Starlift: Logistics Networks for Persistent, Ensured Superiority in Cislunar Space

1. Statement of Objectives

The United States' ability to operate freely in space has led to unprecedented technological innovation and advancement along with new peacekeeping capabilities and challenges. For the United States to maintain superiority in the space domain, we must establish robust logistics networks that supply and strategically position vehicles between the Earth and moon. **We propose to establish the foundational celestial mechanics, operations, and autonomy concepts that optimize the performance of 'Starlift': a network of spacecraft providing intercept, servicing, and provisioning (including propellant delivery) capabilities throughout cislunar space**.

The long-term stability of cislunar space, and the establishment and maintenance of U.S. freedom of operations in this domain, require the ability to quickly and efficiently intercept any object in this space. Intercepting spacecraft must be capable of a broad variety of tasks including servicing, refueling, inspection, and deterrence. The logistics networks for fielding and maintaining the spacecraft fleets required to meet these goals do not currently exist. While the DoD has significant expertise in terrestrial logistics and supply chain management, it is not self-evident that the techniques developed for ground operations are directly applicable to space. In particular, whereas distance and accessibility are the primary cost heuristics for the majority of terrestrial supply networks, they become less important in the space domain, where geometric distance need not scale with transit time or fuel costs. **This work will establish to what extent terrestrial logistics optimization techniques are applicable to space networks, and develop novel in-space logistics.**

Furthermore, we will demonstrate how the three-body domain provided by the Earth and moon allow for the utilization of novel orbits in network definition and management. In particular, **we will demonstrate how the availability of frequent lunar flyby opportunities can significantly decrease network fuel requirements and can be exploited for highly fuel-efficient intercept opportunities.**

Starlift will require autonomous, structurally flexible space robots that can perform on-orbit servicing and assembly operations where system mass suddenly and substantially changes in the transfer of components and volatiles. **We will investigate the applicability and efficacy of newly proposed methods (e.g. optimal whiplash compensation for flexibility, deterministic artificial intelligence, etc.) in direct comparison to state of the art.**

The specific goals of the proposed work are to:

(1) Define the complete set of metrics under which the utility of a cislunar logistics network can be evaluated and one or more objective functions for network optimization;
(2) Produce one or more optimized network designs, including reference orbits, fleet description, and distribution of resource hubs;
(3) Produce a validated, subsystem-level design for the modular spacecraft composing the network;
(4) Develop and evaluate new techniques to autonomously control highly flexible, variable-mass space robots for on-orbit servicing and assembly; and
(5) Develop a clear program of infusion leading to industry and DoD technology transfer and including roadmaps for on-orbit technology demonstration.

2. Research Effort

2.1. **Introduction and Background.** We propose to design and evaluate the operation of Starlift: a logistics and supply network covering the region of space between the Earth and moon. The final design of this network will consist of a set of subsystem designs for network components, sets of orbits on which these spacecraft will reside (evaluated in a full-force model of the Earth/moon system), and a concept of operations, including detailed scheduling rules. The goals of the proposed network (Figure 1) are threefold:

(1) Provide servicing and repair capability to both existing and future assets throughout cislunar space;
(2) Provide the ability to resupply volatiles throughout cislunar space; and
(3) Provide inspection and intercept capabilities throughout cislunar space.

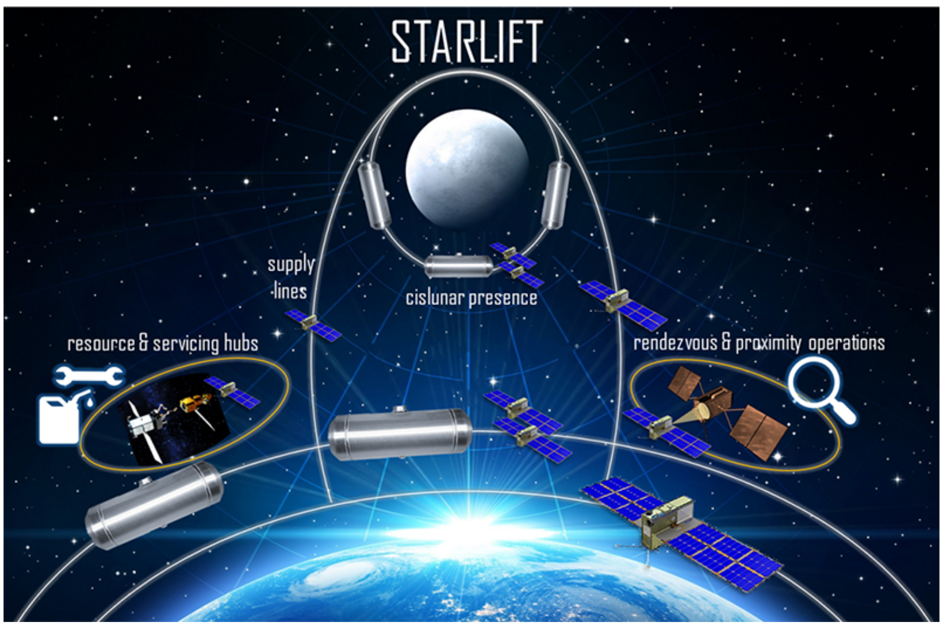
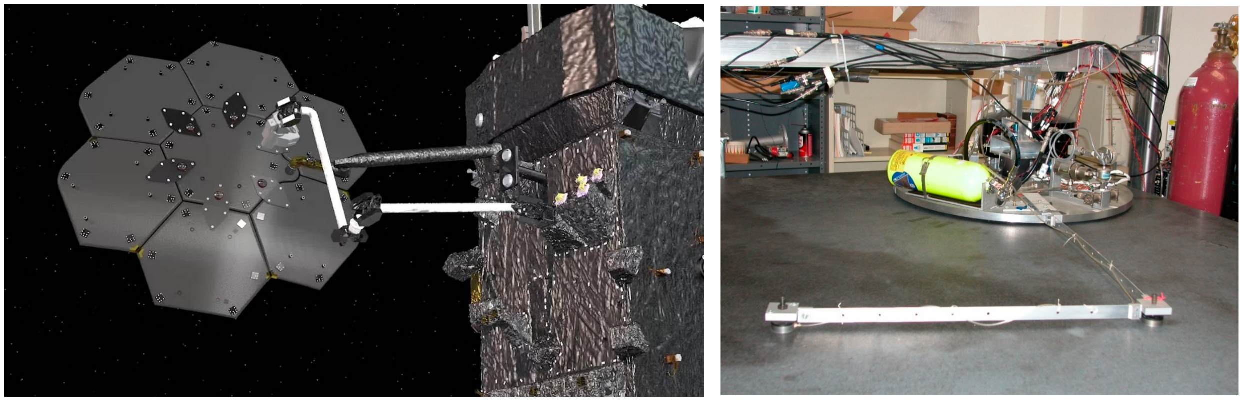


Figure 1. *The Starlift network concept.*

These three goals have significantly different time scales associated with them. Servicing and volatile resupply are typically long-lead time activities, which can be scheduled and planned in detail well in advance of execution. Repair is a mid-term activity, and depends on the acceptable downtime of the asset being repaired, as well as whether its failure represents a risk to any other spacecraft or the Earth. Inspection can take the form of long-range monitoring, or direct interaction after an intercept. There will likely be cases where intercept of spacecraft will be high priority activities that must occur with minimal lead times. Any and all high-priority activities should be accomplished with a high degree of autonomy, eliminating human-in-the-loop and ground contact bottlenecks whenever possible. **We propose a highly flexible network with assets coordinated among a variety of orbits throughout the cislunar volume, and operating in a primarily autonomous mode, with direct ground control focusing on the identification of high priority targets of activity.**



(a) (b)

Figure 2. *Robotic assembly and manufacturing in space (A) NASA and Maxar Technologies SPIDER (planned) robotic assembly in space. Photo taken from* Maxar and NASA will demonstrate orbital spacecraft assembly with a new robotic arm *(2020). (B) autonomous robotic laboratory free-floating simulator on planar air bearing table. Photo taken from (Sands, 2019). This testbed is the subject of modeling and control efforts leading to the discovery of whiplash compensation of flexible space robotics (see §2.2.5).*

Currently, placing a pound of material into low earth orbit (LEO) costs roughly ten-thousand U.S. dollars. One key lifetime limitation for spacecraft is the finite quantity of fuel brought to orbit. Other lifetime limitations include gradual degradation of solar panels, reducing electrical power generation, and failure of other spacecraft components (e.g., electrical devices like radios, gradual decay of moving parts like gyroscope bearings, etc.). An attractive remedy, which is currently an active area of research, is in-situ resource replenishment and requisite disassembly and assembly (construction) as depicted in Figure 2a. Benchboard spacecraft robotic laboratories (Figure 2b) are useful for validating advanced thinking about such systems. **We will expand upon the state of the art in on-orbit servicing and resupply by optimizing the designs of servicing spacecraft within the context of a functional space logistics network.** We will consider aspects of spacecraft modularity, autonomy, and control. We will also study subsystem optimizations within the context of network operations, with a particular focus on propulsion.

There currently exists an enormous wealth of literature on terrestrial supply chain and logistics networks. In the modern literature, these topics are generally considered under the umbrella of operations research (OR), with a particular focus on numerical optimization. Commercial and consumer network optimization tends to focus on facility location, capacity/production, and routing (Melo et al., 2009) and recent work has progressively focused more on network design under uncertainty (Govindan et al., 2017). Equal attention has been paid to military logistics networks (e.g., Xiong et al., 2017), and mixed military-civilian supply networks. In fact, entire texts now exist on the application of OR concepts to military decision making (Fox, Burks, et al., 2019).

