient for low-inclination easterly orbits and would provide CAV missions access to virtually any trajectory. Unfortunately, no existing launch sites have the capability of launching to a wide range of trajectories due to the safety concerns that limit the flight of launch vehicles over or near populated areas. ICBM launch facilities during the Cold War were at remote in-land CONUS locations to increase security and survivability, issues which remain relevant to ORS siting. While these sites were relatively remote, the public safety risk due to expended launch vehicle stages or launch vehicle failure was a minor consideration with respect to the effect of the events subsequent to an ICBM launch event. Notices to airmen and mariners (NOTAM and NOTMAR) are commonly made at the Eastern Test Range (ETR) and Western Test Range (WTR) to ensure the airspace and water in and around the launch site is clear prior to a launch, for protection of the mission and for public safety. Such notifications are essential because the actual reliability of launch vehicles is approximately 98 percent, seemingly independent of the vehicle design or heritage.[8] Operational security precludes such prelaunch notifications; launches must occur based primarily upon operational considerations. Responsive space access will not be possible if launch vehicle reliability is not dramatically increased and the overflight of populated areas allowed. The overflight of populated area has two negative characteristics: the risk to public safety resulting from a vehicle failure and the noise generated along the flight path. Although the Space Shuttle Columbia debris did not injure anyone on the ground, there were several near misses.[9] The partially reusable concept helps mitigate those risks, however failure of a launch vehicle during ascent, with significant propellants on-board, remains a significant hazard.

Weather has been a frequent cause of schedule delays for ETR and WTR launches, particularly with space shuttle launches. An aerospace contractor studied potential basing locations for an Air Force Research Laboratory (AFRL) Space Operations Vehicle (SOV) concept, comparing the climatologic factors at Cape Canaveral, Florida; Eglin AFB, Florida; Minot AFB, North Dakota; Edwards AFB, California; and Holloman AFB, New Mexico.[10] Although this study indicated that operations would be limited by weather— snow and ice at Minot during the winter, rain and thunderstorms at Eglin in the summer, and winds at Edwards, Minot, and Holloman— Holloman launches would be the least impacted. Consolidating the primary siting considerations, Holloman AFB seems well suited for an ORS base, particularly with the booster landing site flexibility offered by the lakebed at adjacent White Sands Missile Range. Sites in New Mexico, Texas, and Oklahoma could offer other potential base locations.[11]

Figure 3 shows the primary facility requirements for the ORS base, consisting of launch pads, a launch operations center, vehicle integration facility (VIF), vehicle hangars, payload storage and preparation facilities, vehicle maintenance facility (VMF), propellant storage and handling facilities, and a runway. Multiple launch facilities enable a surge capability of several sorties per day. After the second stage vehicle separates, the booster vehicle lands on the runway and is taken to the VMF where maintenance or inspections are conducted for routine items and anything identified by the on-board integrated vehicle health management system. Payloads are prepared and integrated with the second stage vehicles and taken to the vehicle integration facility for integration with the booster. The vehicle is integrated horizontally and prepared for launch on a transporter/erector assembly. It is then taken to the launch pad, rotated into the vertical launch configuration, and prepared for launch.

Propellants arrive at the base via truck or rail for storage in tanks and dewars, with piping distribution systems to each launch pad. The hydrocarbon propellant, RP-1, is a kerosene fuel product; its handling and operational requirements are similar to jet fuels used on flight lines today, so no special infrastructure is required. The liquid oxygen (LOX) rocket engine oxidizer has a normal boiling point of –270º F; it requires special handling to ensure safety and must be stored in vacuum jacketed storage tanks to limit the boil-off loss. Liquid oxygen is a common industrial product, so its storage and handling operations are well understood. Most Air Force bases have demonstrated the safe use of liquid oxygen for breathing oxygen on-board aircraft or at the hospital.

