GLEX-2012.08.2.6x12677

ENTRY, DESCENT, AND LANDING FOR HUMAN MARS MISSIONS

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One of the most challenging aspects of a human mission to Mars is landing safely on the Martian surface. Mars has such low atmospheric density that decelerating large masses (tens of metric tons) requires methods that have not yet been demonstrated, and are not yet planned in future Mars missions. To identify the most promising options for Mars entry, descent, and landing, and to plan development of the needed technologies, NASA's Human Architecture Team (HAT) has refined candidate methods for emplacing needed elements of the human Mars exploration architecture (such as ascent vehicles and habitats) on the Mars surface. This paper explains the detailed, optimized simulations that have been developed to define the mass needed at Mars arrival to accomplish the entry, descent, and landing functions. Based on previous work, technology options for hypersonic deceleration include rigid, mid-L/D (lift-to-drag ratio) aeroshells, and inflatable aerodynamic decelerators (IADs). The hypersonic IADs, or HIADs, are about 20% less massive than the rigid vehicles, but both have their technology development challenges. For the supersonic regime, supersonic retropropulsion (SRP) is an attractive option, since a propulsive stage must be carried for terminal descent and can be ignited at higher speeds. The use of SRP eliminates the need for an additional deceleration system, but SRP is at a low Technology Readiness Level (TRL) in that the interacting plumes are not well-characterized, and their effect on vehicle stability has not been studied, to date. These architecture-level assessments have been used to define the key performance parameters and a technology development strategy for achieving the challenging mission of landing large payloads on Mars.

I. INTRODUCTION

The very low density of Mars' atmosphere is a major challenge to decelerating spacecraft and landing them safely on the planet. Current technology, utilized to land up to 1 metric ton (mt) vehicles on Mars, is derived from 1960's and 1970's Viking era technology. The use of a 70-degree rigid sphere cone forebody aeroshell, a supersonic disk-gap-band parachute deployed within a particular range of Mach number and dynamic pressure, and even the particular thermal protection system material, are all based on 50-year-old developments. Recent missions to Mars have pushed the bounds of those systems such that enabling larger payloads to the surface now requires new technology developments. In the case of human scale missions, requiring landed payloads of 20 to 40 mt, or even human precursors, with landed usable payloads of 5 to 10 mt, a shift in the entire entry architecture paradigm is needed.

NASA's internal Human Architecture Team (HAT) is conducting ongoing assessments of the approaches and technologies that may allow humans to someday explore the surface of the Red Planet. This team includes experts in propulsion, power, flight mechanics, structures, surface operations, habitat design, systems engineering, and numerous other disciplines. The team's charter is to determine feasible architectures (from Earth launch to the Mars surface, and return) for sending humans to Mars, which will in turn define the requirements for technology development in the next two decades. The work presented herein was performed within the Mars sub-team of the multi-Center HAT, in 2011 and early 2012.

II. BACKGROUND

Methods for landing humans on Mars have been studied for decades. At first, the concepts required farfetched systems that defied the laws of physics. Fortunately, most studies over the past 20-30 years have the advantage of improved knowledge in some aspect of the problem, such as the environments, the way humans live in space, or the performance of interplanetary flight systems. Meanwhile, technology improvements and applying new capabilities to the problem can reveal novel solutions. The existence of system models, in some cases validated by ground or flight tests, enables technology impacts to be assessed in the context of the overall mission. Recent studies[1,2,3] have considered the feasibility of several scalable technology options to enable larger masses to surface of Mars. These options include the mid-range lift-to-drag ratio (Mid-L/D) rigid aeroshells, inflatable aerodynamic decelerators (IADs) deployed at both hypersonic (HIADs) and supersonic (SIADs) speeds, rigid deployable drag devices, and supersonic retropropulsion (SRP).

One such study, the Entry, Descent and Landing Systems Analysis (EDLSA), started with Design Reference Architecture 5 (DRA5)[4] and considered various technology combinations to land a 40 mt "black box" payload on Mars. The following combinations of technologies were considered and are shown in Fig. 1.