Significantly less prior art exists when it comes to space logistics networks. While the concept of propellant supply depots dates back to the early space age (Farquhar, 1971), most work to date has focused on mission-specific depot placement in support of human spaceflight (e.g., Baine et al., 2010; Jagannatha and Ho, 2018) or asteroid mining (e.g., Dorrington and Olsen, 2019), etc. **There does not yet exist a systematic exploration of dedicated logistics networks for supply, support, and monitoring of cislunar space. Our proposed work seeks to close this gap.** Of particular interest is how much of the existing supply chain management (SCM), facility location, and location routing methodology is directly applicable to our goals, what aspects must be reformulated, and what tools need to be created from scratch.

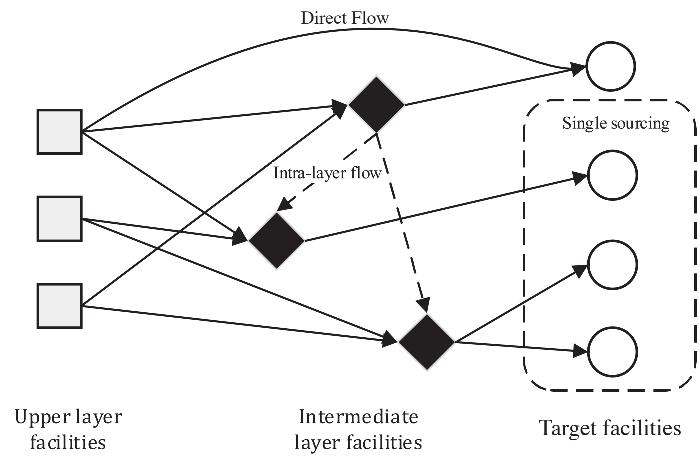


Figure 3. *A simple supply chain network graph exhibiting different classes of material flows. Adapted from Govindan et al. (2017).*

The fundamental mathematical tools for network analysis and optimization have been developed through deep study of canonical problems including the Traveling Salesman Problem (TSP) and Traffic Signal Scheduling Problem (TSSP). Investigations of these problems (and their countless variants) have left us with robust solution methods including Mixed Integer Linear and Non-Linear Programming (MILP; MINLP; Klanšek, 2015) and constraint programming (CP; Freuder and Wallace, 2005). These problems are applicable to the space domain as well, but seldom in their simplest, static forms. The relevant TSP formulation for any on-orbit servicing or interception activities is minimally a dynamic, time-dependent, moving-target one (Bourjolly et al., 2006).

The classical TSP can be formulated as an undirected acyclic (or in some variants potentially cyclic), weighted graph, with nodes representing potential destinations and edges weighted according to the transition costs between pairs of destinations. Figure 3 shows a schematic representation of a solution to an arbitrary supply chain problem, encoded as a directed graph, with direct and indirect flows between originating and target facilities. One measure of network robustness is the number of target nodes which end up being single sourced. In a terrestrial supply chain formulation, the nodes may represent supply depots or manufacturing plants, distribution centers, forward operating bases, etc. Edges connecting pairs of nodes can typically be encoded with static weights (as the costliness of moving material from a manufacturing plant to a supply depot is usually the same no matter when it is done), however, time-variation is possible (i.e., if access to a location becomes suddenly denied, or there are seasonal variations in ease of access to a particular location). The equivalent formulation in space is *always* dynamic. **There is no way, in general, to create a static encoding of the costliness of transfer of material from one point on-orbit to another, because points in space never remain stationary.**

The key cost metric in space operations is always the amount of fuel that must be expended in order to achieve a given transfer. For all currently used propulsion systems, fuel mass is a monotonic function of the magnitude of the change in the orbital velocity vector (Δv), and so this is a primary quantity of interest when performing orbital analysis and optimization of any space operations. Because an orbital intercept consists of matching position and velocity with a moving object, starting from a point that is also changing its position and velocity in inertial space, the Δv requirements for transfer between any pair of orbits are highly time-dependent. Some transfers become infeasible at a given starting time under the practical limits of a given propulsion system, whereas they can be completed easily later in the orbit (a well-known example of this are launch windows associated with deep space trajectories, and particularly interplanetary transfers). For most transfers (and especially when using low-thrust, high-efficiency electric propulsion), there is also usually the ability to trade between transfer time and fuel expenditures. Taken together, this means that a given edge weight in our network graph is not only a time-dependent quantity, but not even necessarily single-valued. While networks of such complexity are evaluated in terrestrial applications, they are typically built upon simplifications and static initial approximations, which can produce reasonable starting points for subsequent optimizations. **Very few such simplifications are reasonable in the space domain, which motivates our proposed development of entirely new heuristics and approaches to the network optimization problem.**

As a final note, while the sourcing of consumables is an incredibly important aspect of any logistics network, it is not a primary focus of our proposed research. For spacecraft, important volatiles are primarily fuel and oxidizer (and especially oxygen, hydrogen, water, etc.), but can also encompass a wide range of consumables including cryogens and other task-specific materials. **A supply network operating throughout the cislunar volume should consider the possibility of resupply from both the Earth and moon.** Lunar access will frequently be more efficient than Earth access, and having supply chains stemming from both the Earth and moon makes resource denial significantly more difficult for adverse actors. Given the current focus by NASA and others on a return to operations on the lunar surface, it is likely that lunar resource extraction will be feasible in the future, and we will assume that our logistics network assets will have access to these resources.

2.2. Technical Approach.

2.2.1. *Network Analysis.* The network design supporting a theoretical orbital supply chain will be modeled to meet forecast demand patterns of a given set of satellites that are capable of being serviced for a given set of consumable products such as cryogenic fuels. Demand rates will be forecast using historic consumption patterns of similar orbital assets to those planned for the network. The objective function of the optimization for the network would be to minimize the cost for the established network over a fixed period of time subject to the constraint of meeting the forecast demand. **Cost will be a function of launch costs, and consumption rates for the various distribution network scenarios. Initial costs for establishing the network will be separate from the optimization, but will be used to identify the payback period of certain scenarios.**

The order fulfillment process for the network will be triggered by a reorder point established for each on-orbit asset and product line. Reorder points for consumables will be a function of consumption rates, safety stock levels and the lead time required for order fulfillment. Once the network is optimized based on deterministic assumptions, a Monte Carlo simulation will provide a sensitivity analysis for the operational network due to the stochastic nature of consumption, lead times, and events demanding network response under various scenarios. Alternative distribution networks will analyze various combinations of Earth resupply, moon resupply and on-orbit resupply nodes. Weight and volume restrictions of the moon and on-orbit supply nodes will be based on current maximum Earth launch capabilities. Transportation of consumables between nodes are relegated to theoretical autonomous orbital vehicles. **The capabilities and capacities of these vehicles can be adjusted within simulation to understand their impact on the network, and will be continuously updated throughout the project to match findings from the spacecraft design, autonomy and modularity subteams** (see §2.2.5).

As stated in §2.1, the fundamental cost heuristic is that of required Δv for various on-orbit operations. While launch costs can be tracked separately as part of the network establishment costs, any post-launch fuel expenditures required to achieve network orbits must be counted against the propellant carried by individual spacecraft, and thus must factor into the optimization. The Δv required to insert on an orbit post Earth launch and to maintain the orbit between network operations varies greatly by orbit. As an example, the soon to be launched James Webb Space Telescope (JWST), which is destined for a Sun-Earth L2 orbit, has a nominal Δv budget of 66.5 m/s for post launch maneuvers to achieve orbit insertion, although simulations indicate a likely value closer to 25 m/s (the difference being due to the range of possible injection states from the launch vehicle; Petersen et al., 2014). JWST has a planned stationkeeping budget of 2.43 m/s per year, meaning that the Δv used for orbit maintenance could exceed that of insertion after $\sim$10 years of operation (Dichmann et al., 2014). In contrast, the Transiting Exoplanet Survey Satellite (TESS), which is in a high-Earth, lunar-resonant orbit, had an orbital maneuver Δv allocation of 215 m/s (150 m/s nominal), but no required orbit maintenance (Dichmann et al., 2016).

On top of the orbital insertion and maintenance Δv requirements, there are multiple of other metrics that must be evaluated in order to gauge network utility. Chief among these are heuristics for how well Starlift spacecraft placement matches the goals listed in §2.1. One aspect of this is the average time and Δv required for a network element to intercept any spacecraft on any orbit within the relevant volume of space, weighted by the projected density of future spacecraft upon such orbits (i.e., exponentially decreasing with distance from the Earth and moon). Related to this is the level of network redundancy—the number of spacecraft available to perform a given task at any point in time. We must also be able to track the effective amount of mass (either volatiles or replacement parts) that network elements could transfer to other spacecraft (again with the same orbit density weighting). This is related to the required frequency of network resupply and the ratio of network elements acting as depots vs. active network components. While we have completed a preliminary analysis in defining the set of metrics that will be used in our network optimization cost function (see §2.2.3), **a key task in the first year of work will be to reevaluate our metric set to ensure that we are fully capturing network architecture costs and benefits**. Subsequent work will involve implementing tools to efficiently evaluate all metrics for a complete proposal architecture for use in large-scale optimization.

2.2.2. *Orbital Analysis.* The primary orbital design tasks for the proposed work include the identification of orbits relevant to the needs of a space logistics network, and the analysis of network operations on these orbits.