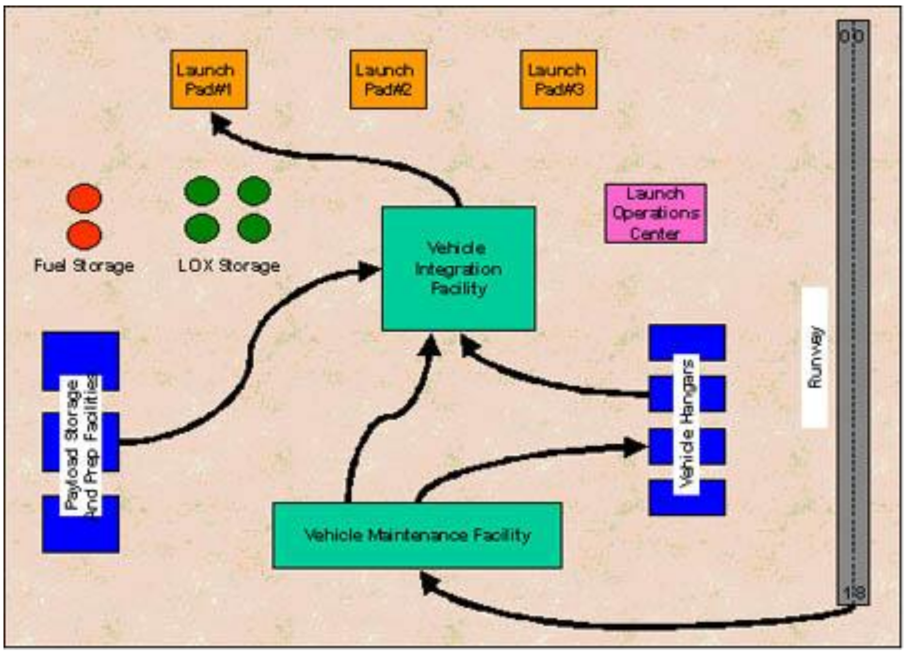

Figure 3. ORS Operations Complex

Personnel and Training

Due to the unique militarily missions, a blue-suit operation is envisioned: however, use of contractor personnel or a military-contractor combination may also be attractive. The systems design presented in this paper considers factors such as training, safety, and personnel turnover associated with Air Force personnel operating the system, so specialized contractors are not required. As other authors have discussed, a unique relationship could be established wherein the

Air Force's ORS assets are used by civil or commercial missions— almost the reciprocal of the cargo aircraft Civil Reserve Air Fleet.[12,13]

Operational training needs to sufficiently simulate the wartime surge mode to develop confidence in operations (probably looking similar to a Strategic Air Command B-52 Emergency War Order exercise during the 1980s). For a reusable vehicle, one of the primary exercise objectives would be to demonstrate the turnaround capability and understand the unplanned maintenance requirements. Conducting actual launches may be necessary at least yearly. This type of training will be very expensive with actual launches; however, with proper planning, these exercises would simply deploy required space assets or conduct prototype testing of new systems.

Technology Challenges

The primary technology challenges for an operationally responsive launch vehicle lie in the areas of propulsion, avionics, and health management systems— the development risks in these areas must be mitigated before a viable system can be developed. Other technology challenges in the areas of aerostructural systems, power systems, mechanical systems, and payloads are essential to meeting the goals and objectives. It is important to note that the technology challenges associated with future space launch vehicles do not necessarily require inventions or new developments in physics. The challenges lie in gaining significant improvements from existing systems or technologies to increase reliability, obtain longer operational life, and gain better performance at lower cost.

Propulsion System Background and Challenges

Liquid rocket engines and gas turbine engines are fundamentally different types of machines. The power density, cooling requirements, start and shutdown transients, and other operational environments are much more severe in liquid rocket engines. Jet engines use oxygen from the air in the atmosphere to burn with the fuel, whereas rocket engines use oxygen stored as a cryogenic liquid oxygen in the vehicle's tanks to burn with the fuel. Jet engines are started to a low power level and allowed to warm-up prior to being throttled to full power, usually on the order of minutes. However, rocket engines must start at full power, on the order of a few seconds— three to six seconds on average. This rapid application of severe environments: high pressures, large forces, severe vibrations, and intense temperatures, places tremendous demands on the rocket engine hardware.

RP-1 was the fuel used by the F-1 rocket engines on the first-stage of the Saturn V launch vehicle. Two primary technical challenges exist for using RP-1 in reusable rocket engines; first, the risk of "coking" in the combustion chamber coolant channels, and second, ensuring that any residual fuel in the engine does not contaminate the oxidizer system. Coking is a phenomenon whereby the kerosene thermally decomposes and deposits form on the inside of the small coolant passages; these deposits cause degraded performance and possibly engine failure. National Aviation and Space Administration (NASA) and the Air Force Research Laboratory (AFRL) are currently conducting risk reduction activities to quantify the coking phenomena for advanced RP-1 cooled engines, and developing mitigations for those risks.

