

Low Cost Space Demonstration for a Single-Person Spacecraft

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This paper introduces a concept for a single-person spacecraft and presents plans for flying a low-cost, robotic demonstration mission. Called FlexCraft, the vehicle integrates propulsion and robotics into a small spacecraft that enables rapid, shirt-sleeve access to space. It can be flown by astronauts or tele-operated and is equipped with interchangeable manipulators used for maintaining the International Space Station (ISS), exploring asteroids, and servicing telescopes or satellites. Most FlexCraft systems are verified using ground facilities; however, a test in the weightless environment is needed to assess propulsion and manipulator performance. For this, a simplified, unmanned, version of FlexCraft is flown on a low-cost launch vehicle to a 350 km circular orbit. After separation from the upper stage, the vehicle returns to a target box mounted on the stage testing the propulsion and control capability. The box is equipped with manipulator test items that are representative of tasks performed on ISS, asteroid missions, or for satellites servicing. Nominal and off-nominal operations are conducted over 3 days then the vehicle re-enters the atmosphere without becoming a debris hazard. From concept to management to operations, the FlexCraft demonstration is designed to be low-cost project that is launched within three years. This is possible using a simplified test configuration that eliminates nine systems unique to the operational version and by “designing-to-availability.” For example, the propulsion system is the same as the Manned Maneuvering Unit because it capable, simple, human-rated and all components or equivalent parts are available. A description of the launch vehicle options, mission operations, configuration, and demonstrator subsystems is presented. In addition, discussions on the use of mockups, cost reduction, management approach and the innovative application of Army helicopter simulation facilities are included..

I. Introduction

VISIONS of a single-person spacecraft are not new (Fig.1). In 1954, Werner vonBraun conceived of a bottle suit and science fiction is replete with designs most notably, the pod featured in the 1969 movie *2001 A Space Odyssey*. In addition, there have been numerous engineering studies however after all these years, not one has flown. FlexCraft is designed to fly, first as an expendable, robotic demonstrator then as a human-rated spacecraft operating at the International Space Station, servicing satellites, and exploring asteroids. Because all other FlexCraft systems can be verified on the ground, the demonstrator focuses on testing the propulsion and manipulator systems in the relevant weightless environment. For this, the FlexCraft demonstrator is a simplified, unmanned, version specifically configured for propulsion and manipulator testing.

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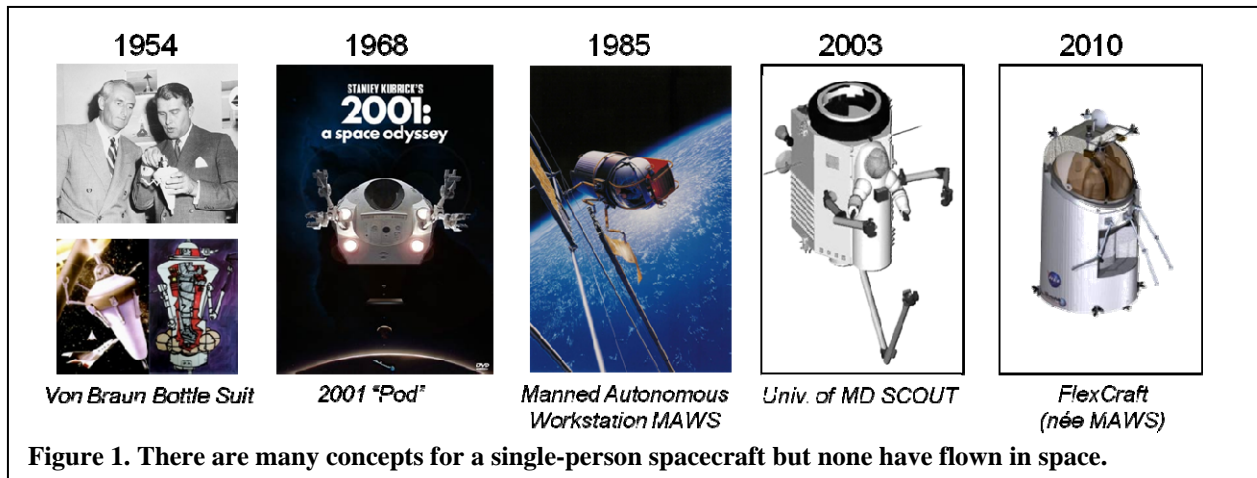


Figure 1. There are many concepts for a single-person spacecraft but none have flown in space.

II. Demonstration Mission

The demonstration mission was conceived to be low-cost and fly within three years. These constraints became an ally rather than the adversary, helping to shape a focused, effective, and achievable mission plan. Early analysis

REMOVED/SIMPLIFIED

1. Simplified Canopy Closure
2. Demonstrator Manipulators
3. No Displays and Controls
4. No ECLSS
5. Heaters, but no active thermal control
6. No experiment/sample bin
7. No internal outfitting
8. No Hatch
9. No docking mechanism

ADDED

1. Test instrumentation
2. Test Communications

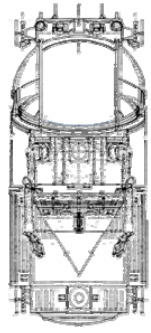


Figure 2. Nine systems removed

confirmed the human-rated Manned Maneuvering Unit (MMU) propulsion system as the safest and most effective solution. Equally important, the parts are still available. With respect to the non mission-specific hardware and software, the approach was “Design to Availability.” This meant if the item was not available for ground test and launch integration, then change the design until it was. This was not as radical as it sounds, because the FlexCraft demonstrator is very simple, less complex than most automobiles, and there are flight-rated alternatives for every system. To further simplify the mission and lower cost, nine systems, such as the life support, were eliminated from the demonstration configuration. To validate propulsion system, it is critical that the demonstrator thruster performance and geometry be

the same as the operational vehicle. The Minotaur 1 and Falcon 1e are two “low cost” launch vehicles providing a good fit for the demonstrator volume, mass, and center of gravity (Fig. 3). With a demonstrator mass less than 400 kg, a circular orbit of 350 km was selected. Including insertion error and mass margin, this altitude is high enough to provide adequate test time while low enough to assure a destructive reentry in less than 30 days.