2.2.2.1. **Relevant Orbits.** Given the broad range of activities and behaviors desired from the proposed logistics network, we will need to employ a heterogeneous set of spacecraft orbits, and tools for the rapid analysis, design, and optimization of such orbits. As a first step, we must identify all potentially useful orbits for further investigation. An exhaustive search through all possible orbits in cislunar space is impossible, as there are literally an infinite number of possible orbits in this domain. However, such a search is not necessary, as **potentially useful orbits for a logistics network naturally fall into families with qualitatively similar behavior. Within these families, there will further be optimal individual orbits minimizing cost functions based on the metrics described in §2.2.1**. Here we will list the currently identified families of orbits to be investigated. Note, however, that this list is not necessarily final, and a task in the first year of work will be to refine and extend this group, as needed (see §2.4.1). We will make heavy use of Poincaré (recurrence) maps and numerical tools for the automated extraction of map topological structures (Schlei et al., 2014; Tricoche et al., 2011) in our analysis of orbit families and the identification of additional, useful orbits. Poincaré maps chart the intersection of the flow of a dynamical system with a lower-dimensional subspace (a Poincaré section) transverse to the flow. The map itself forms a discrete dynamical system, and structures within the map can be used to identify trajectory behavior in the original system, including periodic, quasi-periodic, and chaotic structures. Poincaré maps are used extensively for orbit design and analysis, and particularly for the analysis of 3-body systems (Kolemen et al., 2012; Koon et al., 2011). Modern analysis tools have extended the utility of these tools by adding the ability to automate the detection and extraction of topological structures of interest, which previously required human interpretation.

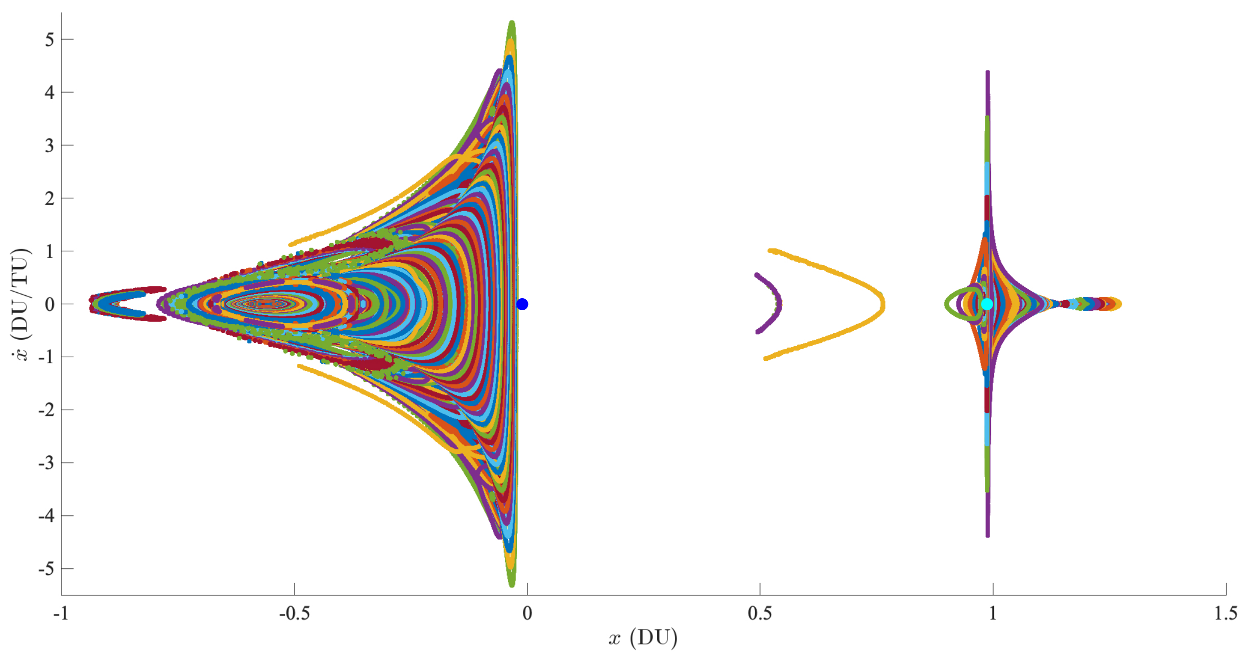


Figure 4. *Poincaré map for the Earth-Moon system. The abscissa represents the orbital position along the Earth-moon line in a rotating frame while the ordinate is the rotating frame orbital velocity in this direction, in canonical units. Points are plotted for zero crossings in the orthogonal direction when the orthogonal direction velocity is negative. Contours of different colors represent discrete initial conditions for a range of effective orbital energies (or equivalently Jacobi constants) ranging from minimum energy to escape energy. Closed curves indicate quasi-periodic structures. The blue and cyan circles near (0,0) and (1,0) represent the Earth and Moon, respectively. Chaotic regions have been cleared for legibility (cf. Fig. 5 of Schlei et al., 2014).*

Figure 4 shows an example of a combined Poincaré map for the Earth-moon system for a broad range of initial conditions. The map is constructed explicitly to exclude regions of chaos (which typically appear as dense groupings of individual points) and to accentuate periodic and quasi-periodic structures (which appear as fixed, isolated points or closed curves, respectively). The map represents the intersections of trajectories within this system with a subspace defined as zero position and velocity in the direction orthogonal to the Earth-moon line in a rotating frame defined by that line. All values are given in canonical distance and time units (DU and TU) such that 1 DU is the distance from the Earth to the moon and 2π TU is one lunar orbital period. Automated extraction of topological structures from maps of this type allows us to efficiently group whole families of quasi-periodic structures (which typically center on a fully periodic structure), exclude regions of chaos (which is not desired for long-term stable orbits), and to discover resonant structures, as described further, below.

The first, and largest, family of potential orbits are mid- to-high Earth orbits (MEO to HEO), ranging from below to above the geosynchronous band. As the vast majority of current space assets reside in this region, it is natural to expect a large fraction of any future space logistics network to be focused here. However, connections to the rest of the network, as well as the expectation that more and more spacecraft will operate further out in cislunar space in the future, require that we consider a broad range of orbital energies. Given its importance to both civilian and military infrastructure, the equatorial geosynchronous (geostationary) region deserves special attention. We will evaluate the utility of placing network spacecraft assets in the region between the geostationary band and the supersynchronous 'graveyard' regions where geostationary satellites are frequently retired. These supersynchronous network elements would have regular access to the entirety of geostationary space, without the need for the stationkeeping requirements imposed on geostationary satellites by Earth geopotential perturbations. Another intriguing possibility enabled by this spacecraft placement is the future potential to mine the graveyard orbits for useful materials.

While the final network architecture is likely to include multiple specialized structures like the supersynchronous orbits discussed above (and equivalent lunar orbits), it will also need utility orbits that traverse large regions of near-Earth space and can link isolated orbits to replenish network elements and intercept non-network spacecraft. Here, we can consider highly eccentric MEO and HEO orbits that are continuously perturbed such that they provide continuously variable coverage of the space they traverse. These can be thought of as complements to the well known frozen orbits such as the Molniya, Tundra, and QZSS orbits (Kishimoto et al., 2007), which are inclined specifically to have no periapse advance due to Earth oblateness. Because the goals of the network do not require any particular pattern of ground coverage, but do place a premium on rapid access to all of cislunar space, quasi-periodicity in network orbits is actually beneficial. As such, Earth geopotential effects including periapse advance and nodal regression, which are typically minimized (or tightly controlled, as in the case of sun-synchronous orbits), can become major features in network orbit design. Of course, these effects become significantly less pronounced with increasing orbit altitude, and so for near-lunar orbits, we must seek other sources of quasi-periodicity, such as those provided by the three body orbits described below.

Similarly, it is worth considering non-Keplerian orbits enabled by constant perturbations from other sources. The most well-known of these are the cylindrical geostationary orbits (Baig and McInnes, 2010; Forward, 1984), originally envisioned as enabled by the use of solar sails. These structures provide geosynchronous behavior outside of the equatorial plane, and

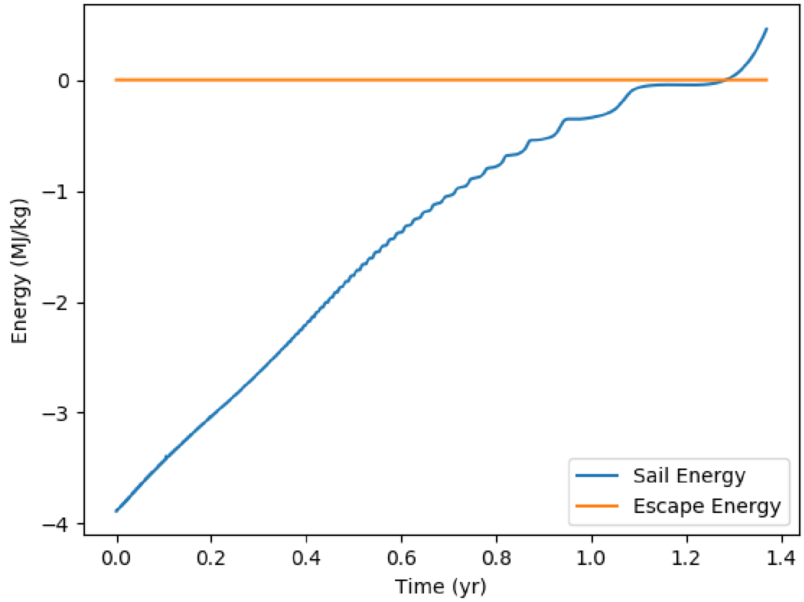


Figure 5. *Orbital energy of a sample low-thrust Earth escape trajectory as a function of time. From Savransky et al. (2019).*