Architecture 1, nearly identical to the DRA5 entry configuration, utilized a 10x30 m Ares 5 shroud as the mid-L/D entry vehicle for aerocapture (AC) and entry, and supersonic retropropulsion for descent and landing. Architecture 2 considered a 23 m inflatable HIAD for aerocapture and entry as a lighter-weight alternative to the rigid aeroshell. Architecture 3 considered an all-propulsive entry. Architecture 4 considered the circumstance where a single HIAD could not be used for both AC and entry and, therefore, utilized the 10x30 m rigid aeroshell for aerocapture and entered with a HIAD. Architecture 5, like Architecture 4 assumed a rigid aeroshell for aerocapture but considered an alternative to SRP by increasing the size of the HIAD to allow it to reach subsonic speeds at sufficient altitudes to enable successful landing using subsonic retropropulsion. Architecture 6 is similar but assumes the same HIAD is also used for aerocapture. Architecture 7 considers the option of using a mid-L/D rigid aeroshell and SIAD to reach subsonic speeds at engine initiation and likewise, Architecture 8 pairs a HIAD and a SIAD to reach subsonic engine initiation.

Several modeling improvements were made from DRA5 to the EDLSA assessment, which sought to increasing the fidelity of component models including mass modeling, aerodynamic and aerothermodynamic modeling of the entry shapes, and thermal protection system options considered. The trajectory analysis introduced bank angle controlled entry guidance and supersonic engine design considerations. Figure 2 show the general simulation trajectory strategy used to analyze all architectures. All trajectories considered entry from a 1 Sol orbit. The velocity at the start of guidance and heading alignment was unique to each architecture but the nominal trajectories utilized three bank reversals. The transition between the entry vehicle and the descent stage was modeled as a simple free fall with a duration of 20 s for the rigid aeroshell configurations and 15 s for inflatable structures.