The oxidizer-rich staged combustion (ORSC) oxygen/RP-1 rocket engine is one of the greatest technical challenges needed for an ORS system. The United States has never developed such an engine.[14] Instead, during early rocket engine development of the fifties and sixties, the US headed down an evolutionary path of continual improvement and increasing size with gas generator engines.[15] However, the Soviet Union chose an evolutionary path of development with staged-combustion engines. The Soviet Union developed a large ORSC engine for its space shuttle and evolved that design approach to create the RD-180 rocket engine, which was sold to the United States and subsequently used on the Atlas III and Atlas V launch vehicles. While a good engine, the RD-180 was designed and produced in Russia.[16] The RD-180 does not meet the operability and long-life requirements for an ORS system, and since NPO Energomash, a Russian company, owns its design information, modifications needed to meet ORS requirements are not known. NASA's Marshall Space Flight Center managed studies for large ORSC liquid oxygen/RP-1 engines with two US aerospace contractors: Boeing's Rocketdyne Propulsion and Power; and Northrop Grumman Space Technologies. Since the United States has no direct experience with kerosene staged combustion cycle engines and therefore may encounter unknown issues with its operation and operational environment, development and testing of a prototype engine is essential to reduce the risk for an operationally responsive spacelift vehicle. Unfortunately, with president's recent announcement of NASA's new space exploration objectives, NASA has had to dramatically cut back on its ORSC engine development projects until it clearly identifies a need for such a propulsion system.

Aero-structural Challenges

Propellant tanks need to safely and repeatedly withstand the intense loads from operation at the low temperatures of the cryogenic propellants and forces generated during launch. For structural mass efficiency, the design of the propellant tanks must be integral with the vehicle structural design, and the tanks may carry a substantial part of the vehicle load in ways that previous tanks have not. Composite tanks have been a major area of research within the last decade due to the potential strength advantage of graphite and carbon fiber composite structures. The usefulness of those materials has been clearly demonstrated in most recent military aircraft designs, which use significant amounts of composite structures. For ambient temperature liquids, such as kerosene based RP-1, composite tanks have a relatively high technology readiness level and little development is needed. However, for cryogenic liquids such as liquid oxygen and liquid hydrogen, composite tanks still need significant development.

The ORS system has minimal thermal protection requirements since it does not have liquid hydrogen cryogenic fuel and only the booster vehicle returns for reuse, doing so early in the launch profile and avoiding the significant aerodynamic heating encountered by vehicles returning from orbit. The ORS system may also take advantage of state-of-the-art materials and structural design approaches to minimize the size of the vehicle. However, programmatic life cycle cost analyses will determine if advanced materials and design approaches are the best solution.

Avionics and Health Management Challenges

There are two primary technical challenges exist in the area of avionics for a responsive launch vehicle: (1) avionics hardware and software for autonomous vehicle operations and (2) integrated vehicle management systems. With the recent advances in electronic and computer technologies in the commercial world, there are few significant hardware areas of concern.[17] It is primarily a detailed electronic system integration problem. The recent usage of unmanned aerial vehicles for reconnaissance, through autonomous or remote operation has demonstrated their ability to function. However, controlling a vehicle during a freefall from 200,000 ft, starting its jet engines and flying it back to the launch base for landing is a significantly different problem than flying a low speed UAV. Autonomous flight control software that can automatically adjust for a variety of mission trajectories and weather conditions is a technical challenge that can build on the autopilot software used during shuttle reentries and commercial aircraft instrument landing system (ILS) and auto-land approaches and landings, but still may require artificial intelligence.

Integrated vehicle health management (IVHM) systems that monitor vehicle and subsystem health will be critical to operationally responsive spacelift. These management systems have two critical roles: (1) the real-time identification of an impending failure, the initiation of in-flight mitigation actions to save the vehicle or subsystem, and then guide the maintenance activity during its turnaround to restore it to a fully mission capable (FMC) status; (2) to continually monitor the vehicle and its subsystems' performance, identify trends, and determine which systems need an inspection or maintenance action.