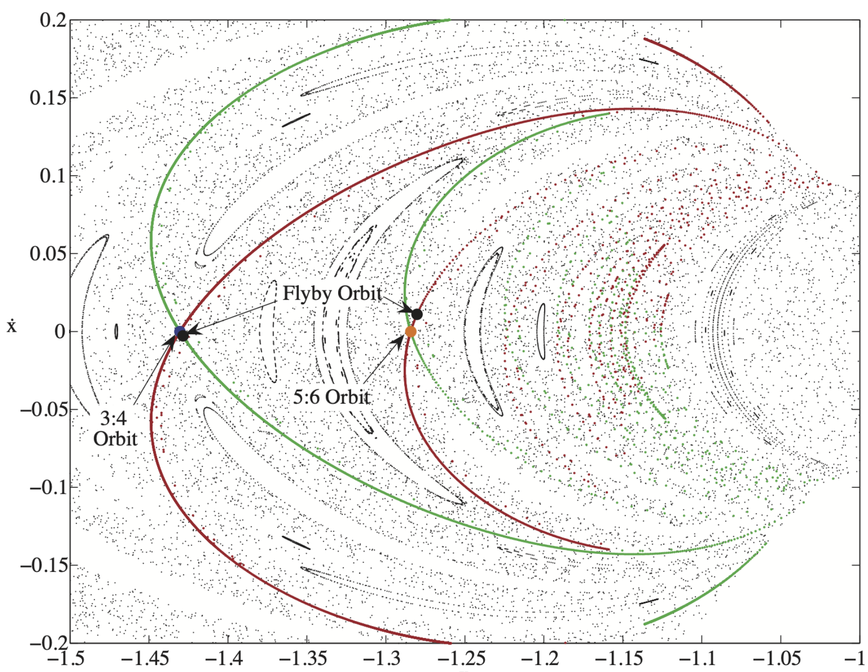


Figure 6. *Flyby trajectory and stable (green) and unstable (red) manifolds of a 3:4 resonant orbit overlaid on a Poincaré section for the 3-body problem. The flyby trajectory nearly follows the invariant manifolds, transitioning between pairs of resonances. Adapted from Anderson (2005).*

may be potentially useful for network hub placement. At the same time, it has been shown that solar sail solutions exist for consistently changing orbital energy (i.e., spiraling in and out of from low-Earth orbits). Figure 5 shows an example of such an outward trajectory based on a simple energy maximization control law (Coverstone and Prussing, 2003). Network elements could potentially traverse trajectories of this type in order to cover the entire range of the space in which the network would operate. These same trajectories could be implemented with high-Isp, low thrust electric propulsion, which, given the relatively low technology readiness of solar sails, will be our primary focus.

Another interesting subset of HEO are the lunar resonant orbits (Gangestad et al., 2013), sometimes referred to as P/n orbits, previously demonstrated by the Arcus mission concept (Plice et al., 2018) and TESS (Dichmann et al., 2016). These orbits (and especially $P/2$, used by TESS and $P/3$, adapted by IBEX post launch (McComas et al., 2012)) provide incredible long-term stability and frequent Earth proximity along with the availability of the moon for frequent potential flybys, which can enable incredibly cheap (in terms of Δv) and efficient re-positioning and intercept opportunities. Flybys in three-body systems have been extensively studied, primarily in the context of Jovian and Saturnian moon tour trajectories (Anderson, 2005; Koon et al., 2011; Marsden and Ross, 2006, etc.). Analysis of the invariant manifolds of unstable resonant orbits (Figure 6) allows for the identification of flyby trajectories leading to extremely low-thrust, low Δv transfers within the three-body system, which can be exploited for rapid, efficient repositioning of network elements.

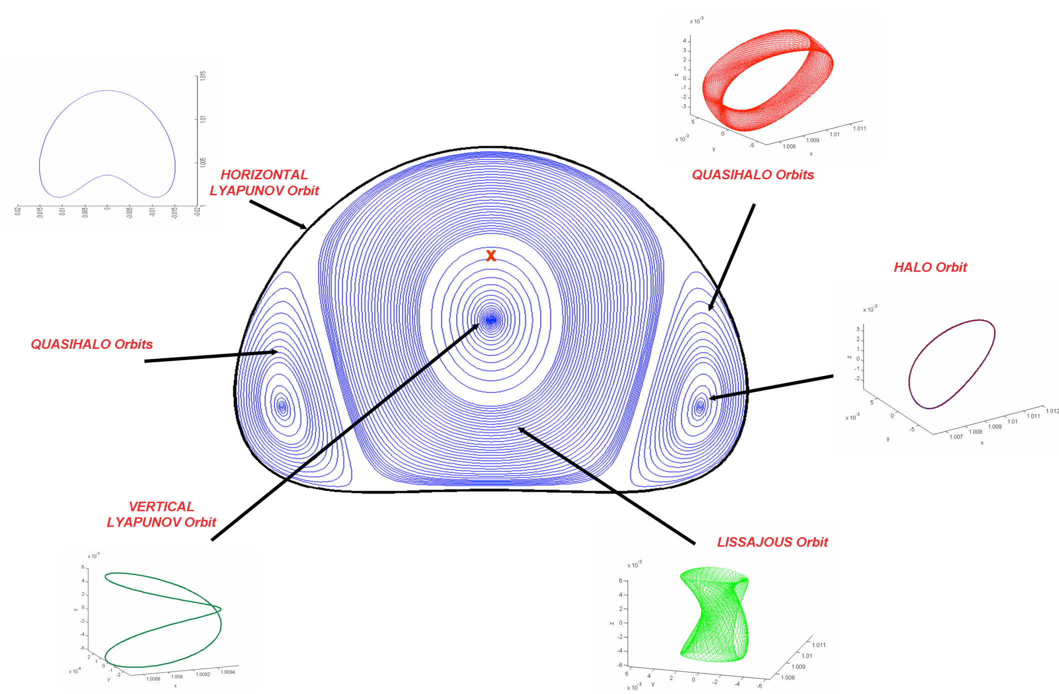


Figure 7. *The periodic and quasi-periodic orbits about the second co-linear Lagrange point (L2) of a three-body system, in the Poincaré section defined by crossings of the orbital plane of the primary bodies. Adapted from Kolemen and Kasdin (2012).*

Next are the periodic and quasi-periodic structures about the co-linear Lagrange points of the Earth-Moon system. Figure 7 shows a Poincaré map encoding all such structures for L2 (Kolemen and Kasdin, 2012), and similar structures exist for the other co-linear points (L1 and L3). Although we can find stable orbits about the off-axis Lagrange points (L4 and L5), the high energy costs of insertion into these orbits make them somewhat less attractive, and so they will be a secondary focus of the initial investigation. The Earth-Moon system mass ratio supports the existence of stable structures about the colinear points within the context of the restricted three-body problem, which map to real orbits that are long-term stabilizable with minimal fuel expenditures. Of particular interest are the halo and Lyapounov structures, which provide fully periodic solutions with significant components out-of the moon's orbital plane, and the associated families of quasi-halo and Lissajous quasi-periodic orbits.

As previously mentioned, the quasi-periodic orbits are actually significantly attractive for logistics network spacecraft, as they represent stable structures that continuously permute the geometries of spacecraft upon them. This translates to having spacecraft acquire different viewing geometries of cislunar space at each orbital period. For a network of heterogeneous assets, this represents the highest probability of having a relevant asset positioned in a convenient location for utilization at any given time. We have also previously demonstrated that spacecraft randomly phased on Lissajous orbits will have frequent close encounter opportunities (Savransky et al., 2019; Soto et al., 2019a,b), which may be important in cases where network assets need to exchange parts or consumables.

For the Earth-Moon system, there has been recent interest in periodic structures about the Earth-Moon L1 and L2 points, including distant retrograde lunar orbits (DRO; Capdevila et al., 2014) and near-rectilinear halo orbits (NRHO; Lee, 2019) that have been evaluated for the Lunar Gateway. The specific orbits that are optimal for Gateway are likely to also be incredibly useful in the context of a logistics network, but represent only a small fraction of useful three-body structures that can be exploited in network design and operation. Both the DRO and NRHO (and similar orbits) have multiple important features relevant to the proposed work. L1 orbits provide a constant view of both the Earth and Moon, thereby serving as ideal communications relays and monitoring station orbits. Large L2 orbits, on the other hand, can enable communications with the far side of the moon, or spacecraft in lunar orbit when they are occulted by the moon. In fact, the original development of the halo orbit was motivated by exactly these considerations (Farquhar, 1967).

We will develop a generalized framework for evaluating spacecraft operations (both intercept and stationkeeping) on orbits of all of the types described above, leveraging existing and open source tools including efficient, high-order numerical propagation in full force models of the spacecraft environment (Hughes et al., 2017; Tamayo et al., 2019). We will employ optimal control techniques in simulating spacecraft operations, and, in the case of low-thrust transfers, will utilize homotopic indirect methods, as described in Jiang et al. (2012), to find minimum-fuel solutions. **We will also develop control techniques uniquely suited for each orbit type, explicitly evaluating the use of lunar flybys for on-demand retargeting operations.**

2.2.2.2. **Network Operations on Orbit.** The fundamental orbital maneuver associated with Starlift operations will be intercept and rendezvous. We can split this into two parts, first solving the transfer problem between a network spacecraft's orbit and the target orbit, and then considering the proximity operations between the interceptor and target. The transfer problem is a case of the well known Lambert's problem: the boundary value problem of finding a conic section (two-body orbit) about a central body connecting two points in space (and time). While Lambert's problem is, of course, an idealization, it provides an incredibly useful starting point in identifying network elements for which a given transfer is feasible, and an initial approximation of the required transfer time and Δv. Figure 8 shows a classification of all possible solutions for a general Lambert problem joining points P_1 and P_2 with an orbit section about central body F. Orbits are split into classes of closed and open orbits, following the nomenclature established in Kaplan (1976). It is important to note that there are initial velocity vectors that fundamentally yield no solution to this system.