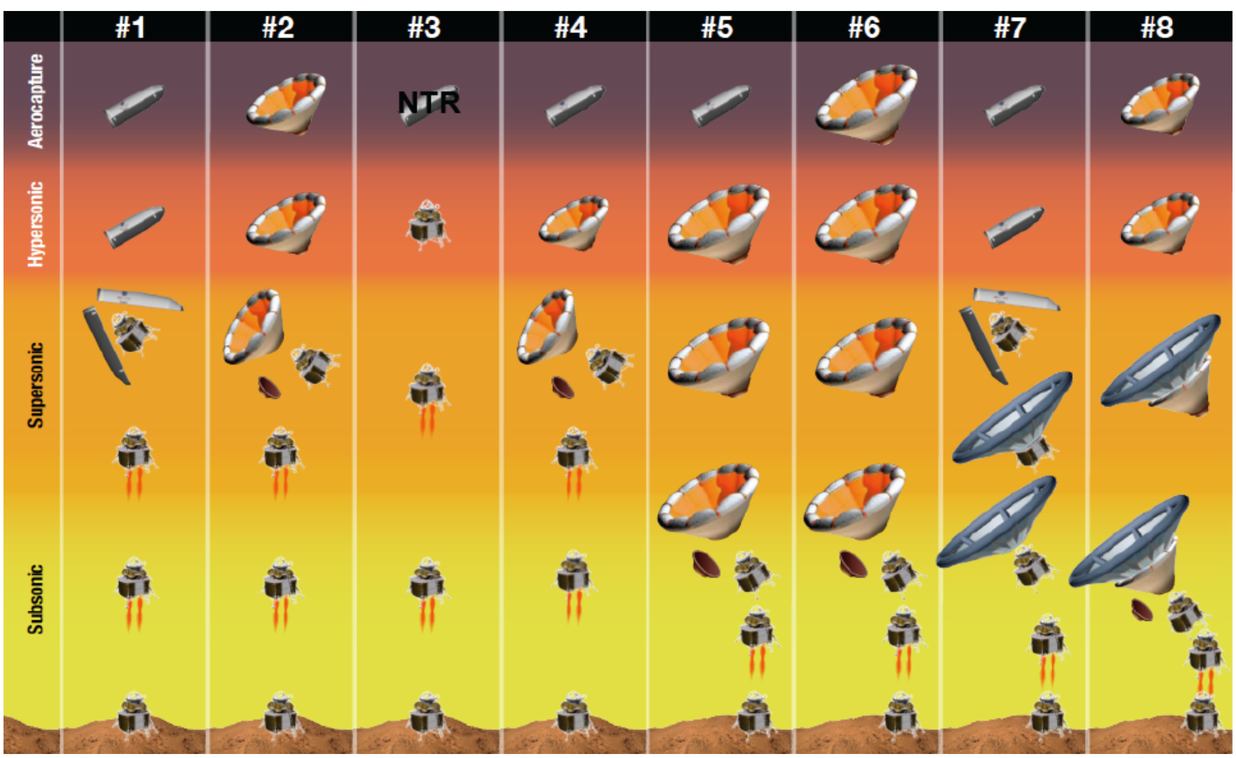

Figure 1. EDLSA Technology combinations form 8 unique entry, descent and landing architectures.

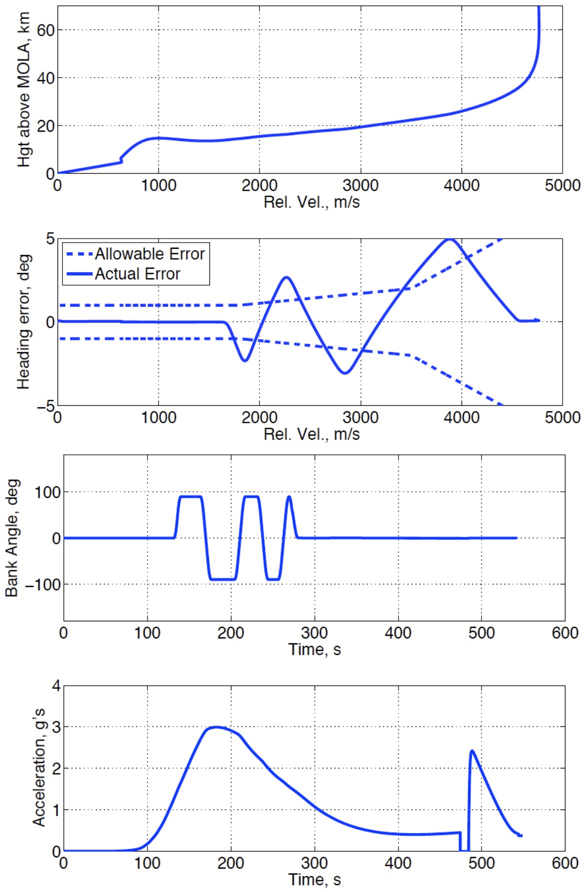

Figure 2. Architecture 1 Trajectory: (Top) Altitude above the Mars Orbiter Laser Altimeter (MOLA) areoid vs velocity; (Second) Heading error to target vs. velocity; (Third) Guidance bank reversals vs. time from entry; (Fourth) Acceleration vs. time from entry.

Keeping in mind the Human Systems Integration Requirements[5] (HSIR) on peak accelerations for a deconditioned crew and to include margin in the trajectory, the peak acceleration allowed during entry and while on the engines was limited to 3 Earth g's for all trajectories. See the bottom of Fig. 2. Trajectory termination occurred after the vehicle slowed to a velocity of 2.5 m/s, which was held for 5 seconds prior to touching down at 0 km above the MOLA areoid. Within this trajectory framework, the deorbit mass of all the architectures was minimized to land a 40 mt payload using the Program to Optimize Simulated Trajectories[6] (POST2). The complete Architecture 1 entry trajectory is shown in Figure 3. Additionally, several aerocapture and entry trade studies were performed. The purpose of the EDLSA study was to determine which technologies showed enough feasibility to warrant continued investment.

Based on the analysis performed for the EDLSA study, the technologies recommended for investment included the mid-L/D vehicle, due to its relative high Technology Readiness Level (TRL), the HIAD as a mass savings alternative, and Supersonic Retropropulsion for descent and precision landing.

