EVA/Robotic Servicing in the Commercial Space Era

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Abstract

With the start of commercial crew flight to International Space Station (ISS) in 2017, US-supplied human access to low Earth orbit (LEO) will again be available upon need, ideally for significantly less than the cost of a shuttle flight. Besides performing crew rotation to the ISS, commercial crew vehicles may be capable of a wide variety of missions previously accomplished by the shuttle program. Chief among these is in-orbit spacecraft servicing, which was performed to great effect throughout the three decades of shuttle flight operations. This paper examines the requirements for EVA/robotic collaborative servicing in the commercial crew era, chosen from the three vehicles initially in the NASA Commercial Crew competition (Boeing *CST100*, SpaceX *Dragon*, and Sierra Nevada *Dream Chaser*).

All these vehicles offer the basic ability to transport crew and some cargo to the target servicing site in LEO, performing rendezvous and proximity operations as part of their basic design requirements. Initial versions of these vehicles lack some of the features that made the shuttle an ideal servicing platform, including large internal and external payload capability (in terms of both size and volume), a grappling manipulator, and EVA support via an airlock and logistics for multiple EVA sessions per flight. For each vehicle under consideration, accommodations were conceptualized and implemented in a solid modeling program to verify dimensions, kinematics, reach envelopes, and other necessary metrics for operational feasibility. Since none of these vehicles are currently equipped with an airlock, options for adding an airlock module were assessed for each system. Similarly, robotic system concepts were developed for each vehicle, based on the constraints of unpressurized cargo capacity for each design.

Although three vehicles were originally in contention, this paper focuses primarily on the SpaceX Dragon and the SNC Dream Chaser vehicles. The Boeing CST100 details available to date do not have sufficient detail in the spacecraft's service/propulsion module to allow assessment of potential volumes for servicing-related systems, and the operational scenarios for the two capsule designs are similar enough to justify focusing on the better-documented Dragon. The Dream Chaser, while not picked for further development under the NASA Commercial Crew program, is an interesting counterpoint to the capsule designs due to the complications of developing EVA and robotic systems concepts compatible with the strict mold line restrictions of a high-lift aerodynamic vehicle.

Both vehicles provide adequate, if challenging, volumes for unpressurized cargo. Dragon has the "trunk" adapter behind the entry vehicle, which was designed from the outset for unpressurized storage. While Dream Chaser did not have planned external accommodations, the launch vehicle interface structure (LVIS) provides sufficient volume and attach points for basing robotic systems internal to that structure. While the Dragon trunk provides a significantly larger and more accommodating launch volume for robotic systems, a grappling manipulator would be required to "walk out" of the internal volume of the trunk. The grappling manipulators for both vehicles require additional degrees of freedom to stow in the allotted volume, but unstow to produce a 5-6 m reach capability when deployed. The Dragon version has the additional advantage of direct visibility from the Dragon viewing windows, while Dream Chaser internal control will of necessity be based on video camera feeds.

The paper considers various approaches to providing airlocks for each vehicle. Dream Chaser can accommodate an internal airlock, although intrusions into the nominal aft pressurized volume due to external systems and tankage severely limited internal airlock dimensions. A design was also developed for a rigid external airlock, which also served as a mounting location for one or two 5-6 m serving arms. Although there may be options for an internal airlock in Dragon, it was felt to impose too many restrictions on the internal layout, so all airlock options for that vehicle to date were based on an inflatable airlock module.

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The paper develops notional scenarios for servicing from each vehicle, using Hubble Space Telescope as a well-documented canonical test case. Since robotic manipulators deployed from the commercial crew vehicles are of necessity shorter than the shuttle remote manipulator system, the shuttle paradigm of docking the client spacecraft in the payload bay and working around it is not feasible; instead, the servicing spacecraft must be capable of being positioned near the site of each task to allow easy crew and robotic access. This led to the development of "dual-arm" configurations, where one large manipulator provides a physical interface to the client spacecraft and repositions the servicing vehicle, while the second manipulates orbital replacement units and is available for EVA positioning and restraint via manipulator foot restraints. Secondary human-scale dexterous manipulators were also designed and evaluated for impact on the servicing scenario, both in pure telerobotic mode and as assistance to the EVA crew. Past and current results of such analysis show the dexterous manipulators to be a significant "force amplifier" for EVA operations.

With support from Sierra Nevada Corporation, a fiberglass mockup of the Dream Chaser crew cabin was obtained and installed in the University of Maryland Neutral Buoyancy Research Facility. This system was used to assess EVA operations from the Dream Chaser vehicle, using test subjects in an MX-B pressure suit simulator developed at the UMd Space Systems Laboratory. These tests, while cursory in nature, demonstrated the feasibility of EVA egress and ingress via the aft hatch of Dream Chaser. They also illustrated the challenge of EVA translation external to an aerodynamic surface, with limited opportunities for emplacement of hand rails and other EVA aids. Lacking adequate EVA interfaces, the need for robotic manipulators is enhanced by the additional requirement for use as EVA mobility and restraint aids.

Results documented in this paper illustrate that there are feasible solutions for challenges such as providing airlocks and robotic servicing systems for each type of commercial crew vehicle, compatible with both the spacecraft interfaces and the limitations of their launch vehicles. While the topic needs research at finer levels of detail, such as extensive neutral buoyancy simulations of operations from each vehicle, the results to date indicate that commercial crew spacecraft will be highly capable of supporting routine and extensive servicing operations in low Earth orbit; given similarities to beyond-Earth orbit systems such as Orion, the same technologies will be beneficial as far out in space as humans ultimately travel.

I. Introduction

Over a seven year period from 1966 through 1972, the United States flew 21 human missions aimed at developing the technology and procedures for landing human on the moon, and succeeded six times in performing lunar exploration. (This assumes that the Gemini and Apollo programs were solely dedicated to lunar exploration, although Gemini developed techniques in orbital rendezvous, docking, and extravehicular activity which are still used to this day.) The total crew time in space associated with these missions came to 9446 person-hours.

In less than two years between 1973-1975, the Skylab program encompassed three flights, with a total crew time of 12,350 person-hours. Focused on learning how to live and work for extended periods in space, this single program exceeded the total crew time of Gemini and Apollo by more than 30%.

Starting in 1981, the Space Shuttle program had 134 orbital missions, with a total crew time of slightly over 200,000 person-hours. While the statistics for the International Space Station are harder to separate out, at the time of writing the ISS has been permanently inhabited for 14 years 136 days, with an estimated crew time of approximately 600,000 person-hours of flight experience.

The point of this exercise is simple: in the history of U.S. human space flight, there were seven years and 21 missions dedicated to lunar surface exploration, with a total experience base of 9450 crew-hours. In comparison, in the 42 years since the launch of Skylab, the U.S. has performed 137 missions and accumulated more than three-quarters of a million crew-hours living and performing useful work in space, including servicing Hubble Space Telescope and a number of other satellites, as well as the construction and maintenance of ISS itself. Comparing experience bases between the two flight objectives reveals that more than 80 times as much experience has been obtained in on-orbit operations as compared to lunar exploration, even ignoring a large element of the Apollo architecture which was dependent on on-orbit operations as well.