The transfer time is directly computable as a function of the transfer trajectory's semi-major axis (a) as:

$$t = \frac{1}{\sqrt{\mu}} \int_{s-c}^{s} \frac{r}{\sqrt{2r - r^2/a}} \, \mathrm{d}r \, ,$$

where c is the distance between P_1 and P_2, and s is half of the perimeter of the triangle FP_1P_2. An enormous wealth of literature exists on efficient solutions for Lambert's problem (e.g., Battin and Vaughan, 1984; Correas, 1976; Prussing, 2000; Sun, 1979; Sun, 1981, etc.). Modern work on this problem has also focused on finding global existence proofs for trajectory solutions and treating perturbations in the system (Albouy and Urena, 2020; Woollands et al., 2017). **We will leverage this existing body of work, along with computational tools previously implemented by members of the proposing team, in order to create tools for the rapid evaluation of Lambert solutions for arbitrary transfers of network elements, that will serve as initial guesses for trajectories to be evaluated within a full force model.**

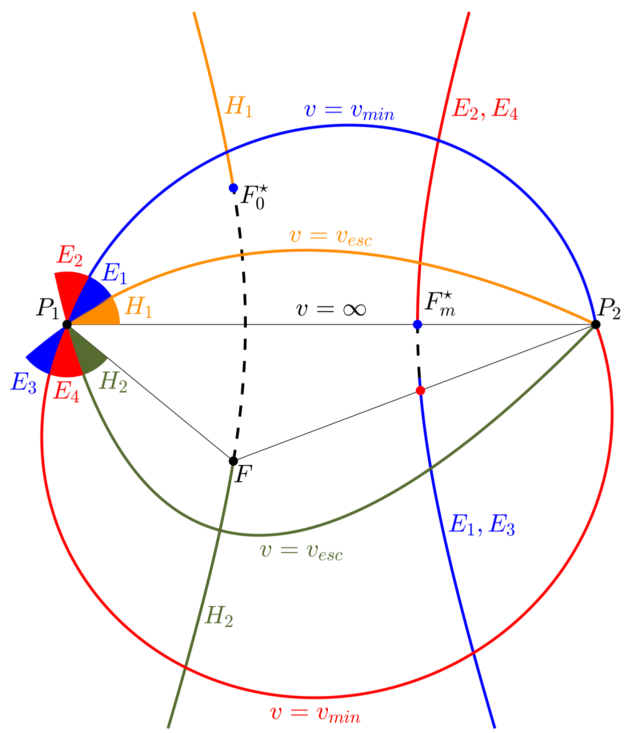


FIGURE 8. *Classification of possible transfers in Lambert's problem joining points P_1 and P_2 via two-body orbits about attractive center F. $E1 - E4$ represent sections of elliptical orbits, $H1$ and $H2$ are hyperbolic transfers, and the two v_{esc} lines are the two possible parabolic trajectories. The hyperbolae intersecting the central triangle represent possible locations for the vacant focus of the transfer orbit. Shaded regions correspond to the loci of all possible initial velocities of transfer orbits of each type, and the two unshaded regions about P_1 represent initial velocity vectors in which no transfer solution exists.*

For the evaluation of network task scheduling, we will leverage existing work by members of the team on a closely related problem: the dynamic scheduling of observations of space assets. This work, as detailed in Savransky et al. (2010), Savransky et al. (2017), and Savransky and Garrett (2015) deals with the optimal allocation of integration time on multi-use space observatories. Just as the problem considered here, this task requires us to solve dynamically evolving graph problems with time-dependent costs and constraints, coupled with multiple possible actions at any given time, each with different potential reward pay-offs. As such, the problem represents an online, dynamic, time-windowed, prize-collecting TSP: exactly the class of problem we wish to analyze for Starlift.

Of particular interest are the results of Savransky et al. (2017), later expanded in Keithly et al. (2020), which demonstrates that a non-linear time-allocation optimization can be efficiently solved via sequential least-squares quadratic programming (SLSQP; Kraft, 1994) by first solving a reduced problem that maps to a binary-integer linear program (Williams, 2009). This problem type, while formally NP-complete (Karp, 1972), is fully tractable for a limited space of possible options (where, given modern hardware capabilities, 'limited' means on the order of thousands) using standard branch and cut methods (Lougee-Heimer, 2003). **This precursor work is directly applicable to Starlift logistics operations, where multiple network elements may be available to respond to multiple events of interest at any given time, where each event has varying levels of priority, and varying benefits and penalties as a function of response time.** Our work will adapt existing tools for solutions of this problem class to directly service the Starlift goals.

2.2.3. *Network Optimization.* There are two levels of network optimization that must be considered: network design and network operation. The latter assumes a fixed proposal solution to the former and attempts to optimally allocate existing network resources. As such, these two optimizations can be implemented in a nested structured, with the outer optimization loop modifying the network design, while the inner loop attempts to minimize operational cost functions based on the metrics described in §2.2.1. As discussed in §2.1, a large body of optimization work already exists for evaluating the inner optimization loop. We will specifically focus on MILP, SLSQP, and constraint programming methods for network resource allocation optimization. In this work, we will make heavy use of existing and open source tools, including Google's OR tools (Perron and Furnon, 2019), the Common Optimization INterface for Operations Research (COIN; Lougee-Heimer, 2003), and the parallel global multiobjective optimization framework (PAGMO; Biscani and Izzo, 2020).

For the outer loop, there is less formal theory to guide us, and we are forced to rely on metaheuristic optimization approaches. In particular, we will focus on methods that have historically produced the best results in relevant fields: Genetic Algorithms (GA; Mitchell, 1998) and Particle Swarm Optimization (PSO; Kennedy and Eberhart, 1995). Evolutionary algorithms are particularly attractive for this type of problem as their encoding structure is well suited to network graph representation. **We will develop encoding techniques to directly represent Starlift network elements and their orbits**. This encoding will be paired with well-established and widely available evolutionary computing tools, as well as existing tools previously developed by members of the proposing team.

Due to the number of inherent tradeoffs in the network design, we do not believe that there will be a single, globally optimal Starlift design and operations concept. Rather, **our goal is to produce the Pareto frontier of possible Starlift implementations over the multidimensional design space of metrics described in §2.2.1.**

2.2.4. *Spacecraft Design.* Network optimization must proceed under the constraints of the vehicle capability, which makes it important to consider the the spacecraft design. While there are many useful advances (in the context of network operations) that can be made throughout all spacecraft subsystems, we will focus particularly on propulsion and control (discussed further in §2.2.5), as we believe these elements will have the greatest impacts on network performance.

2.2.4.1. **Propulsion Systems.** Like terrestrial networks, Starlift will be most capable when comprised of a fleet of diverse vehicles, each with complimentary maneuverability and roles.

One of the most important free parameters in the system definition is the selection and distribution of propulsion systems across the fleet's vehicles. The on-board propulsion system will determine a vehicle's maneuvering capabilities and longevity. Both well-established and novel propulsion systems will be evaluated in the Starlift design tradespace. A range of both high-Isp electric and high-thrust chemical systems will be catalogued and incorporated in the network optimization. **The selection of both the thruster hardware and propellant will be incorporated in the end-to-end optimization problem.**

Factors such as on-orbit storability of propellant, modularity of propulsion system, and propulsion system lifetime will be considered. A unique feature of the Starlift architecture will be the constraint that all network nodes remain connected by resource chains. This guideline will maximize utility of resources and will keep network assets intact. **The ability to maneuver between nodes and maintain positive propellant margins across the network will be a key strategic advantage enabled by Starlift.**

Table 1. *Sampling of Propulsion Systems and Metrics for Optimization Studies*

Mode	**Type**	**Propel-lants**	**Storage Density**	**SWAP Reference**	**Thrust/ Power**	**Isp (s)**	**Life-time (hours)**	**TRL**
Electric	Hall	Xe, Kr	...	SPT-140, BHT-XX, X3	50 mN/kW	1500-2000	10^4	9
Electric	Field emission	Ionic liquid	1-5 g/cm^3	Accion Systems TILE	...	1000-5000	10^3	8-9
		In	7.3 g/cm^3	Enpulsion IFM-XX				
Electric	Ion engine	Xe	...	NEXT	35 mN/kW	3000-5000	10^4	9
Chemical	Mono-prop	N2H4, MMH, HAN	...	MOOG, Aerojet	0.1-100 N	200-300	10^0-10^2	9
Hybrid	Electro-spray/ Mono	HAN-based, others	...	Accion Systems		...	10^0-10^1	6
Hybrid	Mono/ Bi-prop	MMH+ NTO	...	MOOG, Aerojet	0.1-100 N	200-350	10^0-10^2	9
Hybrid	Electrol-ysis	H2O	1 g/cm^3	Tethers Unlimited	0.1-10 N	200-400	10^0-10^2	8-9

Table 1 gives a sampling of the propulsion system architectures and system-relevant parameters that will be considered in the Starlift optimization analysis. Propulsion systems demonstrated at TRL6 or above will be considered in this work. The restriction to high TRL systems will allow for near-term implementation of an on-orbit system.

Beyond contributing to the design optimization, the propulsion focus of this effort will include trade studies with network architecture implications. The goal to design a network of modular and serviceable assets must permeate all of the subsystems, including propulsion.