Mechanical & Electrical Challenges

Hydraulic systems on the NASA space shuttles are one of the primary causes of poor operability. Hydraulic systems control the main engine thrust vector control and the aerodynamic flight surfaces. Great care must be exercised to avoid contamination of the hydraulic systems to avoid causing faulty operation or failures. Hydraulic systems are also prone to leakage, so inspection and maintenance must be continually performed to ensure the hydraulic system is leak free and operates properly. Hydraulic fluid can also contaminate other systems and could present a flight hazard. Use of electrically operated control systems may help improve a launch vehicle's operability. The precedent of using electrically operated flight control systems has already been established in the designs of some recent commercial and military aircraft. An all-electric launch vehicle requires a more capable power system; the specific launch vehicle trade study would determine whether auxiliary power units (APU), fuel cells, batteries, or some combination of both is needed. Significant progress in battery and fuel cell technology, supporting environmentally friendly automobiles, has been made over the last decade. APUs are necessary when more power is needed than can be supplied by the batteries or fuel cells. Although the F-16 and the space shuttle use hydrazine fuel driven APUs, the hazards and operational constraints associated with hydrazine make it undesirable for use in a future APU system. Technology development is needed to increase power system specific power, storage efficiency, reliability, and operability.[18] Power production is the first half of the problem; the second half is converting that electrical energy into a mechanical effect.

Electro-mechanical actuators (EMA), electro-hydraulic actuators (EHA), and pneumatic actuators (EPA) convert electrical energy into mechanical motion. Actuators control the thrust vector of the main engines during powered ascent, the movement of the aerodynamic control surfaces, and the positioning of some propulsion system valves. EMAs consist of an electric motor and a series of gears to reduce the speed and increase the delivered torque. Electro-hydraulic actuators combine the benefits of an electric system with the benefits of hydraulic systems. EHAs use an electric motor to drive a hydraulic pump, and the hydraulic pressure acting on a cylinder provides the mechanical actuation energy. EPAs are similar, but instead of a hydraulic pump, a compressor builds pneumatic pressure. EHAs and EPAs avoid the operability issues associated with a central hydraulic/pneumatic supply and distribution system.

There is very little experience in the use of electrically operated actuators for rocket and launch vehicle systems. In some cases, the required force, or torque, is greater than that required for aircraft or ground actuators. In other applications, the rate at which the actuator must operate is greater than current systems can provide. A launch vehicle is a closed system and electrical systems can get hot quickly. During operation in an aircraft, the duty cycle (amount of time between operation) of an EMA is relatively long and the actuator has an opportunity to dissipate heat to its environment. The requirement for high power, high temperature, and fast-acting actuators necessitates technology development.

Responsive Payload Challenges

As Col Pamela Stewart previously observed, “Responsive space is nothing without responsive payloads.” Therefore, technology development must address the issues leading to the current high cost and long development time for satellites. Launch vehicle payload integration and checkout and on-orbit checkout and activation are very lengthy processes, which are currently on the order of months for each. Although the use of a common payload interface bus for the Delta IV and Atlas V EELVs has made substantial improvement, the integration and launch preparation still requires weeks to accomplish. Although in recent critical situations on-orbit checkout was reduced to a few weeks, it still failed to meet ORS needs. Simplification of the satellite’s systems will address much of the concern, however a technical challenge lies in the development of a standardized bus system that can perform automated internal self-diagnostics. The standardized bus would contain the core satellite subsystems upon which the specific mission payload is built. This standardized core would contain the power generation, storage, and heat rejection systems, electrical power management and distribution systems, on-orbit propulsion system, satellite function communications, structural, and launch vehicle interfaces. Much of the knowledge and technology developed by the micro-satellite industry will be a starting point. Such a concept may seem obvious, however unique requirements and infrequent acquisition have prevented such an approach in the past.

Summary

An operationally responsive space system will provide transformational capabilities for the warfighter. It can be used to meet a theater commander’s on-demand requirements for additional communication, navigation, or ISR capabilities and provide a global strike capability to meet objectives. The operational concept for an ORS system fits well within the experience of the Air Force, supports the AFSPC mission areas, and the technology challenges are modest and achievable. The recommended approach supports the spiral development process and allows incorporation of the experience gained with the system in evolutionary development.

Notes

1. Maj Gen G. A. Berezkin, “Lessons and Conclusions from the War in Iraq,” *Russian Academy of Military Sciences Analysis of War in Iraq,* CEP20030911000356 (Moscow: Voyennaya Mysl [in Russian],11 Jul 03), 58–78. Major General Berezkin, doctor of technical sciences, is the deputy chief of the Central Institute of Military-Technical Information of the Russian Federation Ministry of Defense.