It is somewhat inexplicable, then, that in the renewed focus on human exploration of the moon, Mars, near-Earth objects, or other destinations beyond low Earth orbit (LEO), there was a de facto assumption that all on-orbit operations (save ISS replenishment and maintenance) should come to an abrupt end. Following this line of thought, when ISS is deorbited in 2024 or whenever, all human space flight would be solely focused on planetary exploration, using architectures which were themselves designed to minimize on-orbit operations. This seems a poor payback for 750,000 hours of crew time accumulating a knowledge base in on-orbit servicing which we are now prepared to throw away.

For future human access to space, NASA exploration activities are based on the development and use of the Orion spacecraft (Figure 1), dedicated to launch on the Space Launch System also under development. Three corporations competed in the first phase of the Commercial Crew Transportation program: SpaceX with their Dragon 2 spacecraft, derived from the cargo vehicle in active use for commercial cargo transport to ISS (Figure 2); CST-100, an Apollo-style capsule developed by Boeing Corporation (Figure 3); and Dreamchaser, a lifting body spacecraft developed by Sierra Nevada Corporation (Figure 4). At the downselect, Dreamchaser was eliminated, and flight funding supplied for up to six crew rotation missions each for Dragon 2 and CST-100, starting in 2017. Plans currently call for two U.S. crew rotation missions per year, which would mean the basic CCT contract would sustain ISS operations through 2022. Current agreements to continue ISS operations through 2024 would only add two more missions for each vehicle; another eight missions total would be added if ISS were extended through 2028. There is no guarantee that both vehicles will be used equally throughout the tenure of the ISS program; based on the current contract providing a minimum of two flights, one vehicle could conceivably be retired after two flights and the other used for 14 crew rotations through 2024, or 22 missions through 2028. Continued operation of either or both commercial crew vehicles beyond the ISS is predicated on the development of a robust and profitable commercial human space market, which has been speculated about for some time but has yet to materialize.

Figure 1. Lockheed Orion spacecraft with initial ATV-derived service module

Figure 2. SpaceX Dragon 2

Figure 3. Boeing CST-100 spacecraft

Figure 4. SNC Dreamchaser spacecraft

This paper addresses servicing performed in whole or part by human astronauts, in a manner similar to that evidenced by the shuttle history. There have been a number of proposals for fully robotic servicing, which would make the entire point moot. However, a closer look would show that robotic servicing is currently far less capable than human servicing, and that there are a number of specific tasks which have been performed successfully by humans which are still beyond robotic capabilities.

This is not to say, though, that this paper focuses on purely human servicing activities. Over a number of years, the

UMd Space Systems Laboratory has performed experimental and analytical investigations of both pure robotic and collaborative human/robotic servicing, primarily using Hubble Space Telescope as the test case. The Ranger Dexterous Servicing System (Figure 5) was developed under NASA funding as a shuttle flight demonstration. The system incorporated a pair of dexterous manipulators designed to have the same capabilities as an astronaut in a space suit.[1] The system was tested alone, and in conjunction with the UMd MX-2 pressure suit as one of the investigations of EVA/robotic collaboration (Figure 6). These studies have shown, as per Figure 7 for the case of the SM-1 servicing mission, that the combination of dexterous manipulators and EVA crew could have performed the same mission in about half the EVA time, largely by using the robotics to assist the astronauts by preparing the work sites, pre-emplacing orbital replacement units and tools, and cleaning up and closing out work sites post-EVA. Sample missions with less dexterous activities and more straight ORU replacement tasks, such as SM-2 and SM-3A, produced EVA savings of as much as 80% over the actual timelines from the servicing missions.[3]

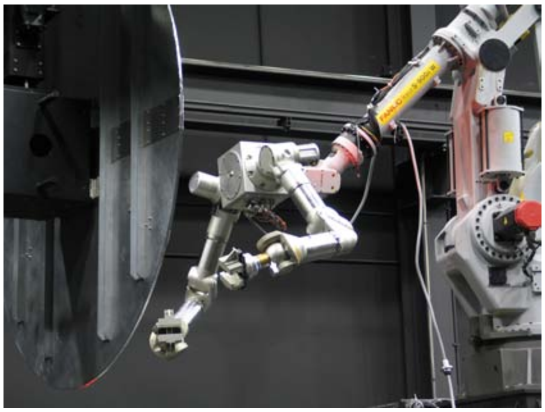

Figure 5. Ranger dexterous manipulators performing grappling and servicing activities at Naval Research Laboratories Rendezvous and Proximity Operations Laboratory

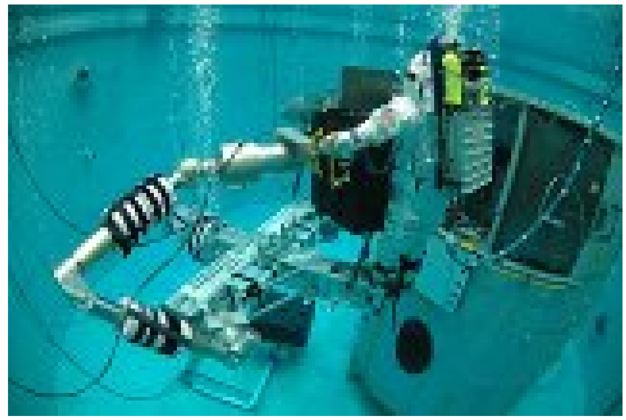

Figure 6. Ranger Dexterous Servicing System in collaboration with MX-2 subject in servicing Hubble Space Telescope mockup at the UMd Neutral Buoyancy Research Facility

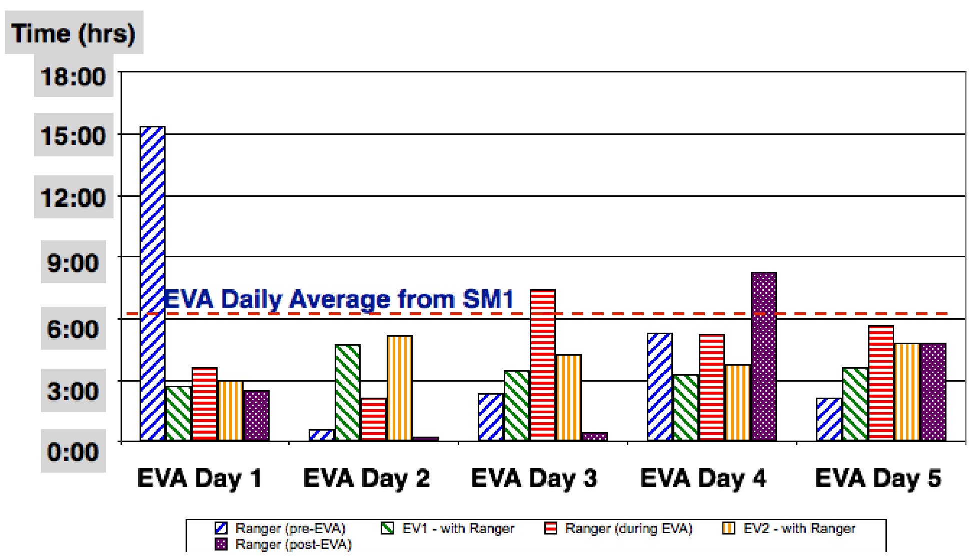

Figure 7. Task completion times for EVA/robotic teams performing HST SM-1 servicing mission[3] The red dotted line is the average time for the actual SM1 servicing mission. The UMd Ranger dexterous servicing system was used to establish the capabilities of the collaborative robotics system. For each day, the five columns are, left to right: robotic system alone prior to EVA, EV1 required time, robot collaborating with EVA crew, EV2 required time, robot performing "clean-up" after the end of the crew EVA.