In keeping with this vision, propulsion solutions will be evaluated for their **compatibility with detachment and servicing**. For a SmallSat platform, this may mean detachment and replacement of the entire propulsion assembly, with fueled, replacement systems readily available on orbit (Figure 9). For larger, cargo delivery vehicles, this would mean integrating the propulsion system with a chassis, detachable from the cargo load. **Guided by these system-level goals, the propulsion system will be selected and optimized not based on intrinsic specifications, but on its ability to support continuous resource flow across the Starlift network.**

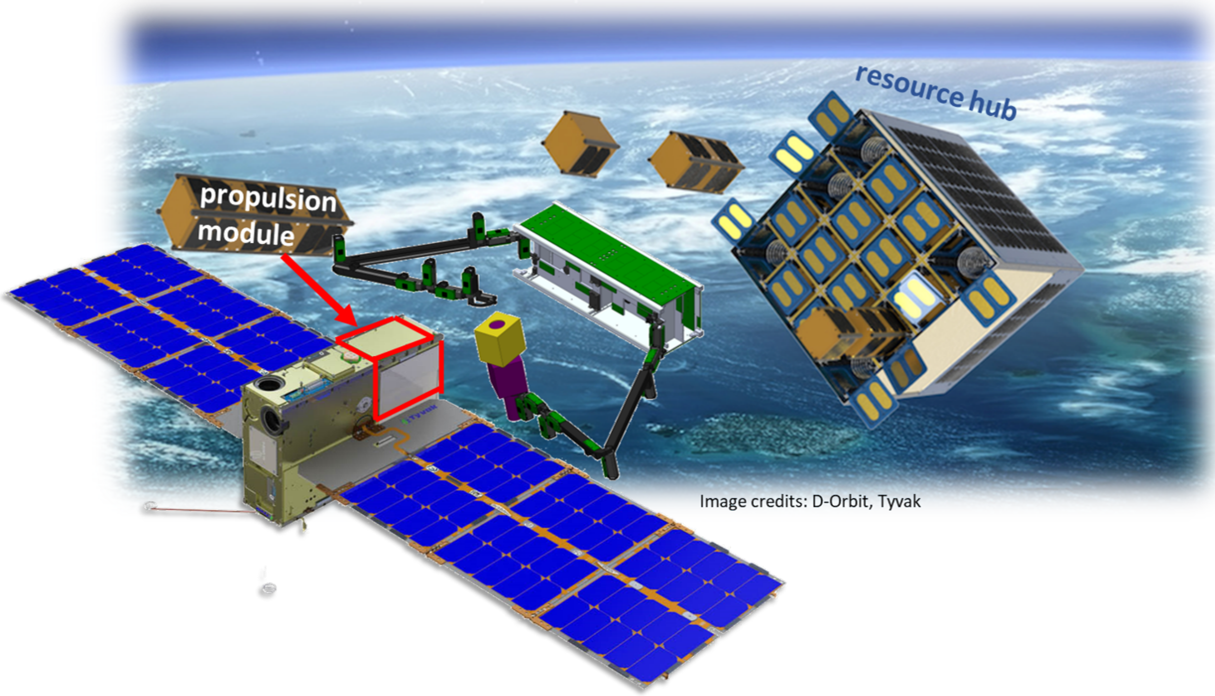
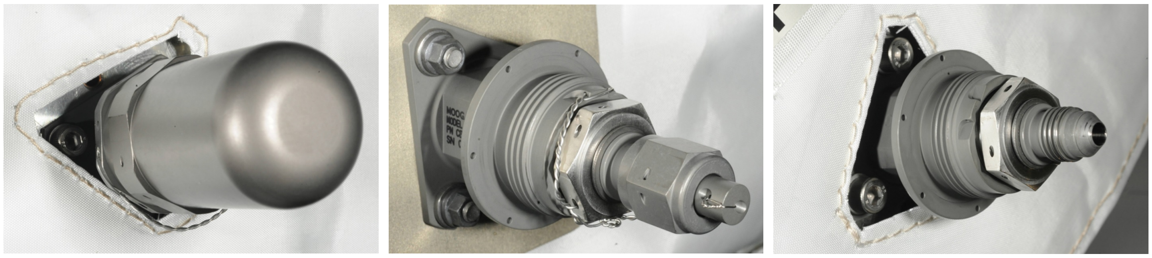


Figure 9. *Propulsion System Modularity*

2.2.5. *Modularity and Autonomy.* Following recent demonstrations of remote-controlled robotic refueling on orbit, research enhancing autonomy has the potential for high payoffs in the context of the high cost of crewed space operations and increased responsiveness of space systems to dynamic situations. In order to define the building blocks of the Starlift network elements, **we will investigate the efficacy of two recently developed methodologies: optimal whiplash compensation including novel input trajectory shaping, and deterministic artificial intelligence utilizing the same input trajectories. We will furthermore validate these approaches with free-floating spacecraft simulator labs.**

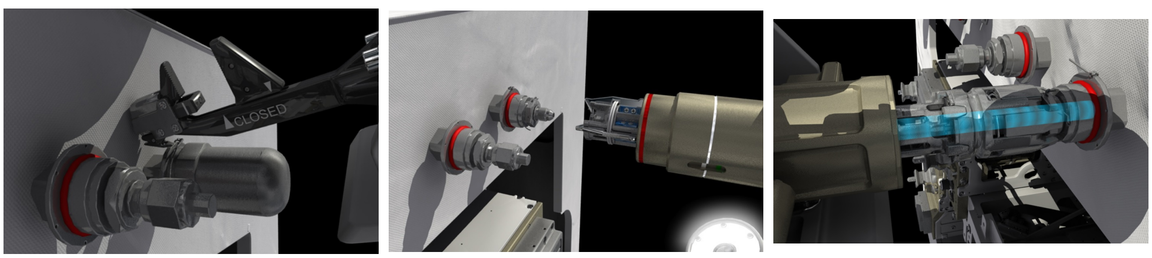
In addition to being remote controlled, a sub-optimal solution to small, flexible spacecraft for on-orbit robotic refueling uses hardware with sufficient material stiffness to avoid deleterious effects of controls-structural interaction, which was well studied at the end of the previous century. On the contrary, lightweight (flexible, non-stiff) small space robots must contend with a system's structural modes. A lightweight refueling robotic spacecraft must intercept and rendezvous with the target spacecraft, grip the potentially tumbling spacecraft



(a) (b) (c)

Figure 10. *Disparate satellite fuel valves illustrating a challenging aspect of refueling an arbitrary spacecraft on-orbit (a) tertiary cap with "lock wire" visible underneath (b) safety cap/actuation nut with securing lock wire, and (c) exposed fuel valve. Photos taken from NASA Goddard public website: https://nexis.gsfc.nasa.gov/rrm_refueling_task.html*

at some point, and then connect apparatus (assembly parts, connection of refueling hose, etc., depicted in Figures 10 and 11).

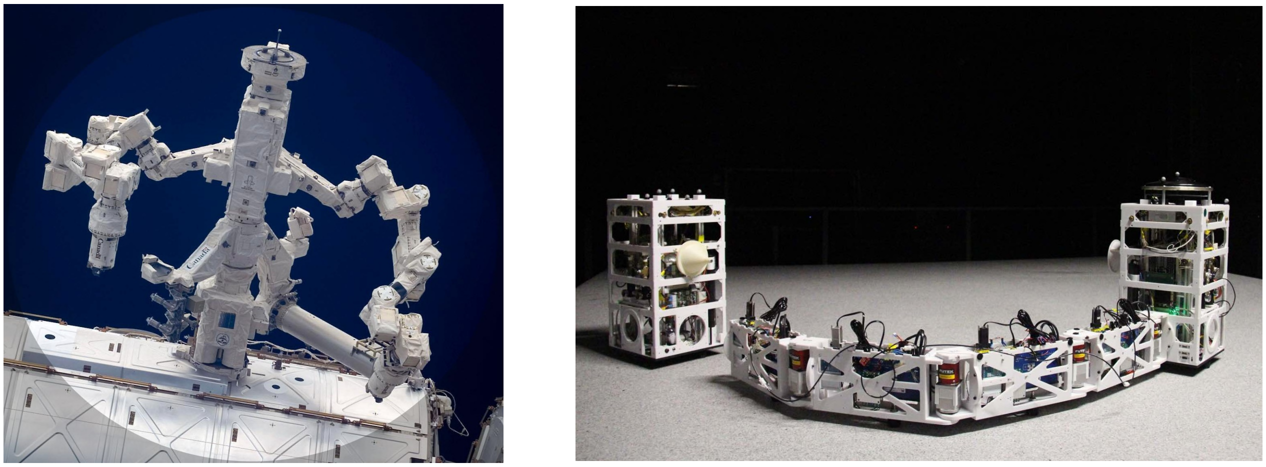


(a) (b) (c)

Figure 11. *Operations required to connect to various satellite fuel valves illustrating a challenging aspect of refueling an arbitrary spacecraft on-orbit (a) start with wire cutting; (b) connect nozzle tool with hose and transfer fuel; (c) leave behind quick-disconnect when refueling complete (for future refueling operations).Photos taken from NASA Goddard public website: https://nexis.gsfc.nasa.gov/rrm_refueling_task.html*

Following successful intercept and rendezvous, gripping and assembly/refueling operations present additional opportunities for mission failure if the flexible spacecraft's modal oscillations result in (for example) missing the spacecraft while attempting to grip, failing to connect to the refueling valve, or seeking to install a component at a slightly incorrect point due to modal displacement. New discoveries to enhance intercept and rendezvous in addition to refueling valve connection performed on orbit will be validated on hardware laboratory mimics operating on planar air bearing tables at the Naval Postgraduate School (depicted in Figures 12 and 2; see §2.4 and §4).

Classical methods to maneuver to intercept, rendezvous and grip targeted spacecraft begin with state feedback and gain compensation, adding second-order filters to compensate for disturbance of resonances and anti-resonances associate with the so-called "free-free" modes of vibration. These classical methods are used as benchmarks for comparison to modern and novel approaches. Modern methods initially optimized the classical forms and proceeded to develop open-loop optimal methods like "input-shaping" where the commanded motion



(A) (B)

Figure 12. *University hardware laboratory parallel to orbital experimentation. (A) NASA's remote-controlled robotic refueling mission on-orbit. Photo taken from Kremer (2012) "Robotics Refueling Research" (B) U.S. Naval Postgraduate School's autonomous robotic laboratory free-floating simulator on planar air bearing table. Photo taken from nps.edu public website*

trajectory is shaped to counter the disturbing vibrations by time-delaying the commanded state trajectory in an open-loop topology. **Stemming from Pontryagin's method for constrained, nonlinear optimization, recently proposed whiplash compensation inspires continued focus on trajectory shaping, but remains limited by its open-loop nature. The Office of Naval Research's consortium on robotics just developed a novel approach integrating all of the most successful approaches: input trajectory shaping, open loop and closed loop optimization, and nonlinear adaptive and learning methods for time-variable masses and mass moments in addition to online external-disturbance estimation and rejection. This method is called deterministic artificial intelligence (D.A.I.).**

2.2.5.1. **Modeling.** Modeling space robots from first principles articulated by Chasles (1830) begins with application of Newton's second law of motion (Newton, 1687) for translation and Euler's moment equations for rotation of a rigid body (Euler, 1776). Utilizing the finite element method, the robot may be discretized into a chosen number of nodes for application of these first principles establishing a system of differential equations whose order is driven by the chosen number of nodes.