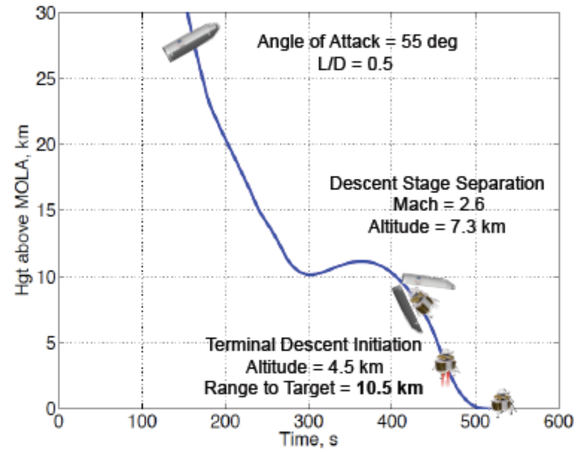

Figure 3. Architecture 1 entry trajectory.

However, as with any study considering missions indefinitely in the future and an order of magnitude larger than the current state of the art, several shortfalls are identified. First, the level of fidelity of the models was limited, so only three degree-of-freedom analyses were performed. Second, very little information exists on the dynamics or ability to control large inflatable vehicles during aerocapture or entry, so many assumptions and idealizations on controllability of the HIAD had to be made. Third, few detailed vehicle packaged concepts exist for landing systems of this size, therefore little can be said of the flight stability for launch, aerocapture, entry or terminal descent. Also, the separation of the entry vehicle from the descent stage is not modeled due to this lack of information. Therefore a simple freefall event of 15 to 20 s was allowed. Finally, no attempt was made to ensure the ability to perform precision landing or hazard detection and avoidance for descent.

Therefore, to determine if the architectures and technologies recommended by EDLSA are viable and accurately inform the technologies for consideration and development, additional analysis was needed. The next phase of analysis, described in the following section, is being performed by the Human Architecture Team to address specific gaps in previous studies and serves to inform subsequent Mars Design Reference Architecture studies.

III. HAT DETAILED ANALYSIS

To address the major shortfalls of the Mars entry analyses of DRA5 and EDLSA, HAT has identified several areas for more detailed study. Specifics of the EDL design depend on the package being delivered which, to date, has been considered a "black box" with the appropriate L/D to enable top-level architecture assessments. However, verifying the feasibility of a particular architecture configuration, including the stability and controllability of the vehicle during aerocapture and entry, the ability to separate from the descent stage, and to accommodate the payload and descent system within a launch fairing require knowledge of the packaged components. The current HAT analysis considers these aspects of only Architectures 1 and 2 shown in Figure 1.

Initial packaging arrangements for both vertical and horizontal landers are presented that are based on most recent descent and ascent vehicle propellant sizing. Also, a discussion of the future work to assess and down-select a particular packaging arrangement and how it will be used to inform vehicle transition analysis and guidance and control capabilities through entry and descent is presented. Finally, a summary of the impact of these results on the overall architectures is provided.

III.I Entry Stability

An initial assessment of the entry stability was performed by the Flight Mechanics and Trajectory Design Branch at NASA-Johnson Space Center to determine lines of constant trim required to maintain desired L/D for both the 10x30 m (L/D = 0.5) aeroshell and the 23 m HIAD (L/D = 0.3). The analysis provided initial estimates of the approximate CG locations that would ensure stable flight for the appropriate L/D. The trim lines for the two vehicles are shown in Fig. 4 and 5.

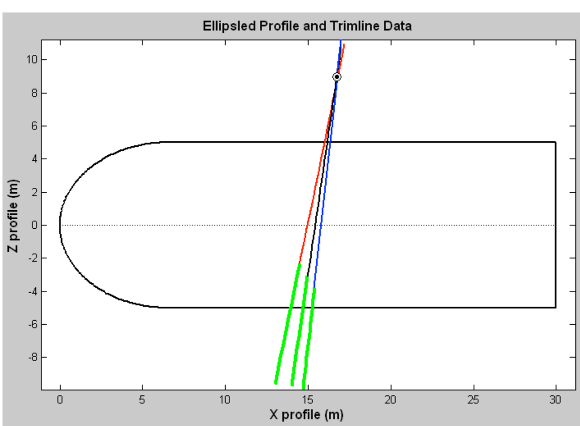

Figure 4. Initial Trim line data for the 10x30 m rigid aeroshell. Green lines indicate potential CG locations that result in mono-stability but may be too low for structural feasibility.