II. Requirements for Servicing

The focus of this paper is to investigate the suitability of using commercial crew vehicles as on-orbit servicing platforms, filling a role left empty by the retirement of the space shuttle. It is appropriate, therefore, to examine the functionality of the space shuttle as a support vehicle for human servicing, and to develop a set of requirements for a human vehicle to be capable of supporting full or partial servicing tasks on-orbit.

As shown in Figure 8, the shuttle orbiter served to support the spacecraft being serviced (in this case, Hubble Space Telescope), creating a rigid physical connection to the "client". The orbiter controlled attitude for both vehicles while connected, selecting attitudes to provide appropriate thermal conditions for both the client and the EVA crew.

Figure 8. Hubble Space Telescope in orbiter payload bay for EVA servicing

Taking the examples of multiple servicing missions performed by the Space Shuttle, as well as other proposed servicing scenarios, it is possible to extract a list of capabilities which are either required or useful for in-orbit servicing. Such a list would include

- Orbital maneuvering, rendezvous, and proximity operations
- Capture of and rigid connection to client spacecraft
- Attitude control of the servicer and client
- EVA access
- External and internal cargo accommodations
- External EVA accommodations
- Robotic systems stowage, reach, and access
- Orbital replacement unit stowage and logistics
- Adequate orbital duration and consumables
- Reboost or other orbit modification

An examination of this list will reveal that the shuttle orbiter was an almost ideal vehicle for on-orbit servicing, supplying all of these functions throughout the three decades of that program. On the other hand, the four human vehicles cited earlier as flying in the "commercial space" era are fully capable of only the first item: orbital maneuvering through proximity operations. Dragon does have external cargo accommodations via its "trunk", although there has been no announcement of trunk cargo capacity for the crewed version. All of the other functions require undesirable operational work-arounds (e.g., cabin depressurization for EVA), additional servicing systems, or other changes to the current vehicle baselines. Examining the most favorable options to fill out the functions on this list is the focus of this paper.

III. Assessment of Commercial Crew Servicing Potential

Given (at least at the initiation of this study) that future U.S. human spaceflight would take place on some number of the vehicles depicted in Figures 1 through 4, the goal was to assess the capabilities, limitations, and possible mitigations to enable routine human servicing from each of these vehicles. It should be noted that a number of organizations are pursuing robotic servicing systems, and these have a valued place in the infrastructure for future on-orbit operations. However, robotic systems typically are designed for the "low-hanging fruit" such as refueling or orbit modification; these operations can be performed on a number of potential clients for each launch, and require minimum specific tools or interfaces to be transported. The vision for future human servicing will be that of complex (i.e., dexterous) servicing of unique high-value systems, such as national defense or large science platforms.

The first phase of this study, begun during the active phase of the Constellation Program, was a point-design to examine the capability to perform the Servicing Mission 4 (SM-4) activities of STS-125 based from the then-current version of the Orion spacecraft. As shown in Figure 9, the Orion would dock with a specialized servicing kit launched into orbit on a smaller evolved expendable launch vehicle (EELV). This pallet would incorporate all of the orbital replacement units and their launch protective enclosures from the STS-125 mission, repackaged along with an external airlock and a Ranger-class dexterous servicing robot. The 10-meter positioning leg would serve to grapple HST upon arrival, and berth it into the flight support structure grapple ring at the top of the pallet. Two 1.5-meter dexterous manipulators would be attached to the positioning leg, along with a repositionable foot restraint for one of the two EVA crew. The dexterous manipulators would be used to support and assist the EVA crew in foot restraints, as well as independently unstop ORUs and open access panels before the EVA egress, and likewise close out servicing locations and stow hardware after the end of the EVA for the crew. Such a system would require no modifications to Orion other than a docking interface for connecting to the servicing pallet, and mounting donning and recharge stations for the EVA suits internal to the cabin. This last requirement, typically co-located with airlocks in prior systems, would significantly constrain internal volume and probably limit the size of the Orion crew for servicing missions.

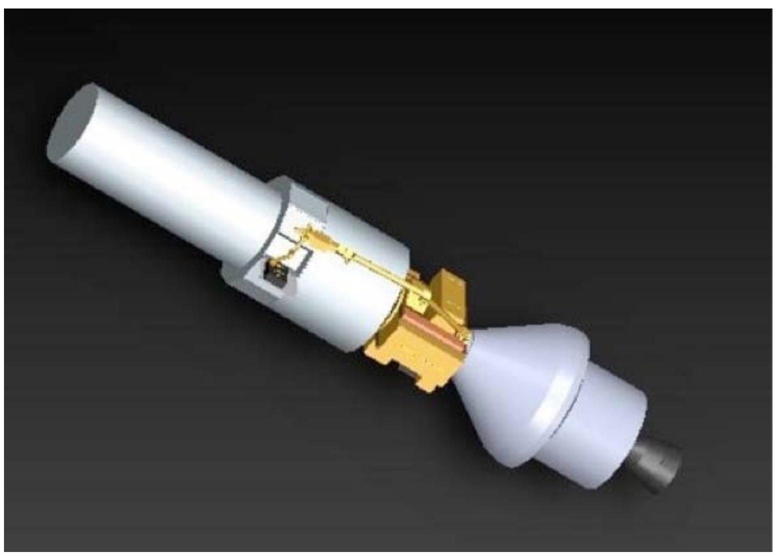

Figure 9. Concept for SM-4 servicing performed from Orion spacecraft with dexterous robotic assistance

While this mission concept was found to be highly productive for dexterous servicing tasks, the requirement for a separate launch of the servicing pallet made this a highly expensive servicing scenario. It should be noted that, at the time of this earlier study, Orion was still planned to launch on an Ares I launch vehicle, with extremely tight payload margins which precluded co-manifesting the servicing hardware. It is likely, given current plans to launch Orion on a Space Launch System heavy-lift vehicle, that the servicing pallet could be launched on the same vehicle as Orion and extracted from the upper stage via a transposition and docking maneuver analogous to that performed by the Apollo command/servicing module to retrieve the lunar module from the S-IVB stage of the Saturn V.

The goal of this paper is to address the potential use of commercial crew vehicles for shuttle-type on-orbit servicing missions, either strictly through the use of extravehicular activity (EVA) or through the incorporation of modern dexterous robotics to facilitate an EVA/robot collaboration in the on-orbit workspace. As discussed in the introduction, there were three vehicles under consideration in the first phase of the commercial crew program: the Boeing CST-100, SpaceX Dragon, and Sierra Nevada Dream Chaser. At the downselect, Dream Chaser (a lifting body with horizontal landing) was dropped in favor of the two capsule designs, Dragon and CST-100. Rather than consider two similar vehicles with similar flight profiles, it was decided to choose a capsule and the only lifting body under consideration, Dream Chaser. Since much more information on Dragon was publicly available, it was the logical choice for the capsule design in the study.