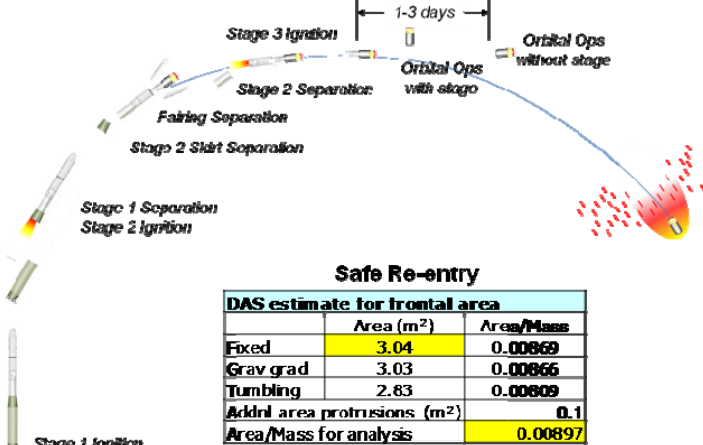
Within mass and cg limits

	Falcon 1e	Minotaur 1 w/ 61" fairing
CG Offset (500 kg)	1 m	1 m
Circular Orbit Alt (km)	Payload to orbit (kg)	
300	975	553
350	955	541
400	940	527

Orbit Lifetime

Orbit lifetime estimate using DAS (select cases validated with Satellite Tool Kit). Recommended target orbit conservatively accounts for orbit injection errors.

	Falcon 1e	Minotaur 1
Target Orbit	325km circular	350km circular
Final Orbit	320 x 310 km	331.5 x 257.4 km
Lifetime	30 days	20 days
Payload	965 kg	545 kg



Safe Re-entry

DAS estimate for frontal area		
	Area (m ²)	Area/Mass
Fixed	3.04	0.00869
Grav grad	3.03	0.00866
Tumbling	2.83	0.00809
Addl area protrusions (m ²)		0.1
Area/Mass for analysis		0.00897

Figure 3. Two launch vehicles available for short robotic demonstration mission

The FlexCraft demonstration mission is not intended to fly to ISS. In fact, for the demonstration flight it is not desirable to operate around ISS because this brings requirements that add to cost and schedule. Operational FlexCraft excursions will vary in time but should not last more than 6 hours. This means a short demonstration flight is acceptable for assessing propulsion and manipulator performance and desirable for reducing cost. Consequently, the mission is planned for 24 hours (approximately 16 orbits and two long shifts for ground controllers) but not to exceed 3 days.

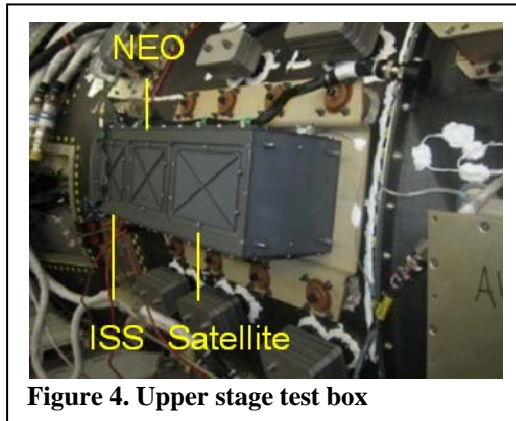


Figure 4. Upper stage test box

attitude-hold posing for photo-documentation *a la* Bruce McCandless in the MMU (Fig. 5). The box is equipped with manipulator tests that are representative of tasks performed on ISS, asteroid missions, and for satellites servicing. FlexCraft will approach the box and conduct propulsion/manipulator operations for as long as the stage remains stable. Once complete or when the upper stage exceeds FlexCraft control capabilities, it will separate having accomplished the principal test objectives. With remaining propellant and or battery life, bonus testing will assess control of off-nominal conditions.

The overall technical approach stresses a simple spacecraft design, the use of mature systems, and buying versus making hardware. The fewer the number of systems the simpler the spacecraft and using mature hardware buys down the risk. The FlexCraft demonstrator uses 90

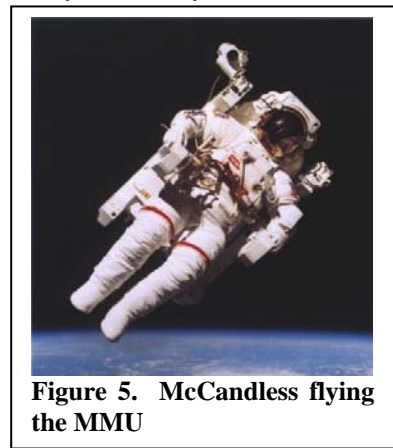


Figure 5. McCandless flying the MMU

percent off the shelf components including the propulsion system, avionics, batteries, and the power distribution units. The approach for the elements that are built is to use conventional space materials and processes. For example, the pressure vessel is made from the aluminum alloy 2219-T87, the ring frames and spares from 7075-T651, and the canopy from a Lexan 1500 polycarbonate. These materials are commonly used, have predictable properties, and are readily available.