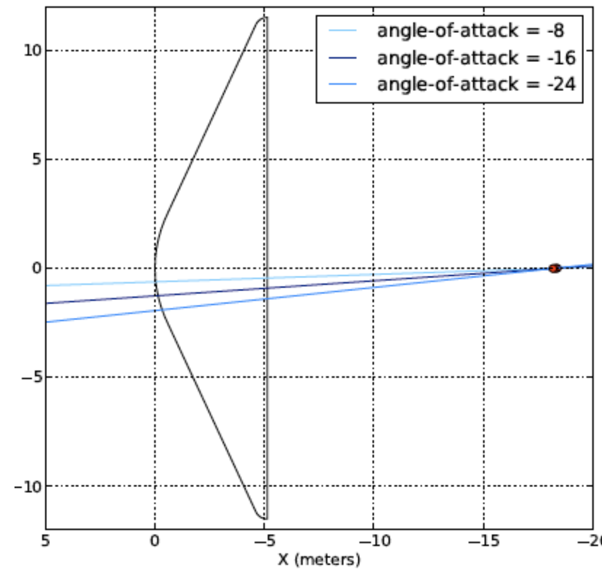

Figure 5. HIAD trim lines for Mach=18 at various angles of attack. Courtesy Ron Sostaric, NASA-JSC.

During launch and terminal descent it is desirable to have the CG location as close to the axis of symmetry as possible. However, as shown in Fig 4, the CG location required to maintain the L/D = 0.5 for the 10x30m rigid aeroshell, assumed to fly at 55 degrees angle of attack, can be several meters off of the center line, especially if monostability is considered. This poses packaging challenges, which are considered in the following section.

The HIAD configuration shown in Fig 5 flies at approximately -22 degrees angle of attack, and depending on the height of the payload, can accommodate CG locations much closer to the centerline of the vehicle than the rigid aeroshell alternative.

III.II Packaging

DRA5 identifies the first human scale cargo mission to include a Mars Ascent Vehicle (MAV), a rover, and other surface systems (e.g., in-situ resource utilization (ISRU) plant, nuclear power plant, etc.) or perhaps a surface habitat, depending on the mission architecture. The HAT ongoing architecture analysis first considered only the powered descent stage and MAV. Several trades were considered: 4 vs 6 person crew, single and dual stage MAV, and entry and return to high (1 Sol) and low (500 km) orbits. Utilizing ISRU on the surface was compared to having to deliver all the propellant required for Mars ascent. Trades were also performed on engine design, including system thrust to weight, I_{SP}, and propellant type. All trades influenced the mass and volume of the delivered system, though no launch, transit or entry-to-landing simulations were performed for any of the systems.

In comparing the descent stage/MAV analysis with the assumptions made for the EDLSA entry to landing flight trajectory and the assumption of supersonic retropropulsion, several modifications were made to the HAT engine design prior to initial attempts to package the system. These modifications included increasing system thrust to weight by including dual thrust chambers on 8 engines and accounting for divert maneuver capability.

The descent stage/MAV combination selected for initial packaging included a 2-stage MAV with oxygen-only ISRU to reduce entry mass (with methane brought from Earth), a 5.5 mt rover and a 7 mt fission surface power system as additional cargo, all entering from a 1 Sol orbit. The LOX/CH4 descent system used a thrust-to-weight (T/W) of 1.5 Earth g's. The packaging assessment herein contains 30.6 mt of propellant for the ascent stage (of that, 23.5 mt of oxidizer is manufactured on Mars) and 19.7 mt of propellant for the descent stage.

With knowledge of the CG locations required to support the L/D for entry, the two-stage assumptions for MAV and descent propellant mass and volume requirements, and sample cargo components including a power supply and rover, an initial packaging effort was performed for both a horizontal and vertical lander. See Figs 6 and 7.