The two spacecraft under consideration are shown in Figure 10. This shows an equivalent and identically scaled version of each vehicle from the side in launch vehicle integration configuration. Dream Chaser is considerably larger than Dragon, which affects both habitable volume and the opportunities to carry pressurized cargo.

Most cargo for servicing missions, however, is unpressurized cargo; this is one of the primary areas in which we will miss the space shuttle orbiter and its (comparatively) huge payload bay. Figure 11 shows the available space for external cargo, which will be tasked to provide launch interfaces for both robotic servicing systems and orbital replacement units. The most available external volume on Dream Chaser is the aft boat tail area in and around the launch vehicle adapter. The majority of this conical adapter is jettisoned at launch vehicle separation, but the interior volume represents the best external storage volume. The Dream Chaser boat tail area external to the launch vehicle adapter is either directly in front of the orbital maneuvering engine on each side, or is in danger of being significantly impacted by thrust plumes every time an orbit maneuver is accomplished.

Dragon, on the other hand, has its "trunk" which serves to carry external payloads on the cargo version, and the crewed version uses the same structure with the addition of aerodynamic fins (used only for launch abort stability) to mount solar arrays for extended vehicle power on-orbit. The large internal volume of the trunk already is designed for mounting external payloads, and will serve well for practically anything which is needed for on-orbit servicing.

Full disclosure: this study was partially facilitated by a small grant from Sierra Nevada to the author's laboratory to study both human and robotic servicing based from Dream Chaser, including some limited neutral buoyancy simulations. While we are very appreciative of the support of SNC for this research, it should be emphasized that the contents of this paper reflect the opinions of the author alone and not those of Sierra Nevada.

With that clearly understood, the logical next step is to look at some of the critical items in the servicing taxonomy presented above, and review options for accomplishing each from both Dream Chaser and the crewed version of Dragon. This will primarily depend on solid modeling for visualization purposes, along with robotic reach analysis and application of experience in both EVA and robotic servicing in the University of Maryland Space Systems Laboratory (SSL).

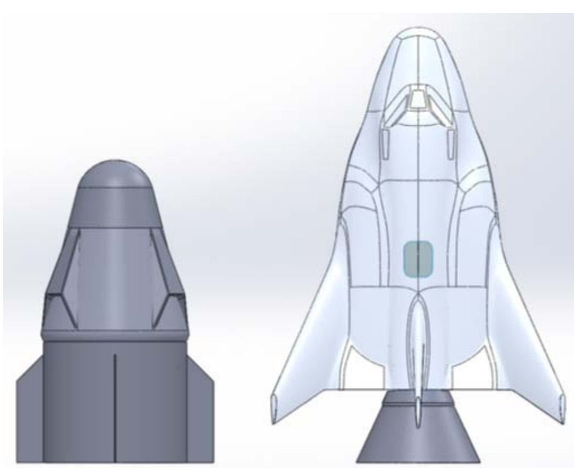

Figure 10. SpaceX Dragon 2 and SNC Dreamchaser comparative top views

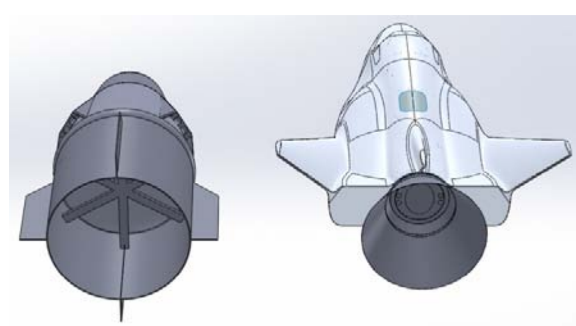

Figure 11. SpaceX Dragon 2 and SNC Dreamchaser showing aft accommodations and launch vehicle interfaces

A. Airlock Integration

One of the major limitations of the current commercial crew vehicles is the inability to perform an EVA without full cabin depressurization. While this approach worked throughout Gemini and Apollo, the requirement for vehicle operations while the cabin is exposed to vacuum drives the design of everything from avionics to food storage. The comparatively large volumes of spacecraft cabins requires either sizable mass investment in scavenging pumps and pressure bottles for holding the cabin air mix, or substantial consumables for atmosphere makeup during repressurization. To simplify operations and increase overall safety, it would be advantageous to incorporate an airlock in the spacecraft, at least for missions with preplanned EVA operations.

The greater size of the Dream Chaser pressure hull, which conforms to the outer mold line of the aerodynamic surfaces, is long enough that an interior bulkhead can conceivably be added to separate the last two meters of the pressure hull adjacent to the docking adapter to create an internal airlock. An initial objective of the SNC study was to look at internal volume of this section of the cabin, and assess it for room to support two crew in pressure suits with integrated portable life support systems (PLSSs). As shown in Figure 12, it is possible to get two suited crew into the aft volume if it were to be set aside as an internal airlock, although the diameter and volume is far below those specified in NASA standards. It is also unlikely that the crew could don or doff their suits in this volume regardless of the suit entry type, and those functions would be best done in the main cabin where there is additional room.

There is no ability to add an internal airlock in a Dragon spacecraft, so without external capabilities it would be necessary to depressurize the cabin for each EVA. However, the crewed version of Dragon has a reusable nose cap, which folds out of the way to allow docking to International Space Station. Since a servicing mission would not require ISS docking capabilities, it may be possible to put an inflatable airlock under the nose cap for a servicing mission, as seen in Figure 13. Such a system would be constrained by mechanisms and other fittings under the nose cap where details have not yet been released. Since it is probable that the airlock would not retract into a package as compact as it can be packed in on the ground for launch, the airlock will likely be jettisoned after the end of servicing activities and prior to entry maneuvering.

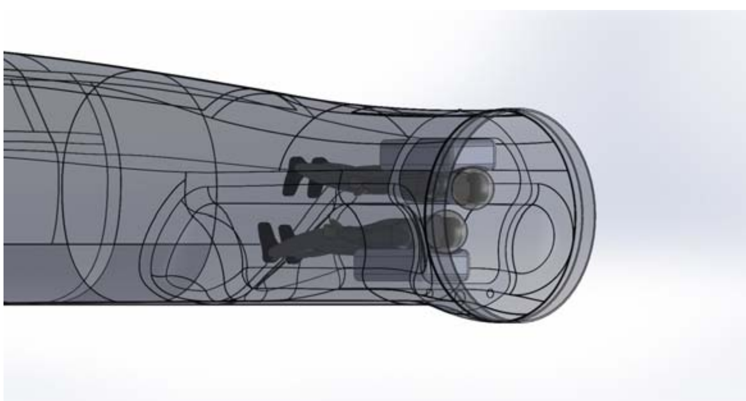

Figure 12. Concept for SNC Dreamchaser internal airlock configuration

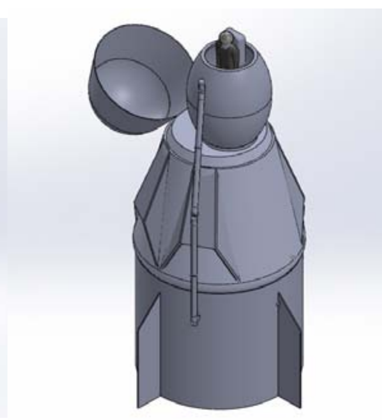

Figure 13. Inflatable airlock concept for SpaceX Dragon spacecraft

B. Robotics Systems

Shuttle servicing operations were enabled by the capability conveyed by the remote manipulator system (RMS) to grapple a payload in proximity operations and berth it to fittings in the payload bay. This allowed non-EVA capture and manipulation of large spacecraft, as well as supporting EVA crew with worksite stabilization, translation of crew and orbital replacement units (ORUs), and providing remote views for situational awareness.

