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On-orbit depot architectures using contingency propellant

Koki Ho*, Katherine Gerhard, Austin K. Nicholas, Alexander J. Buck, Jeffrey Hoffman

Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

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ABSTRACT

This paper introduces new concepts of on-orbit propellant depots for human space exploration based on contingency propellant. The proposed architecture is useful in that it does not require separate depot filling missions, whereas conventional depot architectures require large "prior investment" type missions for depot filling before gaining the returns. Two concepts for this type of depots are shown: "steady-state" architecture and "stockpiling" architecture. In the "steady-state" mode, the depot always keeps the contingency propellant in orbit as well as the reused habitat module. In each mission, the vehicles collect the habitat and the contingency propellant from the depot in orbit on its way to the destination, perform the maintenance for the habitat, and leave the habitat and the unused contingency propellant in orbit on its way back. In the "stockpiling" mode, on the other hand, the habitat module is reused in the same way, but the depot accumulates propellant so that a later mega-mission can carry larger payload. Numerical results show the usefulness of the proposed architectures.

1. Introduction

Apollo program brought humans to the Moon and completed a monumental achievement. The rocket Saturn V launched these Apollo spacecraft from Earth and greatly contributed to the program success. One well-known fact about Saturn-V is that 98.5% of its gross launch mass was its propellant and propulsion system, and the actual payload part was only 1.5% of the total mass [1]. Although the payload mass ratio varies depending on the destination, this trend shows a serious problem in large-scale space exploration: its huge propellant consumption.

One proposed solution to this problem is using on-orbit propellant depots. Propellant depots can be used as gas stations in space so that rockets or spacecraft can be launched with less propellant. They can be placed at Earth–Moon Lagrangian points (EML) or in various orbits such as Low-Earth-Orbit (LEO) depending on the mission architecture. Numerous concepts have been proposed about how to use the on-orbit propellant depots from architectural aspects [1–6], technological aspects [7–13], and the commercial aspects [14–16], all of which show that propellant depots can provide design flexibility to future large-scale space missions.

However, on-orbit propellant depots have an important constraint in that they need to be filled before they provide service to the spacecraft. Conventional studies have proposed that this refill task can be performed either by propellant tanker missions from Earth or by In-Situ Resource Utilization (ISRU). Propellant tankers can be used to bring propellant from Earth to the depots, as shown in the examples in Refs. [1,2] or Refs. [5–7]. ISRU, on the other hand, generates propellant from the in-situ resources, as can been seen in Refs. [4,16]. Examples of ISRU include acquiring rocket propellant by electrolyzing the water extracted from ice at the Moon poles. With ISRU realized, a sustainable base can be created on the Moon asteroids, or planets.

Both of these two concepts are promising, but have a common disadvantage. Those architectures have an underlying assumption that they are supported by a sustained

* Corresponding author. Tel.: +1 617 947 9084.
E-mail address: koki_ho@mit.edu (K. Ho).

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long-term space program that would not be canceled in the middle. For the propellant tanker system to pay off, more benefits should be gained than the large cost for launch missions of the propellant tankers and the depots themselves. This can be realized only when "secured customers" exist who would keep utilizing the depots for a long time. For the ISRU, again, long-term thought is necessary for a successful program. Typically ISRU plant requires missions to launch the plant and the main mission follows after sufficient propellant is generated (e.g. 26 months in the example of Mars Design Reference Architecture (DRA) 5.0 by NASA [17]). The program should start years before the values are actually gained, and cannot be canceled in the middle.

Unfortunately, however, this is seldom the case in the recent space programs. As can been seen in the cancellation of Constellation Program in 2010, it has been difficult to predict the future of space programs. This is partly because the budget is hard to estimate for a long-term program and there are numerous unpredictable political influences. This can lead to a conclusion that space programs requiring large "prior investment" type missions might not work anymore. Next generation space programs need to gain as much values as possible even if the program is canceled after several missions. Neither the propellant tanker system nor ISRU falls in this category.