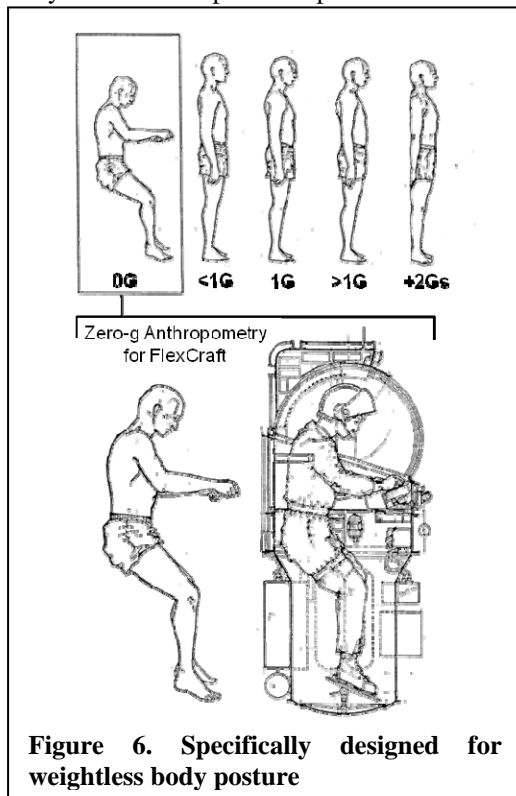


Figure 6. Specifically designed for weightless body posture

A. FlexCraft Configuration.

The overall vehicle configuration integrates an inner pressure vessel for shirtsleeve operations and an outer cylinder for micrometeoroid orbital debris (MMOD) and impact protection. Because astronauts do not sit down in zero gravity, the pressure vessel is shaped around the weightless neutral body posture (Fig. 6). A structurally efficient hemispheric canopy provides a wide field of view for situational awareness and excellent visibility for manipulator work. The canopy is attached to an upper cylinder that accommodates crew arm movements and internal equipment outfitting while a smaller diameter lower cylinder encloses the legs and serves as a tunnel for ingress/egress. The volume between the MMOD shielding and the pressure vessel is used for passive thermal control and packaging the subsystems. Because the demonstrator geometry is the same as the human-rated

version, a sizing study was conducted to assess the internal crew dimensions required for one-size-fits-all. For this, an adjustable mockup was used to fit the anthropometric extremes of the astronaut design population (Fig. 7). Test

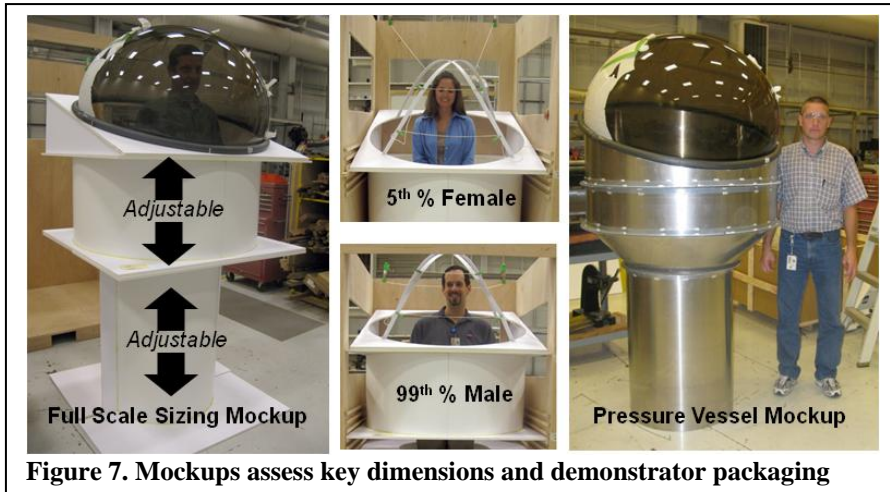


Figure 7. Mockups assess key dimensions and demonstrator packaging

subjects assumed the weightless neutral body posture for the 1g internal volume assessments. Furthermore, sizing evaluations took into account the volume and location associated with internal outfitting however, the robotic demonstrator does not include these systems. Once the key dimensional data was collected, a mockup of the pressure vessel was constructed. This will be used to verify the mounting

of external subsystems along with the routing of plumbing lines and wire harnesses.