To pursue designs for robotic augmentation of the vehicles, a series of candidate manipulator designs had to be performed and assessed. The design that best fit into the interior of the launch vehicle adapter for Dream Chaser is shown in stowed configuration in Figure 14, and fully deployed to full length in Figure 15. This is a seven degree-of-freedom DOF) robot arm in a roll-pitch-roll-pitch-roll-pitch-roll configuration. The only kinematic offset in the arm is at the elbow pitch joint, where it allows full folding of the arm. Both the upper and lower main arm links have secondary bend joints to allow a more compact stowage arrangement, yet open to maximum length to get the largest dexterous workspace possible on the vehicle.

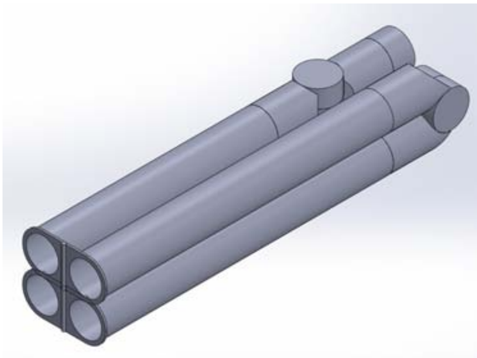

Figure 14. Folding 7DOF manipulator concept for SNC Dream Chaser (stowed)

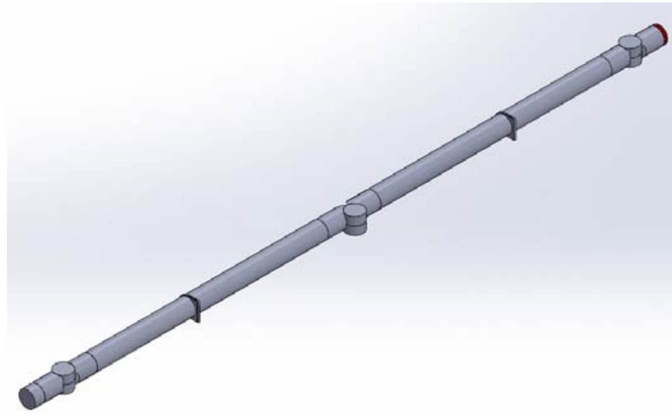

Figure 15. Folding 7DOF manipulator concept for SNC Dream Chaser (full extension)

Based on the preliminary design analysis, each Dream Chaser manipulator would be 4.9 meters long when unstopped with a 15 cm diameter. It would be capable of exerting 100 N and 30 N-m tip force in all poses, and produce a peak tip velocity of 5 cm/sec. Each arm would have a mass of 87 kg, and require 2700W of peak power. One of the critical issues for large positioning arms of this sort is the stiffness, as a low stiffness arm connecting a spacecraft to a servicing client would have the potential to induce instabilities in the attitude control system. This arm would have a first bending frequency of 39 Hz unladen, which would drop to 3.7 Hz if manipulating a 3000 kg payload.

The stowage configuration adopted is shown in Figure 16. Although it may look weird, this configuration has launch restraints on the shoulder, elbow, and wrist joints of each of two identical manipulators, with the mid-link articulation cantilevered in both directions from adjacent launch restraints. The configuration with the aft joints more centrally located than the launch restraints, which have to be around the periphery of the aft hatch, keeps the manipulator segment away from the bulk of the conical launch vehicle interface structure (LVIS) when launch vehicle separation occurs, to miminize the possibility of separation recontact. While nominally the manipulators would be latched at full length and deployed outwards before EVAs begin, Figure 17 shows that there is adequate passageway for a suited crew member to egress the airlock even if the arms stay in launch stowage configuration.

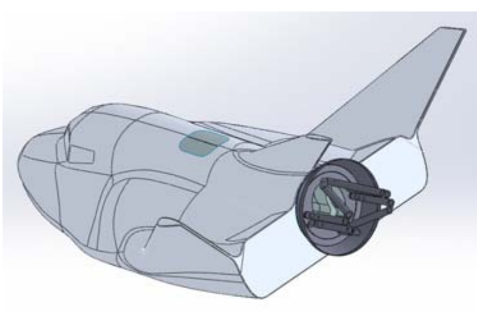

Figure 16. Dual manipulator launch stowage concept for SNC Dream Chaser

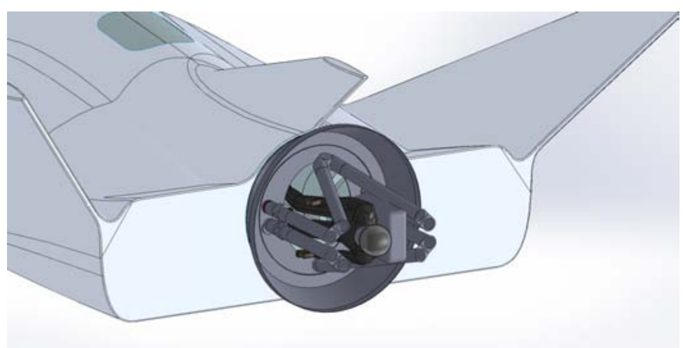

Figure 17. Dream Chaser contingency airlock egress with dual manipulators in launch configuration

Managing manipulator stowage and ORU launch restraints on Dragon is considerably easier, largely due to the presence of the "trunk" external stowage below the Dragon heat shield. Figure 18 shows two manipulator arms stowed on the planar payload restraint structure at the upper end of the trunk internal volume. There are still plenty of access locations for ORU launch restraints or environmental enclosures, and the manipulators have alternative mounting configurations if more of the restraint structure is taken up with ORUs or other payloads, but this was judged to be the nominal manipulator mounting strategy.

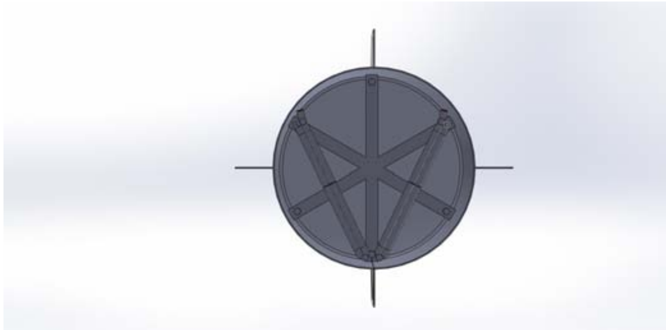

Figure 18. Stowage for dual dexterous manipulators on Dragon

The Dragon manipulators are similar in most respects to the Dream Chaser arms, but the larger diameter and volume of the Dragon trunk allows the use of 6.1 m length manipulators, which do not have to have the launch stowage joints in the middle of the nominal arm links as in Dream Chaser. Although like the Dream Chaser arms this manipulator was designed with minimum kinematic offsets and therefore maximum dexterous work envelope, it is similar to the space station remote manipulator system in that it is capable of "walking off" – maneuvering hand-over-hand to grapple a dedicated power/data grapple fixture on the exterior surface of the trunk as close to the Dragon capsule as possible, in order to provide maximum reach around and over the Dragon capsule itself.