The initial packaging followed a "tanks in space" philosophy and considered the arrangement of the cargo around the descent and ascent stage volumes. Both vertical and horizontal lander configurations were generated to determine optimal packaging arrangements, with the entry configuration of a rigid aeroshell likely to more easily accommodate a horizontal lander and a HIAD thought to better accommodate a vertical lander.

Fig. 6 and 7 are preliminary concepts that will undergo a Figure of Merit-type evaluation and analytical hierarchy process (AHP) to down-select to a single vertical and a single horizontal configuration for further study. The down-selected design is not intended to provide a point design to HAT but rather serve as an example by which to evaluate higher level architecture drivers such as ability to obtain the appropriate entry L/D, the ability to separate the rigid aeroshell or HIAD for descent, and the ability to control the vehicle during entry and powered descent. This analysis will be performed over the next 6 months.

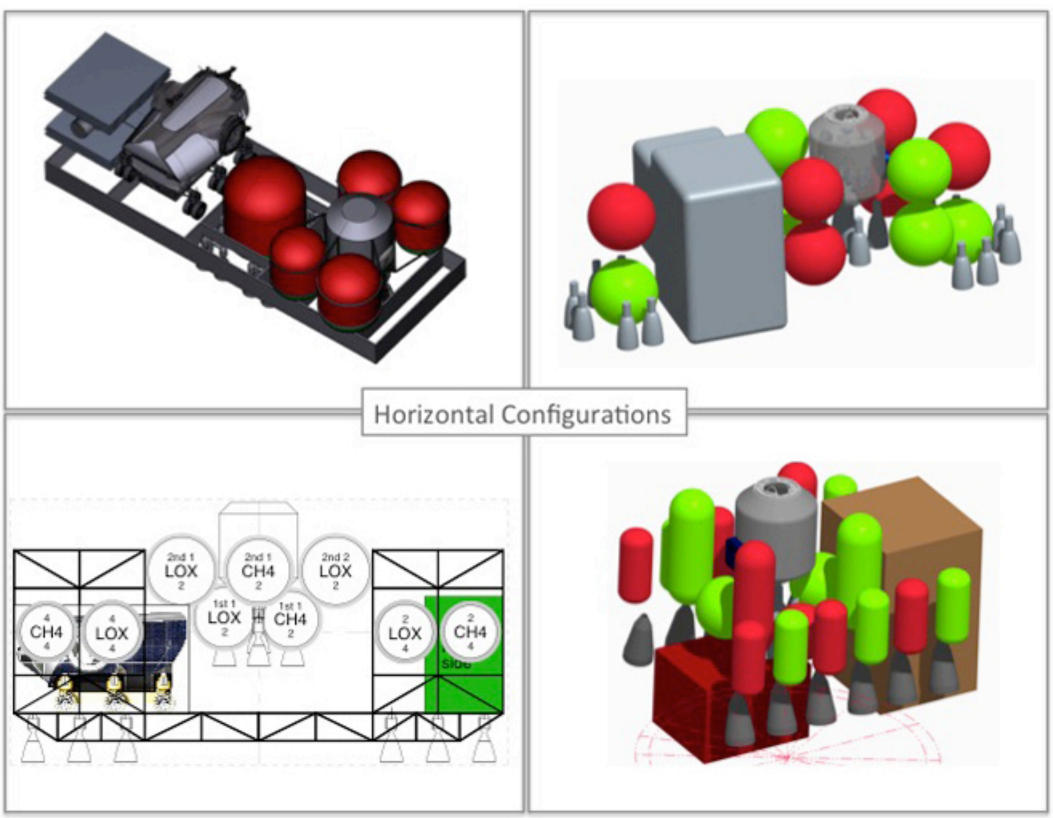