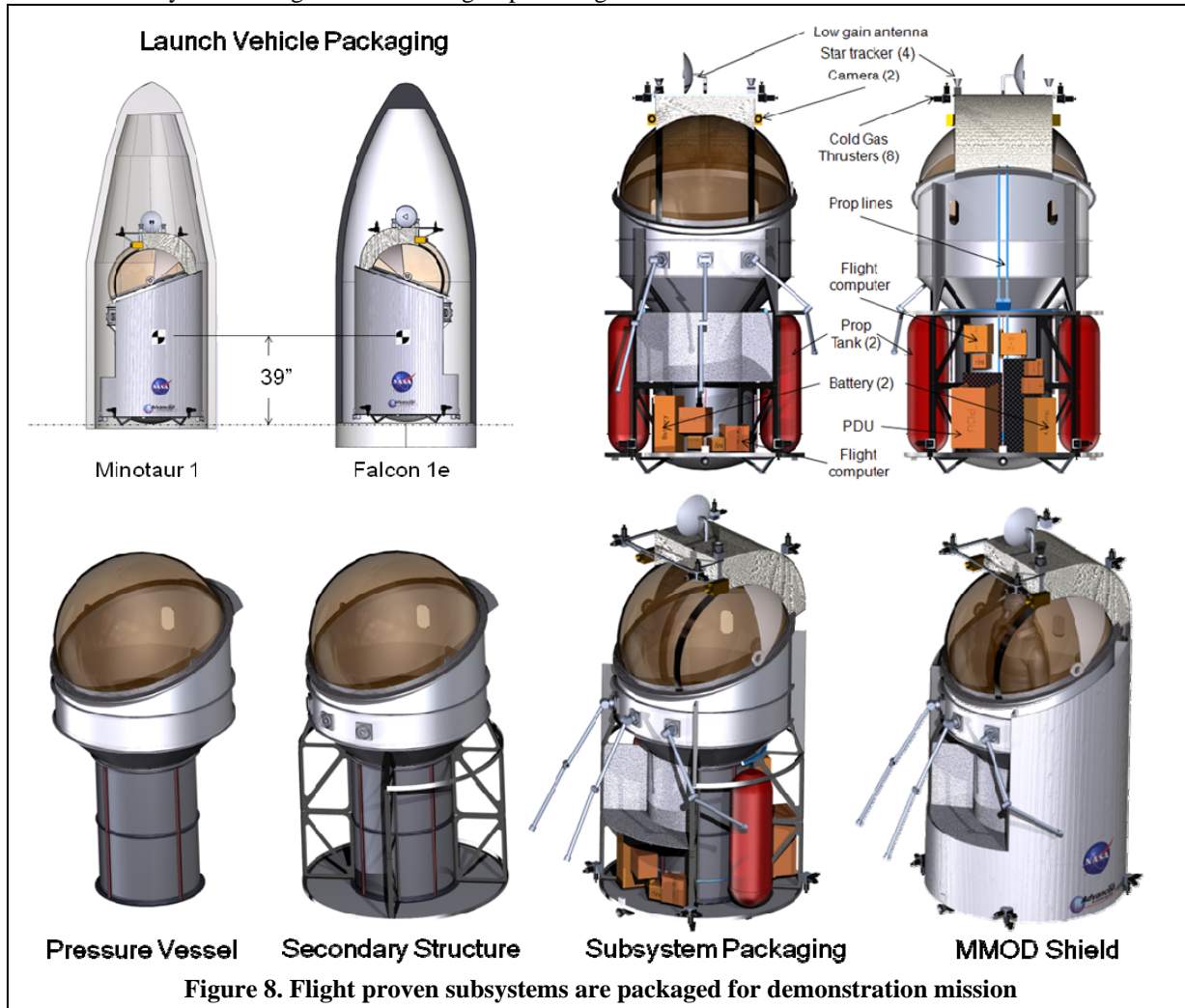


Figure 8. Flight proven subsystems are packaged for demonstration mission

Although the demonstrator is configured for propulsion and manipulator testing, it is conceived with the operational version in mind. Most systems are the same as the operational version and because of their heritage, they are human-rated. For example, using the MMU propulsion system inherits the flight experience of six

astronauts on three Shuttle missions. In addition, the FlexCraft pressure vessel was sized for the human-rated safety factor, because there is little additional mass and this allows a low cost transition to the operational spacecraft.

Table 1. Mass estimate includes AIAA standard growth allowance

FlexCraft - Mass Summary	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Mass (kg)
Mass Breakdown				
1.0 Structures	104.97	18.00%	18.89	123.86
2.0 Propulsion	50.64	3.09%	1.57	52.20
3.0 Power	42.42	10.28%	4.36	46.78
4.0 Avionics	45.47	16.85%	7.66	53.13
5.0 Thermal	21.00	11.33%	2.38	23.38
6.0 Separation Ring	8.70	2.00%	0.17	8.87
Dry Mass	273.20	13.20%	36.06	309.26
7.0 Non-Prop Fluids	1.22			1.22
8.0 Cargo/Payload	58.00	12.91%	7.49	65.49
Inert Mass	59.22			59.22
Total Less Propellant	332.42			368.48
9.0 Propellant	14.25			14.25
Total Gross Mass	346.67			382.73

Using industry-accepted AIAA factors for mass growth allowance (MGA), FlexCraft has a weight (with propellant) of less than 400 kg. Even with an additional 15 percent management reserve, this is within the payload mass and center of gravity requirements for both candidate launch vehicles. Table 1 shows the FlexCraft estimated total mass by subsystem.

B. Demonstrator Subsystems

1. Structures

The demonstrator structure is simple, designed for flexible outfitting, and constructed using conventional space materials and processes. The pressure vessel is

sized for 1 atmosphere (atm) and launch loads are carried through four spars attached to the pressure vessel. These spars define the equipment bays for subsystem packaging (Figure 9). Coupled with circumferential flanges, this arrangement offers efficient load paths for mounting subsystem components, plumbing, and wiring harnesses. All