C. EVA Access

Both systems have a ground access hatch and a NASA-standard docking system (NDS). Access through the NDS is designed to accommodate a pressurized suit; however, the latest configuration of the NDS has fixed (i.e., non-removable) alignment petals which significantly restrict the transit volume. While the docking interfaces are located so as to be the preferred egress/ingress routes for EVA, the development of manipulator concepts allowed the investigation of alternate egress via cabin depressurization and egress via the ground access hatches of each spacecraft. One of the real problems with this for both vehicles is that the ground hatches are in the middle of aft body heat shields; this means that translation aids such as handrails may not be comparable with aerothermodynamic heating, and alternate translation paths for the EVA crew would become necessary. Figure 19 shows the ability of one of the nominal Dream Chaser manipulators to reach past the dorsal tail fin to the vicinity of the hatch to allow crew to use the manipulator itself to translate to the EVA operations area aft of the vehicle without touching the thermal protection system along the way. As this image shows, the reach is marginal to get into the close vicinity of the hatch to allow the crew to egress safely. Figure 13, above, shows the same point with a Dragon manipulator mounted to the upper exterior surface of the trunk and stretching upwards to the inflatable airlock hatch on the nose of the Dream Chaser cabin.

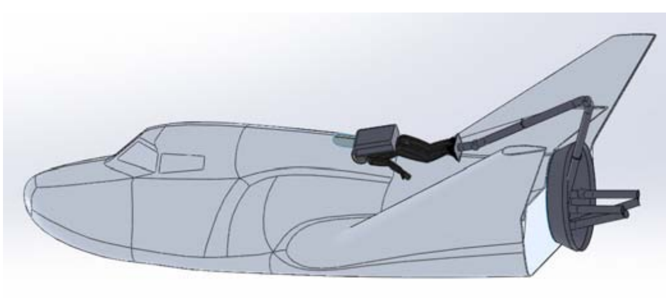

Figure 19. Dream Chaser manipulator providing translation path for EVA egress from ground access hatch

D. Integrated EVA/Robotic Systems

While the previous analysis showed that some form of internal or pre-mounted inflatable airlock was possible with both Dream Chaser and Dragon, none of these approaches were truly satisfying from the standpoint of really optimal EVA access. Similarly, successful robotic mounting concepts were developed for the extremely limited external volume of Dream Chaser, but the arms required extra degrees of freedom for stowage and still were highly constrained in mounted position due to orbital maneuvering system thrusters and other prior claims on the aft boat tail region of Dream Chaser. In such a situation, it is always interesting to examine possible systems which provide a singular solution to multiple problems.

Since the internal airlock of Dream Chaser is theoretically possible but very tight, one concept was to use the space internal to the LVIS to mount a rigid airlock module. This offers a number of advantages: being rigid, it can withstand some incidental impact loads when the LVIS is jettisoned. It is also capable of supporting the base reaction loads of the manipulators, and a base mounting location on an exterior airlock would be advantageous when manipulating large client spacecraft for servicing while trying to stay clear of the tails and other aft aerodynamic surfaces.

A solid model of this aft external airlock for Dream Chaser is shown in Figure 20. As this image shows, the airlock has mounting locations on either side for a 4.6 meter baseline manipulator system. The airlock is large enough to allow both crew to don their suits in the airlock, and the side hatch provides simple external access. One very large advantage of a rigid airlock is that an NDS docking system can be mounted on the aft face, providing a simple and reliable connection between Dream Chaser and the target spacecraft for rigid mounting during EVA external servicing operations. One advantage of this location is that the robotic systems are mounted to the LVIS structure, and will be automatically jettisoned with that structure in the case of an abort off the pad or during an early launch phase.

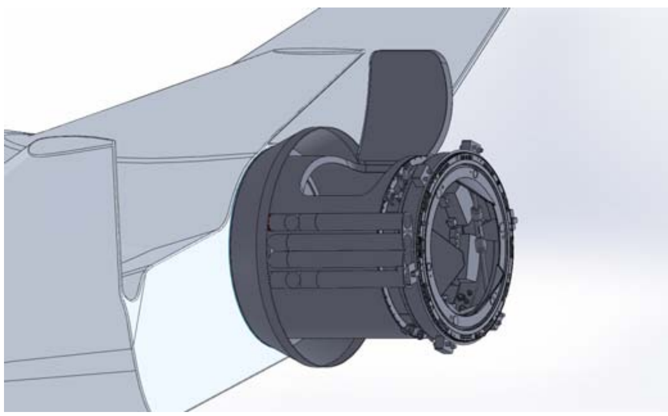

Figure 20. Rigid airlock with pre-mounted manipulators attached to aft bulkhead on LVIS structure

A very similar system could be adopted for the Dragon spacecraft; it could be launched in the Dragon trunk and manipulated onto the nose of the spacecraft for berthing via the dexterous manipulators also carried in the trunk. Alternatively,the rigid airlock module with pre-mounted manipulators could be launched on a payload attach fitting on the Falcon 9 upper stage below the launch restraints for the trunk; the second stage would provide attitude control for a few minutes while the dragon capsule separates, retracts its nose cap to expose the NDS docking fixture, and then flies back into the second stage to dock to the airlock and remove it from the upper stage. Again, the presence of an NDS attached to the Dragon spacecraft at the nose with manipulators brings both the crew and the robotic assistance to the immediate vicinity of the worksite. As was the case with Dream Chaser, the presence of an NDS on the grapple fixture allows the Dragon vehicle to rigidly dock to the target vehicle, and thereby use the second large positioning arm for further supporting the EVA crew.

E. Reference Mission Servicing for Hubble Space Telescope

To evaluate the effectiveness of the servicing systems designed to be added to Dream Chaser and Dragon, servicing activities were envisioned for the Hubble Space Telescope. Although no longer actively expecting further servicing missions, it is the most heavily servicing spacecraft in history other than the International Space Station itself, and much “ground truth” exists for serving tasks already performed on the telescope. In addition, the Space Systems

Laboratory performed the first robotic servicing demonstration on the neutral buoyancy training mockup of HST in the mid-1980's, and for 30 years HST has been a standard performance test case for SSL manipulator systems.

Figures 21 and 22 show two different views of an EVA crew working on the instrument ring of Hubble Space Telescope. One manipulator is mounted to a grapple fixture on the aft end of the telescope, and the other provides positioning for the EVA crew via manipulator foot restraints. The manipulators are sized to be able to keep the telescope as far aft and away from the dorsal fins as possible to protect the thermal protection system and aerodynamic surfaces, while also providing easy access to potential ORU storage in the aft tail of Dream Chaser.