Figure 6. Examples of horizontal configurations for human Mars missions

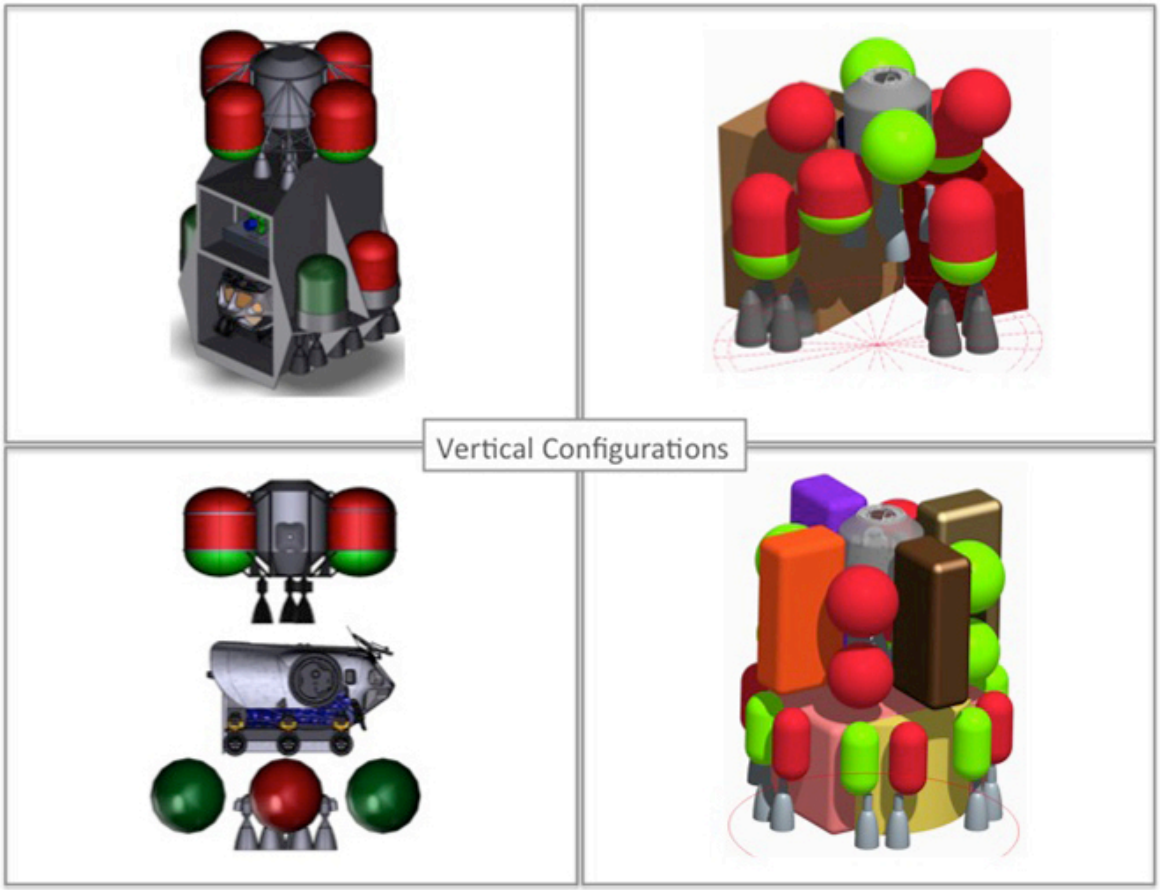

Figure 7. Examples of vertical configurations for human Mars missions.

One significant finding from the work thus far is that the presumed 10x30 m aeroshell may be oversized (this was also noted as a possibility in Ref. 1). None of the configurations in Fig. 6 and 7 exceed 17 m in length while maintaining a 9.1 m diameter for packaging. The consequence of shortening the 10x30 m aeroshell to 8x24 m (to maintain the fineness ratio) or even 10 x 24 m (producing an L/D known to be stable during entry) would reduce the mass of the aeroshell, making it more equivalent the approximate mass of the HIAD, therefore reducing one of the apparent advantages of using the lower TRL technology. Multidisciplinary optimization has previously been applied to the Mid-L/D aeroshell to investigate optimal mass.[7] Additional work is needed to determine the lower limit on the dimensions of the rigid aeroshell, from the perspectives of flight mechanics, aeroheating, and controllability.