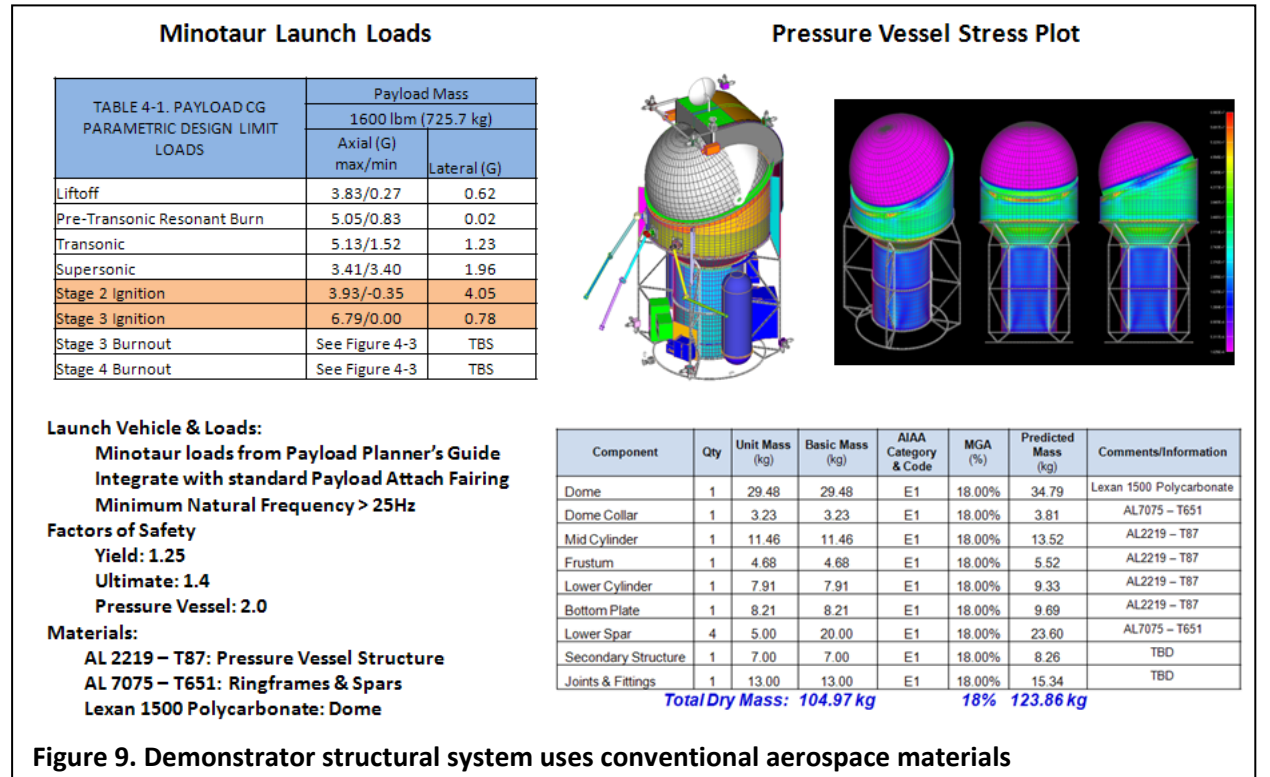


Figure 9. Demonstrator structural system uses conventional aerospace materials

hardware is packaged in a single layer so that no component has to be removed to access another. Likewise, plumbing and wiring harnesses are mounted on the pressure vessel cone, which provides increased surface area for easy access.

2. Propulsion (TRL 8)

FlexCraft is designed to take advantage of the millions of dollars invested in developing the MMU human-rated propulsion system. Astronauts flew this cold-gas system on three missions before it was removed from NASA's flight inventory. FlexCraft uses this system because the compressed nitrogen is non-contaminating; it is a simple and reliable solution; and with a cross-strapped, dual-string architecture, it offers fail-op redundancy with very little increase in mass. Like the MMU, the FlexCraft uses two off-the-shelf tanks that provide a balanced solution with

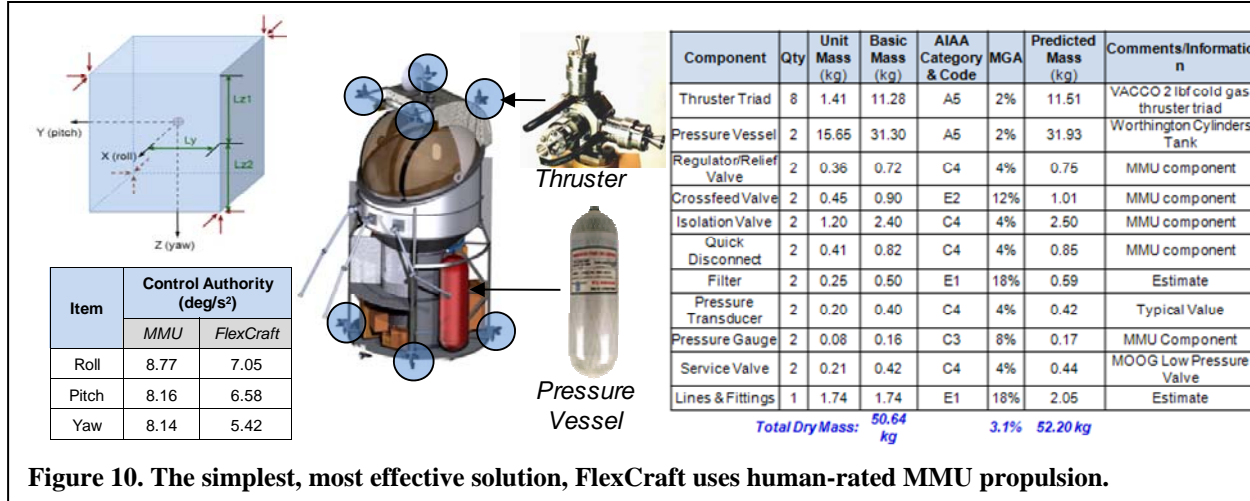


Figure 10. The simplest, most effective solution, FlexCraft uses human-rated MMU propulsion.

minimum plumbing complexity. The MMU was designed for a 6 hour EVA however larger FlexCraft tanks offer 20% more nitrogen. A pressure of 3,400 pounds per square inch (psi) was selected so that the ISS version could be recharged on-orbit. Eight 2-pound (lbf) MMU thruster triads achieve similar performance (Figure 10). The propulsion system's wet mass is 67.67 kg.