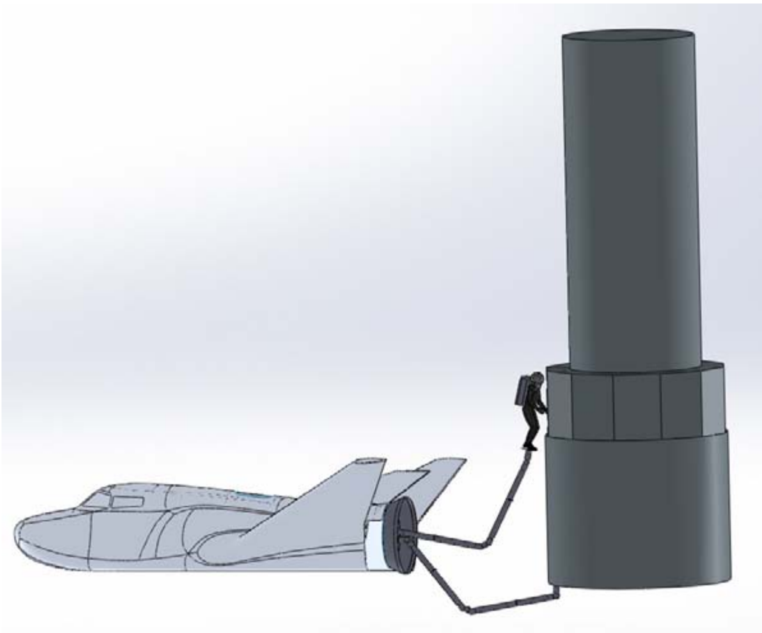

Figure 21. Dual manipulator HST servicing concept for SNC Dream Chaser

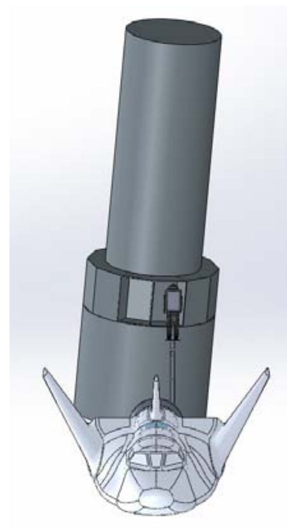

Figure 22. Dual manipulator HST servicing concept for SNC Dream Chaser

Figure 23 shows a similar arrangement for Hubble Space Telescope servicing using the crewed version of Dragon, augmented with an inflatable airlock under the nose cap. Again, one manipulator captures and manipulates Hubble Space Telescope and the second is available for manipulating an EVA crew via manipulator foot restraints. Unlike Dream Chaser, it is likely that crew in the Dragon can continue to visually track HST and the servicing activities from the vantage point of the Dragon capsule, rather than performing the tasks off of the vehicle tail without active monitoring. On the other hand, having to reach around the Dragon spacecraft and the inflatable airlock to reach the servicing target means that there is very little ability to control the distance of the telescope from the airlock hatch of the Dragon. Transitioning from the inflatable airlock launched in place to a rigid airlock, even if there more challenging flight control task required, would allow for more effective and intuitive servicing due to the placement of the manipulators at the front of the Dragon vehicle, and would expand potential options if multiple potential clients each have different thermal illumination constraints.

IV. Neutral Buoyancy Testing

Although time and funding both precluded more extensive experimental efforts, the SSL did manage to take a full-scale Dream Chaser cabin mockup provided by Sierra Nevada and install it in the UMd Neutral Buoyancy Research Facility, and use it to support an EVA demonstration using the MX-B pressure suit simulation garment developed at the SSL for EVA field research. Figure 24 shows the test subject in the MX-B suit simulator posing outside the flight deck windows of the full-scale Dream Chaser pressure hull mockup. This provides a sense of scale for both Dream Chaser and the pressure suit itself. Figure 25 shows the test subject wearing an appropriately sized mockup of a PLSS egressing the cabin via the aft (virtual) hatch to start a simulated EVA procedure.

Although limited resources precluded multiple runs or multiple test subjects, the results to date were highly promising. The SSL succeeded in getting the fiberglass honeycomb mockup (with about 2000 pounds of positive buoyancy)

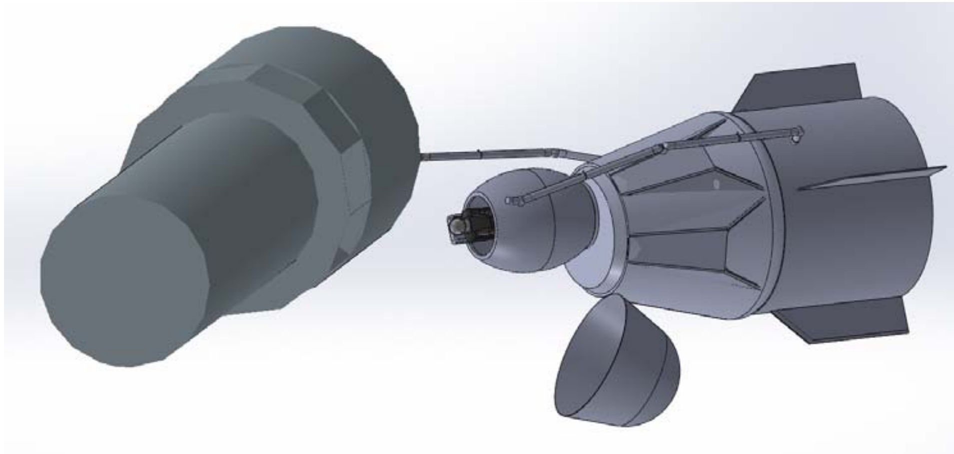

Figure 23. Notional image of Dragon with nose-mounted inflatable airlock servicing Hubble Space Telescope

Figure 24. Test subject in MX-B space suit simulator posing outside flight deck in Neutral Buoyancy Research Facility

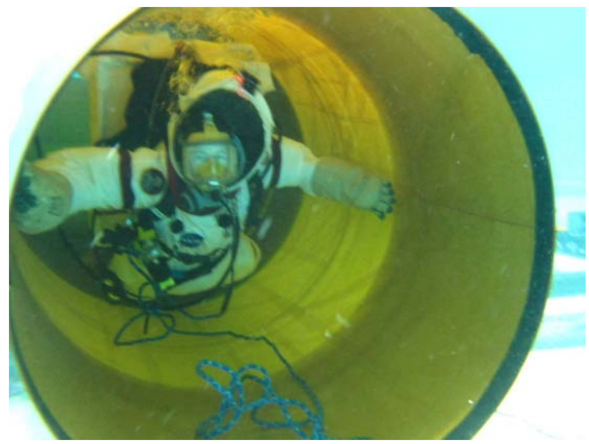

Figure 25. Test subject in MX-B egressing Dream Chaser in neutral buoyancy from aft hatch

into the tank and on the bottom seriously. EVA ingress and egress was repeatedly performed successfully and easily, even with the simulated PLSS. Future plans call for repeating these tests with an umbilical to reduce load and volume constraints on the EVA test subjects.