2.2.5.2. **Classical guidance and control methods.** Traditionally, the nonlinear coupled motion terms in both translation and rotation equations are neglected, linearized, or simplified by assumptions, permitting classical treatment of linear, time-invariant methods. The treatment begins with gain stabilization through feedback and may be augmented with frequency-dependent filtering to shape the frequency-response of the robotic control attempting to negate the deleterious effects of structural flexibility (Wie, 1998).

2.2.5.3. **Modern guidance and control methods.** The term "modern" is often used to either indicate problem formulation in space-variable form also called "state space" form, or alternatively deterministic optimization (as opposed to stochastic optimization commonplace

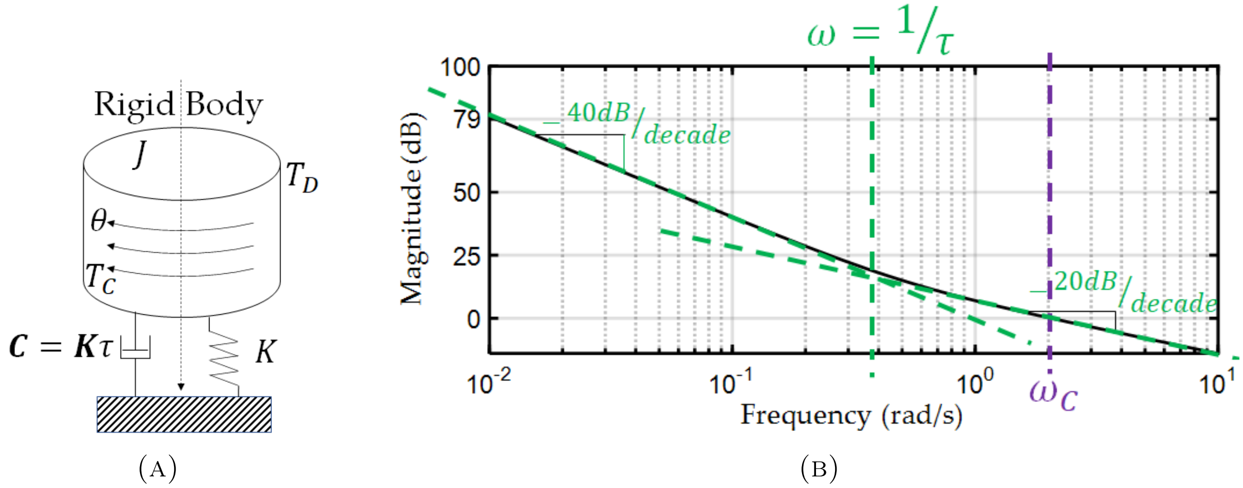


FIGURE 13. *Modeling and analysis of rigid bodies with respect to frequencies (A) modeling rigid bodies as systems with springs, masses (and mass moments of inertia), and dampers. (B) Frequency response analysis of the rigid body portion of the flexible space robot.*

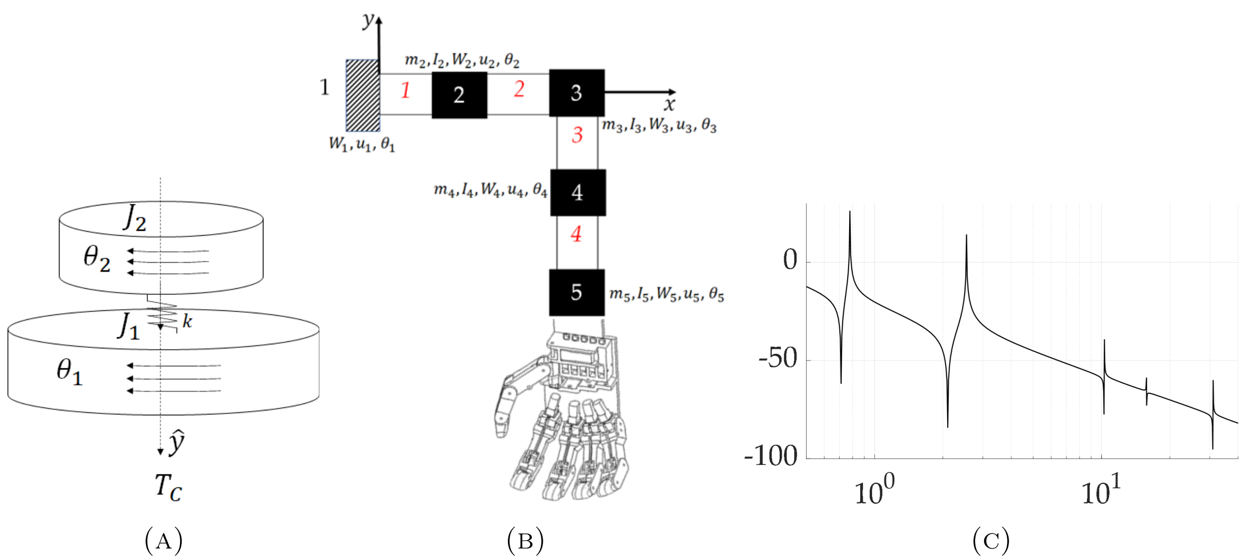


FIGURE 14. *Modeling and analysis of flexible space robots with respect to frequencies (A) modeling flexible bodies as systems with springs, masses (and mass moments of inertia), and potentially dampers. (B) Robotic arm attached to the spacecraft hub modeled by the finite element method. (C) Frequency response analysis of the flexible space robot.*

in classical methods). Modern methods, even optimal instantiations ubiquitously impose a specified limited form of the robotic control equation. Typically, the control is forced to be a negative feedback or errors, where gains associated with each error are discerned to optimize some specified performance function. One very common form of a modern optimal feedback controller is the linear quadratic regulator (amongst others including robust L1 adaptive control and nonlinear adaptive control; Åström and Wittenmark, 1994; Slotine, Li, et al., 1991). An alternative modern method eliminated the mandatory use of feedback to discern a feedforward (open loop) approach to control flexible robotic systems where the

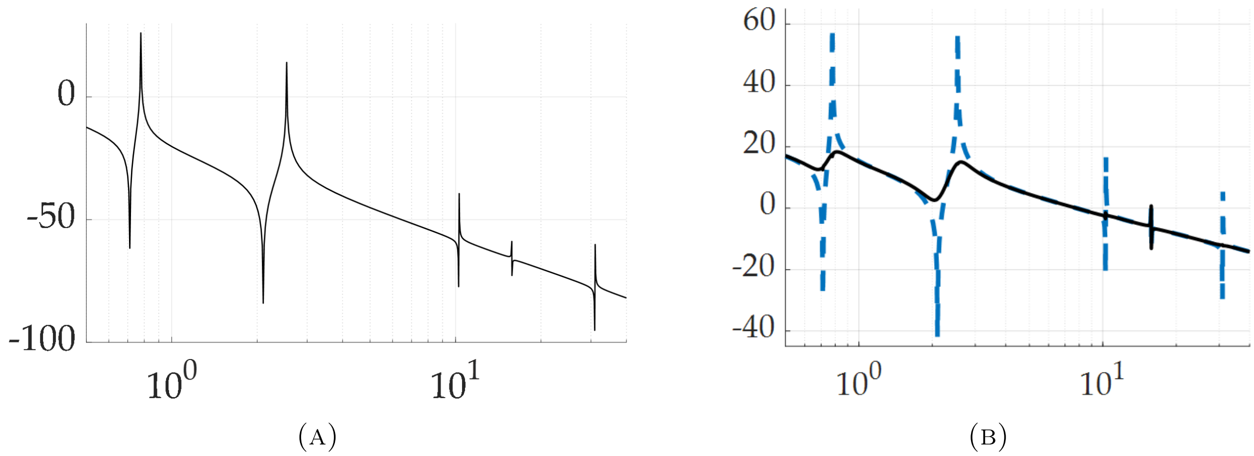


Figure 15. *(a) Modeling and analysis (frequency response magnitude curve) of flexible robot arm attached to rigid spacecraft; (b) Frequency response of classical approach: 1) gain stabilize, then 2) add structural filters to reduce deleterious effects of modal anti-resonances and resonances. The dashed blue line is the gain-compensated flexible space robot's frequency response while the solid black line indicates the addition of classical structural filters.*

deleterious responses of flexible, multi-body motion are codified in a method called input shaping (Singhose et al., 1997) where anticipated strain energy is distributed with time to create a time-delayed control approach for flexible space robotics. The methods (feedforward and feedback) have also been combined.

2.2.5.4. **Recently proposed guidance and control methods.** Post-modern methods eliminate the assertion of the presumed negative feedback form of the control with variable gains. The full nonlinear, coupled governing differential equations may be expressed in vector-matrix form establishing dynamic constraints to form a time-varying, nonlinear Hamiltonian system that may be optimized in accordance with the methods of Pontryagin (1962). **The result of this approach applied to highly flexible space robotics is the recently revealed whiplash compensation and the surprising result that leads to initially opposite-direction commands to counter the deleterious effects of flexibility.** The method was developed on a university bench board free-floating space robot simulator depicted in Figure 2b representing such high-end missions as the NASA/Maxar robotic assembly mission (depicted in Figure 2a) currently under construction. Whiplash compensation as proposed is an open-loop optimal approach (akin to input shaping) focused on shaping the control to optimize rotational motion of highly flexible space robots. The unexpected counter-steering result inspired renewed focus on shaping desired trajectories in the context of optimized control, leading to the just proposed deterministic artificial intelligence stemming from the ONR-developments for underwater robotics.