3. Thermal (TRL 9)

The FlexCraft thermal control system uses space-rated coatings, multilayer insulation, and electrical heater tape to maintain the structure and components within specified ranges for all mission phases (Figure 11). FlexCraft

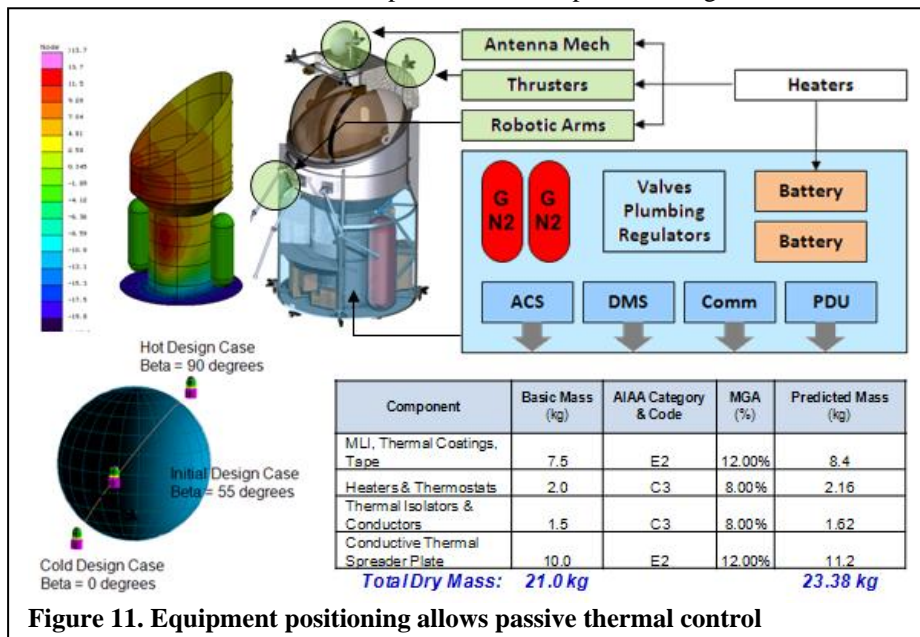
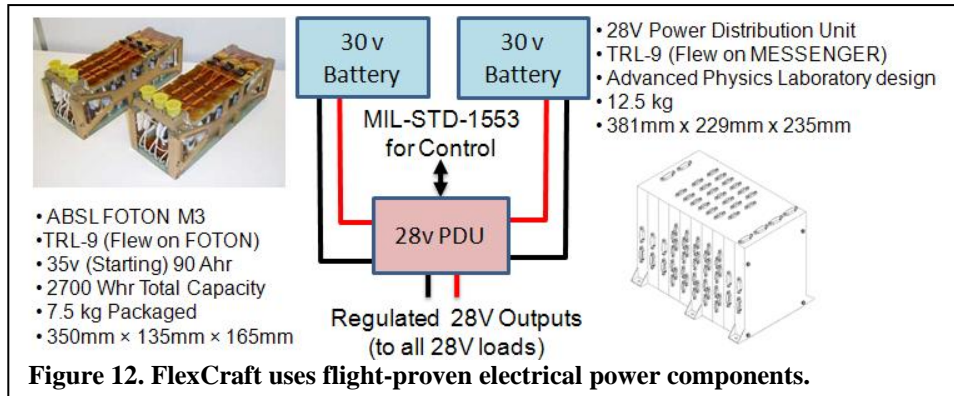


Figure 11. Equipment positioning allows passive thermal control

mechanisms, and thruster triads. Where needed, multi-layer insulation (MLI) would be used for thermal isolation and insulation.