2. Col Pamela Stewart, interview with author, HQ AFSPC, Peterson AFB, CO, 12 December 2003.

3. Col Pamela Stewart, “AFSPC Operationally Responsive Spacelift Analysis of Alternatives Interim Status” (briefing, Core Technologies Conference, 4 November 2003).

4. Ibid.

5. A partially-reusable launch vehicle can also be referred to as a hybrid RLV-ELV, but that terminology will not be used in this paper to avoid confusion with a hybrid rocket system, which has aspects of solid propellant and liquid propellant rocket systems.

6. EELV is the acronym for the Air Force’s *Evolved Expendable Launch Vehicle* program and consists of the Boeing Delta IV and the Lockheed Martin Atlas V launch vehicle family. See Steven A. Isakowitz, *International Reference Guide to Space Launch Systems* (Washington, DC: American Institute of Aeronautics and Astronautics, 2d Edition, 1999).

7. For the purpose of this paper, *call-up time* is defined as the time required to prepare for launch, starting with the vehicles in a stand-by mode in a hangar and ending with the payload integrated into the vehicle and ready for launch operations on the launch pad. *Turn-around time* is defined as the time required to prepare for a launch with the same booster vehicle, the time from “wheels chocked” to ready for launch operations. Launch operations includes all activities on the launch pad beginning with propellant and pressurant loading and ending with the engine start command.

8. *Columbia Accident Investigation Board Report* (Washington, DC: National Aeronautics and Space Administration or Government Printing Office, 2003), vol.1, http://www.caib.us/news/report/volume1/. See chapter 1 for a discussion of launch vehicle reliability.

9. *Columbia Accident Investigation Board Report*, vol. 1. See chapter 10 for significant findings and recommendations relating to public safety and the public’s risk due to reentry orbital debris. Finding F10.1-2 is particularly interesting, “Given the best information available to date, a formal risk analysis sponsored by the Board found that the lack of general-public casualties from Columbia’s break-up was the expected outcome.” This indicates that the orbital debris risk assessment methods are credible.

10. Edwin Scholz, John Duffey, Steven Sasso, Gregory Peraltra, and Lt Lee Jackson, *Overview of SOV Concepts and Technology Needs* (Huntsville, AL: AIAA Joint Propulsion Conference, 20-23 July 2003).

11. The Oklahoma Spaceport, located at the former Clinton-Sherman AFB at Burns Flat, Oklahoma, with its 15,000 ft runway has been chosen by Rocketplane Unlimited, Inc. for its commercial space tourism business. Rocketplane plans to offer suborbital ballistic spaceflights to 100 km by 2007. While this area has a relatively low population density, being mostly farm and ranch land, it is much higher than other areas of the Western United States, indicating the public safety risk for rocket propelled aircraft is quantified sufficiently for private insurance coverage.

12. Lt Col Larry Sills in "Space-Based Global Strike, Understanding Strategic and Military Implications," Occasional Paper no. 24 (Maxwell AFB, AL: Center for Strategy and Technology, August 2001).

13. Maj Michael A. Rampino in "Concepts of Operations for a Reusable Launch Vehicle"(Maxwell AFB, AL: Air University Press, 1997).

14. In a gas generator (GG) cycle, a portion of the fuel and a very small portion of the oxidizer is burned to create a fuel-rich gas to drive the turbine to turn the pumps to create the higher pressure propellants to burn in the main combustion chamber. The GG turbine exhaust gas is then exhausted overboard. Since all of the propellant is not burned in the main combustion chamber, it has low efficiency.

15. In an oxidizer-rich staged combustion rocket engine, all of the oxidizer and a small amount of the fuel is burned in a preburner to generate hot oxygen-rich gas to drive the turbines and pump the propellants to high pressures. This hot gas is then combusted with the remainder of the fuel in the main combustion chamber. Since all of the propellants are combusted in the combustion chamber, this cycle has high efficiency. However, the ORSC cycle requires much higher system pressures and is more complicated, resulting in a heavier engine.

16. As part of the EELV program, domestic co-production of the RD-180 is planned for future Atlas V missions.

17. The Power PC processor developed by Apple, Motorola, and IBM, and used in Macintosh computers today, meets most space radiation requirements.

18. *Specific power* is defined as the power produced divided by the weight of the power production equipment.