This paper proposes two on-orbit depot architectures that do not require "prior investment" type missions. These concepts assume multiple human space exploration missions, but do not include refill tanker missions or an ISRU plant. Instead, they utilize contingency propellant that is designed to be used in emergency and is not used during normal missions. In the proposed concepts, the vehicles leave the unused contingency propellant tank in orbit on the way back from every exploration mission. Also, it is assumed that the habitat module can be reused and is kept in orbit together with the depot. In this way, the later missions do not have to carry the contingency propellant and that habitat module because they can collect them in orbit. Note that this architecture does not require any "prior investment" type tank filling missions because the contingency propellant is necessary in any case, even in those that do not use depots. This concept is similar as the one proposed, but not implemented, for the Space Shuttle programs to scavenge the unused propellant from the External Tanks after each mission [18]. This paper generalizes that idea and proposes new architectures that efficiently utilize unused contingency propellant.

In this paper, the baseline crewed lunar global exploration architecture is first introduced that is used as an example case study. Then, two architectures are introduced: "steady-state" and "stockpiling," and the numerical comparison is performed in order to show the benefits of using these architectures. Note that though this paper takes the lunar exploration architecture as an example, the proposed architectures can be used in other human space missions including exploration missions on Mars or asteroids.

2. Baseline architecture and assumptions

This paper takes lunar global exploration as an example to show the benefits of using on-orbit propellant depots with contingency propellant in it. This chapter shows its baseline architecture, Human Architecture for Lunar Operations (HALOs) [19] and the related assumptions. The architecture without propellant depots is introduced first, followed by the definition of "contingency propellant." Then, the payload mass calculation method that is used for architecture comparison later is introduced. The details of orbital transfers are not covered in this paper, but can be found in typical orbital dynamics textbooks [20]. The orbits and ΔV assumptions used in this paper are summarized in Appendix A.

Note that the basic assumption is that all architectures described in this paper have multiple missions, whether it is with depots or not.

2.1. Direct-to-elliptic-polar-lunar-orbit (D-EPLO)

This section introduces the architecture without using depots, defined as Direct-to-EPLO (D-EPLO) architecture.

The D-EPLO architecture consists of a series of individual, stand-alone missions utilizing existing space systems as much as possible. These missions use a profile similar to the Apollo program and do not require depots or other prepositioned in-space infrastructure. The D-EPLO designation indicates that the vehicle transfers directly from LEO to the Elliptic Polar Lunar Orbit (EPLO). Fig. 1 presents a graphic summary of the proposed mission architecture. Three-crew mission is assumed with nominally 7 surface days, in which case the total mission length is around 17 days.

The following are the acronyms for the key phases and vehicles used in D-EPLO architecture.

- TLI – Trans-lunar Injection. The trajectory from low Earth orbit to cislunar space.
- LOI – Lunar Orbit Insertion. The maneuver to place the vehicle into Lunar orbit.
- TEI – Trans-Earth Injection. The trajectory from Lunar orbit to Earth re-entry.
- CM – Command Module. The crew capsule during TLI and TEI.
- SM – CM support/propulsive stage. Propellant: LH2/LOX. The module providing only the TEI burn.
- CSM – CM+SM (connected).
- EDS – Earth Departure Stage. Propellant: LH2/LOX. Three combined together, used to initiate the TLI.
- LOID – Lunar Orbit Insertion & Descent. Propellant: LH2/LOX. The module performing LOI & Descent. Discarded above the lunar surface at a certain point prior to terminal landing. (Discussed later.)
- LL – Lunar Lander. Propellant: RP-1/LOX. The module performing the terminal landing and ascent to Low Lunar Orbit (LLO). Detaching the landing gear and surface equipment stowage sections prior to ascent, leaving these components on the lunar surface.

This architecture improves the Apollo architecture in various aspects. Fig. 2 compares the Apollo and D-EPLO maneuvers in cislunar space.

In this paper, the mission is assumed to essentially begin in a LEO of 400 km altitude. Two Falcon-Heavy rockets [21] are used to launch the stack to LEO, and the 2nd launch includes an additional rendezvous maneuver