4. Electrical (TRL 9)

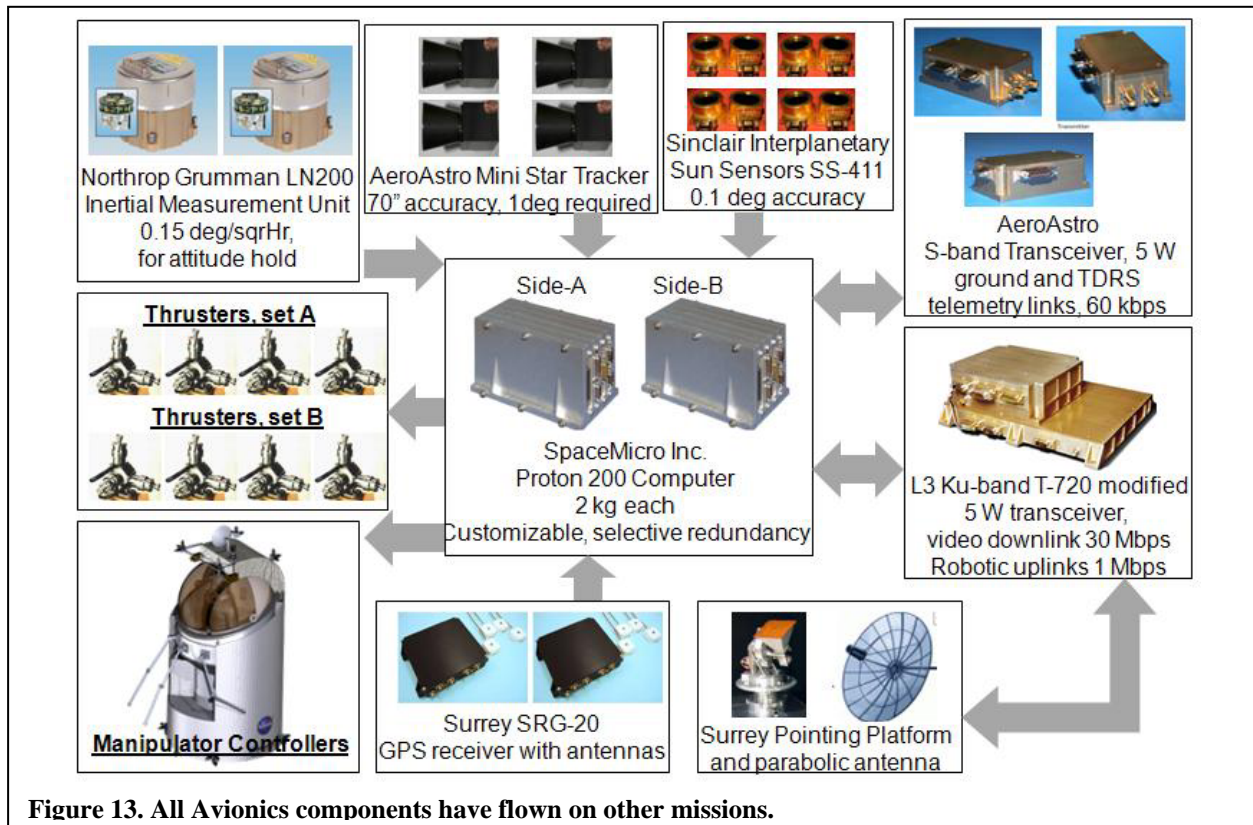
Batteries are the simplest and least costly electrical power system for the FlexCraft demonstration mission. Power is provided by two TRL-9 ABSL Foton M3 Lithium-Ion batteries provide 28-volt power, which is managed by an Advanced Physics Laboratory power distribution unit, which flew on the Mercury MESSENGER mission (Figure 12). The power required for conducting a mission with three propulsion and three manipulator tests is 4,920 Watt-hours (Whr), which is largely driven by communications from



the Tracking and Data Relay Satellite System (TDRSS). This is below the Foton battery's 5,400 Whr capacity but represents a demonstrator-unique load because the operational spacecraft will use line-of-sight communications that draws half the power. FlexCraft is well below the payload mass limit for the launch vehicle. Because Foton batteries weigh only 7.5 kg, a four-battery option will be considered to add margin and extending mission life.

5. Avionics (TRL 8)

Shown in Fig. 13 is the FlexCraft overall control and communications architecture managed by a Space Micro dual 200 Proton computer. This flight-proven computer provides fail-operational redundancy for critical systems



while directing the operation of attitude control, communications, manipulators, propulsion, video cameras, and flight test instrumentation. Whereas will use line-of-sight communications the demonstrator is controlled through TDRSS. However, most of the primary avionics hardware has already been identified and is available off the shelf.

6. Manipulators (TRL 8)

FlexCraft has three docking stations for interchangeable manipulators and end-effectors. These are positioned to provide maximum visibility for the operator. Although the manipulators may each be different, the demonstrator is equipped with three identical manipulators equipped with end-effectors specifically selected for ISS/satellite servicing and NEO exploration. There will be direct control of manipulators in the human-rated FlexCraft, but

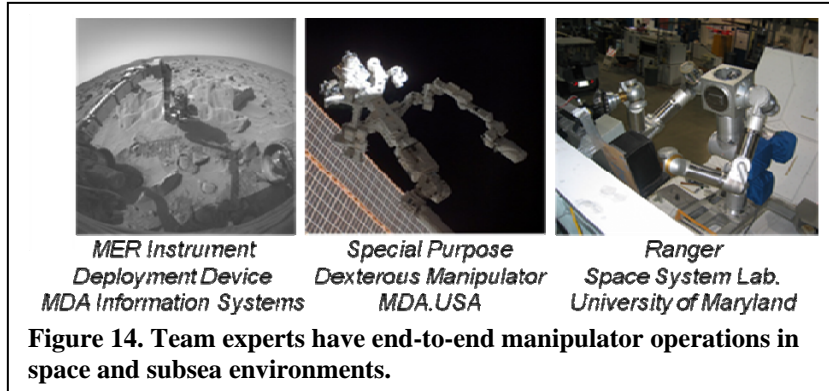


Figure 14. Team experts have end-to-end manipulator operations in space and subsea environments.

because of the Earth-space communications link, the demonstrator operates in a supervised-autonomous mode. As is the case for the operation spacecraft, direct control of manipulators is well understood. The demonstration will assess the interaction of manipulator operations with the propulsion system. Prior to launch, these dynamics will be modeled and simulated then after the mission, they will be compared with test

data. Hardware, software and test formulation will incorporate the experience of leading space manipulator experts. Selected through open, competitive procurement the experts are MDA Information Systems and the Space Systems Laboratory at the University of Maryland (Fig. 14).