Lack of translation aids, particularly on the exterior, severely limited realistic crew translations. Some form of recessed or extending handrails would be necessary to navigate the exterior of the Dream Chaser without a manipulator or some other form of external handrail being made available. Although this test clearly demonstrated the feasibility of repeated and in-depth experimental investigation of EVA support from Dream Chaser, a higher fidelity mockup of the spacecraft and worksite would have to be made to obtain meaningful information.

V. Plans for Further Study

Given the current unresolved status of Dream Chaser and the lack of information on the details of CST-100, near-term continuation of this study will focus on the SpaceX Dragon spacecraft. This system has several strong features to support servicing: the external volume available in the trunk, and residual payload capacity in the Falcon 9 launch vehicle. One issue which is currently unresolved is the availability of external cargo for the crewed Dragon variant. The launch abort system involves acceleration of both the Dragon spacecraft and trunk from the launch vehicle; significant cargo in the trunk could impact the performance of this safety-critical system. If this is the case, it should still be feasible to launch servicing hardware in a package underneath the Dragon assembly, and retrieve it after orbit insertion via a transposition and docking maneuver or by use of robotic manipulators on the servicing package to attach to the trunk after the potential need for launch abort is past.

One of the shortcomings of the inflatable airlock concept presented for Dragon is the inability to mechanically dock the spacecraft to the servicing client, freeing manipulators to directly support the servicing activities. One recent concept developed is that of the servicing module: a complete assembly incorporating a rigid airlock with docking interfaces on each end, robotic manipulators, and interfaces for servicing spares and logistics, including airlock depressurization gases. Besides adding the ability to dock Dragon to the target, such a system would allow the manipulators to be based next to the client rather than on the Dragon trunk, increasing the feasible work volume for a given length of manipulator.

One logical expansion of the servicing module would be to give the system its own reaction control system and limited stand-alone power and life support systems. In this way, the servicing module would evolve into a space utility vehicle, such as the FlexCraft[4] (Figure 26) and SCOUT[5] (Figure 27) concepts. The Space Construction and Orbital Utility Transport (SCOUT) concept, in particular, has many of the attributes required of a servicing module in this context, including dual docking adapters, robotics, and systems to support functioning as an independent spacecraft. The size is adequate to support modifications to serve as an attached airlock for Dragon, fulfilling the last of the major requirements for a servicing module. The overall system fits into the Dragon trunk as is. At the current time this is presented merely as an existence proof for a modular system of the appropriate size and capacity for a dedicated servicing module; near-term plans are to perform a detailed design of a dedicated servicing module and launch interfaces for a Dragon servicing vehicle.

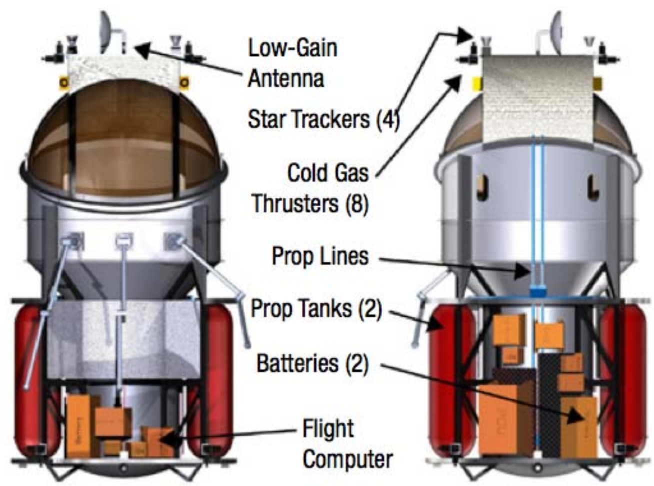

Figure 26. FlexCraft orbital utility vehicle concept[4]

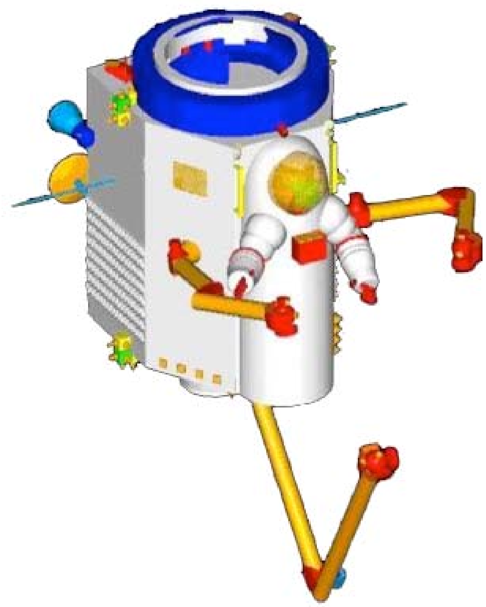

Figure 27. Space Construction and Orbital Utility Transport (SCOUT) concept[5]

The issue of free-flight capability and how that would impact overall servicing functionality of Dragon is one of the topics to also be further studied. The SCOUT system was initially designed to facilitate beyond-Earth-orbit assembly and servicing of advanced space telescopes; in that role the use of a small and low-contamination vehicle served to keep the main spacecraft away from the contamination-sensitive regions of the telescope assembly. Of greater interest for upcoming study is the utility of having two independent spacecraft (Dragon and a SCOUT derivative) performing collaborative servicing operations on a major client, such as a telescope or space platform.

Ultimately, the best assessment of the feasibility and utility of any servicing concept is via a realistic end-to-end simulation, such as in neutral buoyancy. While the requirement for dedicated underwater mockups makes this a more expensive option than computer-based studies, experience indicates that many issues will only become apparent when working the complete task in a realistic simulation environment.[6] Given the availability of functional equivalents of flight manipulators which work in the underwater environment, the cost of an experimental investigation of servicing would be beyond the discretionary funds available to a university, but modest in comparison to most NASA (or corporate) funded research. The successful completion of an initial round of neutral buoyancy testing would go a long way to retiring risk for flight hardware development, and should provide unequivocal evidence of the feasibility of this restored capability in our nation's space program.

VI. Conclusions

Prior to the conclusions, it should be reiterated that it was never intended that this study should "pick a winner" or otherwise rank order the suitability of the spacecraft concepts for on-orbit servicing. The research to date has clearly shown that any of the known commercial crew vehicles could support shuttle-style EVA servicing, and could more readily support an advanced form of EVA/robotics collaborative servicing system; the "best" choice for any given application depends on the details of the candidate servicing task(s).

Both capsules and lifting body vehicles can support extensive servicing operations. Due to the potential to add an internal airlock without seriously compromising interior volume provides a minor "boost" to Dream Chaser for pure EVA servicing; on the other hand, the large exterior "trunk" on the Dragon vehicle provides near-ideal stowage for both ORUs and robotic support and servicing systems. Key issues are external stowage space and residual launch vehicle payload capacity to allow the addition of servicing elements, specifically airlocks, robotic manipulators, and logistics elements.

While a number of interesting issues remain to be examined, including economic viability, this study has demonstrated that on-orbit human servicing need not necessarily come to an end along with the space shuttle program. Any of the spacecraft considered in this paper would be feasible as the basis for an on-orbit servicing capability; how to optimize their functionality in such a role is an ongoing focus of study.

Acknowledgements

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