III.III Additional Studies

In addition to the efforts of the HAT team to define the Mars Human scale missions, a Team X session at the Jet Propulsion Laboratory (JPL) was performed as semi-independent evaluation of the two architectures being considered.[8] An advantage of the Team X approach is that their analysis considers many major subsystems not yet considered in the previous architecture studies. The components included were telecom, power, attitude control system, command and data storage, ground system data storage, and software requirements. The Team X analysis pointed out several areas where further consideration is required. For example, depending on mission architecture and the assumptions made for the duration between an aerocapture pass and entry, power considerations need to be incorporated into the architectures to provide the required power (solar panels, batteries, other) to maintain any onboard cryogenic liquids, heaters, etc. Another example of an area for further consideration is the ability to separate the 9 m HIAD rigid nose cone at supersonic speeds. These and others will be considered in future HAT activity planning.

In addition to entry stability, the flexibility of the architectures to vertical and horizontal landers is being assessed. Both entry vehicles decelerate at different angles of attack. The rigid aeroshell is assumed to trim at 55 degrees while the HIAD trims at -22 deg. These angles of attack result in very different entry load paths as well as transition times required to prepare for terminal descent. In this application, transition refers to a change in the vehicle configuration as it moves from one deceleration mode to another; for example, jettisoning the rigid aeroshell and reorienting the vehicle for the initiation of the SRP phase. An initial study was performed to consider the rates and accelerations of vehicle separation to determine how they compared to simplistic free-fall transition assumptions of the EDLSA study. The results indicated the assumptions of transition times of 15-20 seconds were appropriate but these times did not include (for either configuration) the separation of the 9 m rigid nose cone that to date has been assumed to separate once the vehicle has reached subsonic speeds. Therefore once mass properties are obtained, aerodynamic analysis of various separation schemes will need to be evaluated to determine if the heatshield can be jettisoned at supersonic speeds to enable supersonic retropropulsion initiation. The jettisoned hardware will also have to be analyzed to ensure it does not recontact the vehicle.

IV. FUTURE WORK

The analysis to assess the viability of only a couple of the many human EDL architectures under consideration is just beginning. There are many considerations and challenges ahead. The shape of the Space Launch System (SLS) shroud is yet to be defined which will drive packaged shapes and structural designs to support loads. The overall human mission architecture from Earth launch to Mars arrival has yet to be defined which will also impact the AC and EDL design. To maintain stability for aerocapture and entry may require flaps on the rigid aeroshell or a canted HIAD configuration, neither of which has been analyzed. The ability to guide and control the large vehicles in the Mars atmosphere is unknown. Separating large pieces of the entry vehicle (10 to 30 mt) from the descent stage supersonically is a challenge even to model. Starting engines supersonically remains a low TRL and instruments required for precision landing on Mars are only now being considered.

However, once initial packaging arrangements can be considered, iterations can be performed using 6 degree-of-freedom simulations to evaluate stability, aerodynamic heating, controllability, transition feasibility, divert capability, and engine sizing based on a closed loop system. The ultimate goal is to determine if there are any aspects of the design that fundamentally prevent the continuation of a particular architecture configuration being considered, in order to inform DRA6 and future human Mars studies as to the most viable path forward and to influence technology development decisions today to minimize cost and risk in the future.

V. CONCLUSION

Architecture level assessments define key performance parameters and technology development strategies. The assessments have reached a point where going to the next level of detail is required to determine if particular technology strategies are legitimate.

Efforts to determine which human Mars entry, descent, and landing architectures and technologies are viable requires higher-fidelity models and detailed packaging and mass properties of the expected cargo and payload components. As these cargo characteristics are developed, more specifics of the EDL systems can be defined. These efforts will inform subsequent Mars Design Reference Architecture studies and technology investment programs.

VI. ACKNOWLEDGMENTS

This paper summarizes the interim FY12 Cycle D work as part of a Mars Human Architecture sub-team, supported by various NASA centers including Langley Research Center (LaRC), Johnson Space Center (JSC), Marshall Space Flight Center (MSFC), and JPL. In particular, the authors would like to recognize the contributions of Ron Sostaric in stability and flight mechanics; and Tim Collins, Roger Lepsch, Mike Baysinger, John Teter, Lawrence Taylor, and Dave Paddock of the HAT Mars Lander Team for their structures and configuration efforts.

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