III. Parts Availability and Cost

Conventional design, development, test, and evaluation will not support a launch in three years. For this reason FlexCraft uses available systems and parts. To determine availability, vendors were contacted for 90 percent of the

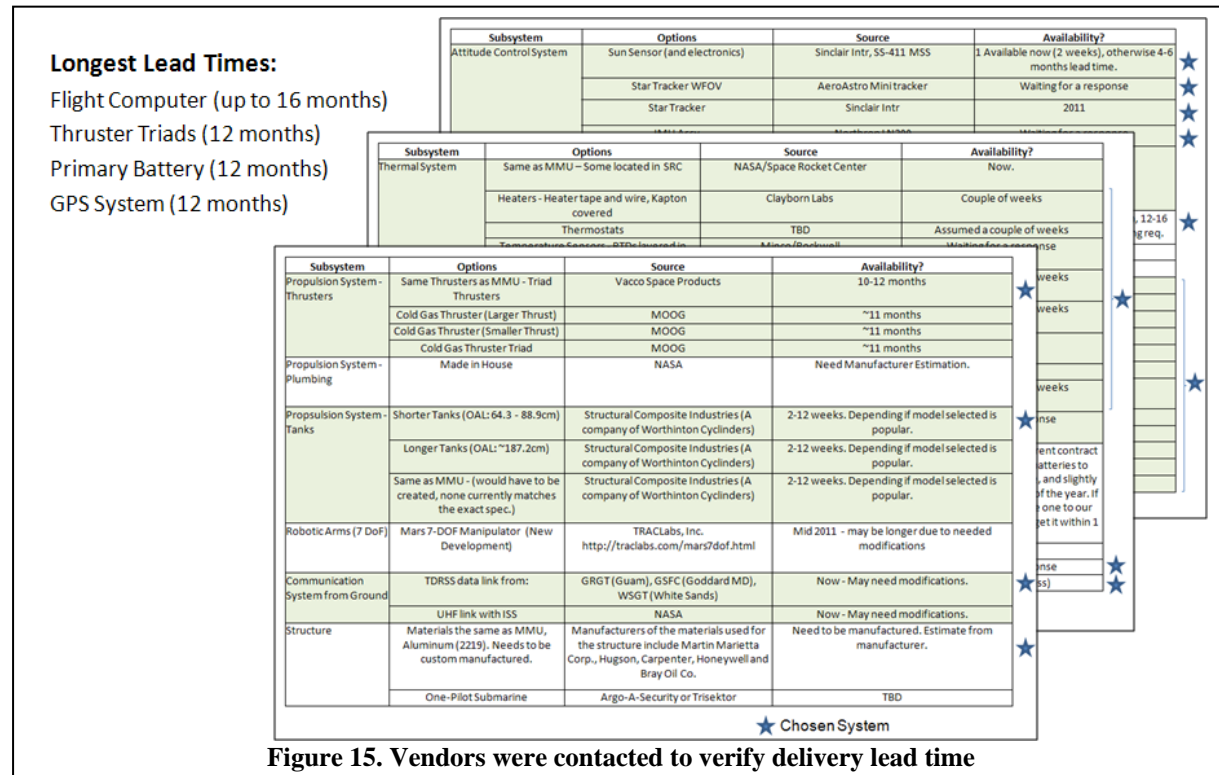


Figure 15. Vendors were contacted to verify delivery lead time

components (Figure 15). The longest-lead item is 16 months for delivery a Space Micro, Inc. Proton 200 computer. This works with the schedule, but there will be a continued effort to find alternative parts that may offer more schedule margin or lower cost.

For FlexCraft, low cost does not come at the risk of meeting mission objectives. Every effort is made to conduct a successful demonstration, however there are creative ways acquire hardware and manage the project that hold cost to a minimum. Table 2 summarizes some of the cost reduction measures.

Cost Reduction	Description
Buy versus Make Hardware/Software	Avoids cost and schedule risk of Design, Development, Evaluation and Test (DDT&E)
Bare-bones configuration	Nine systems omitted or simplified for demonstration flight
"Low-cost" launch vehicle	Lowest cost launch vehicles to accommodate mass, center of gravity and volume
Short mission	Minimal ground operations cost
Short development schedule	Forces decisions which results in reduced cost
Small team	Fewer labor hours
MSFC as prime	No profit built into labor rates
On-site testing and integration	Avoids additional cost for shipping flight hardware, travel for test personnel and schedule complexity
Using the existing engineering support contractors	Avoids additional procurement costs and allows the right skills for the right amount of time

IV. Conclusion

Space suits are a logical choice for planetary operations, however for safe, rapid access to the weightless environment, spacecraft offer compelling advantages. Using the same MMU cold gas propulsion system, a spacecraft can service areas on ISS that are inaccessible by suited astronauts. Possibly more important, in case of an emergency, FlexCraft can return from the most distant point in less than a minute. There is no lengthy pre-breathing or risk of bends (decompression sickness) because the spacecraft operates at the same cabin atmosphere as the host. This feature represents a fundamental change to EVA offering short, frequent, and repeated excursions without the 12.5 to 14 hour overhead and "rest day" required for space suit operations. FlexCraft is sized for the entire astronaut population whereas, there are 24 "pressure suits" and 13 life support systems nominally available to support flight. In addition, without the return capability of the Shuttle, astronauts must conduct suit servicing formerly performed by ground technicians. Shirt sleeve operations eliminate fatigue and suit trauma while providing unencumbered access to displays and controls along with hands-in eating and drinking. Interchangeable manipulators are tailored to the mission and provide advantages not possible with gloved tool operations. Furthermore, the spacecraft can be tele-operated for inspections or hazardous operations.

FlexCraft offers a new capability for weightless crew excursions. The good news is that no new technology is required and it has broad utility not only for ISS, but for human asteroid exploration and satellite servicing. Before making FlexCraft operational the propulsion system needs to be tested in the weightless environment. Using existing hardware along with rapid development provides the proper combination for low-cost, on-orbit verification.

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