2.2.5.5. **Potential guidance and control methods.** The open loop optimal shaping of the commanded trajectory in addition to the unexpected results of nonlinear constrained optimization embodied in whiplash compensation inspire study of alternative trajectory shaping options. This proposal includes sinusoidal trajectory shaping options to provide methods to steer the control signal's frequency content away from problematic frequencies. **This investigation is inspired by the very recently proposed deterministic artificial intelligence method utilizing sinusoidal shaped input trajectories.** Especially since the newly proposed method is parameterized in terms of time-variant mass and mass moment of inertia, the potential for fruitful application to autonomous space robotics seems high since the application requires operations amidst sudden increases and decreases in mass and mass moments. This potential is proposed for follow-on research (following whiplash compensation) permitting deterministic artificial intelligence to be applied to highly flexible space robotics.

2.2.5.6. **Research plan for on-orbit refueling and assembly using flexible space robotics.** To meet the research objectives, recently proposed optimal whiplash compensation of flexible space robotics will be critically evaluated in validating experiments on the flexible spacecraft robotic simulator used to develop the method. This method results from utilization of Pontryagin's analytic method of constrained cost minimization and leads to the unexpected results of initially commanding opposite direction motion to optimally control very lightweight, highly flexible space robotic arms. The outputs of Pontryagin's analysis include the optimal control, but also the optimal input trajectory useful for (later) autonomous trajectory shaping (Sands, 2019). The initial opposite direction motion essentially loads an opposing amount of the deleterious disturbing strain energy initially, while the strain is gradually released resulting in exactly meeting the end conditions with zero residual vibration and rate. The initial theoretical development included in the cited manuscript does not include analysis of variations to reveal robustness, therefore that is an initial task. Subsequently, analysis of whiplash input shaping should be directly compared to optimal input shaping (arguably a state-of-the-art technique). Particular attention will be paid to modifying the nature of the proposed optimal open-loop method in the presence of sensors in a closed-loop system. Additional emphasis will be placed on the effectiveness of the trajectory shaping implications, since they strongly hint towards the potential of the subsequent development of deterministic artificial intelligence, which seems well-designed to autonomously monitor and react to time-varying masses (sometimes suddenly) associated with grasping a targeted satellite to be refueled or assembled. Direct comparisons will also be made to classical structural filtering, which will be declared the benchmark for relative evaluations. Thus, this first proposed work expands whiplash compensation and directly compares it to optimal input shaping and classical structural filtering.

We will develop Deterministic Artificial Intelligence methods for highly flexible space robots. D.A.I. has only recently been developed (in 2020) by ONR for rigid autonomous underwater vehicles (UUVs) and in 2021 by Cornell for DC motor actuators. The Office of Naval Research's consortium on robotics funded development of D.A.I. for UUV applications leading to the publishing journal's top cited paper in the past 12 months (Sands, 2020). The newly proposed method was subsequently adapted at Cornell to DC motor actuators leading to the work in Sands (2021), already the publishing journal's eighth most cited paper in the last six months. The method mandates explicit (autonomous) trajectory design leveraging the former investigation of constrained nonlinear optimal methods leading to whiplash compensation. As instantiated in the two cited references, sinusoidal trajectory generation is utilized hinting at an additional alternative paradigm for flexible robotic control: rather than utilizing broadband autonomous trajectories that require dealing with excited flexible modes, use sinusoidal trajectories designed such that the single excitation frequency and its harmonics are firstly nowhere near structural natural frequencies, but secondly autonomously adjustable to account for grasping spacecraft of unknown mass and mass moment of inertia. D.A.I. parameterizes the problem with time-varying mass and mass moments as state variables rather than parameters. With this parameterization optimal feedforward and (2-norm) optimal feedback eliminate the need for tuning, while input trajectory shaping is driven by maximum actuator capabilities and the location of flexible modes, eliminating under-actuated (or actuator saturation) scenarios. **All the methods discussed here will also be validated on pre-existing university space labs, modified for the purposed of this investigation.**

The nominal process to be followed in all investigations includes analysis first, then verification and extensive study in simulation lastly followed by experimental validation to support petitions for on-orbit demonstrations.

Following successful laboratory validation, transition planning is proposed including a potential spaceflight demonstration through the Space Test Program (STP). The proposing team includes members very familiar with the space experiments review board(s) process (SERB) including former members of the STP. Seeking US Space Force sponsorship (requisite for SERB submission) will enhance transition planning. Years 4-5 plans include advocacy and pursuit of spaceflight in addition to operational development including demonstration of refueling and assembly operations by very small robotic spacecraft where the targeted spacecraft has interesting connectivity requirements (e.g., refueling valves, assembling grip points, etc.). Immediate integration into USSF space wargames is envisioned for each new development through frequent coordination with the USSF technical director for wargaming.

2.3. **Proposing Team Capabilities and Roles. PI Savransky** is an expert in astrodynamics and the design and analysis of space missions. Savransky is currently an associate professor in the Sibley School of Mechanical and Aerospace Engineering at Cornell University, director of graduate studies for Theoretical and Applied Mechanics, and leads the Space Imaging and Optical Systems Laboratory (SIOSlab). He has participated in numerous mission concept studies, formulation activities, and active mission support for a broad range of space missions. Currently, he serves as a co-I for the science investigation team for NASA's Nancy Grace Roman Space Telescope Coronagraphic Instrument, and lead systems engineer for the Gemini Planet Imager 2.0 project (an NSF-funded effort to modernize and recommission one of the world's most powerful ground-based exoplanet imaging instruments). Savransky is also the recipient of a NASA Early Career Faculty award. Savransky will serve as principal investigator for all research activities and be the final authority on all technical and management questions related to the project, in consultation with all co-Is. He will personally supervise one of the associated graduate students in each year of work in carrying out the orbital design and analysis work, and assisting with the network optimization studies, as detailed above and in §2.4. Savransky will also co-advise one or more of the other affiliated students and multiple summer students throughout the course of the work.

Co-I Peck is the Stephen J. Fujikawa Professor of Astronautics at Cornell University, where his research and teaching focuses on Aerospace Engineering and Systems Engineering. At Cornell, he directs the New York State Space Grant Consortium and has filled various administrative roles, including Director of Graduate Studies for Aerospace Engineering. From late 2011 through early 2014, Peck served as NASA's Chief Technologist, reporting directly to the NASA Administrator. In that capacity, he served as the primary advisor to the NASA Administrator on matters of technology-investment strategy, roadmapping, prioritization, partnerships, intellectual property, and commercialization. His work with NASA since 2011 has included collaborations in space-policy development with the executive and legislative branches of the U.S. government. His areas of academic expertise include next-generation space-system architectures, mission design, and GNC. His background represents a breadth of leadership experience in space technology across academia, the aerospace industry, and DoD. It extends from early-stage theoretical work through flight hardware and mission operations. His research has been funded by DARPA, AFOSR, NASA, and prime contractors. Peck currently holds a TS clearance and was a member of the Air Force Scientific Advisory Board in 2015-2016. He also has worked as a consultant in advanced technology and business development for spacecraft contractors including Johns Hopkins Applied Physics Lab, SpaceX, Northrop Grumman, and Lockheed Martin. In addition to this ongoing consulting work, he has over 10 years' experience in the aerospace industry, primarily at Boeing Satellite Systems (the former Hughes Space and Communications), where his responsibilities included commercial and government spacecraft systems engineering as well as mission operations for several spacecraft. At Honeywell, he served as Principal Fellow, the most senior engineering position in the company, focusing on technology strategy, new business, and special programs. He has 19 patents in space technology that stem from this work. Recognized for his teaching and mentorship at Cornell, Peck created and directed the Space Systems Design Studio, in which many students and staff collaborate on several Air Force and NASA-funded flight programs. He will personally supervise one of the associated graduate students in each year of work in carrying out the systems architecture work and will work to ensure alignment with DoD priorities, as detailed above and in §2.4. Peck will also co-advise one or more of the other affiliated students and multiple summer students throughout the course of the work.

Co-I Petro is an Assistant Professor of Mechanical and Aerospace Engineering at Cornell University. Petro has expertise in space systems with a focus on spacecraft propulsion. She performed Ph.D. research in the Department of Aerospace Engineering at the University of Maryland, College Park on performance scaling of spacecraft electric propulsion. As a post-doctoral researcher in the MIT Department of Aeronautics and Astronautics, Petro lead both numerical and experimental investigations of small satellite propulsion technology and technology demonstration missions. Petro's research spans the details of propulsion subsystem design to spacecraft-scale integration and systems architectures. Petro currently serves as the Technical Chair for the International Electric Propulsion Conference and the faculty lead for the interdisciplinary Cornell SmallSat Mission Design School. Petro has been named a Lockheed Martin ARCS Scholar, National Science Foundation and Zonta International Amelia Earhart Fellow, and UMD Clark School Future Faculty Fellow. In 2016, she was recognized as one of Aviation Week & Space Technology's Twenty20s emerging leaders in aerospace. Prior to graduate studies, she worked on the MAVEN Mars Orbiter, the James Webb Space Telescope, and Hubble Telescope missions at NASA's Goddard Space Flight Center. Petro will co-lead the spacecraft design and analysis efforts and lead all propulsion analysis tasks. She will directly supervise one post-doctoral researcher, and co-advise one or more of the other affiliated students and multiple summer students in each year of the work.

Co-I Sands has expertise, recent publications, and teaches courses at the Naval Postgraduate School and at Cornell (in the Fall semester) in flexible space robotics; autonomous spacecraft guidance, navigation, and control; astronautic optimization; and adaptive and non-stochastic learning methods applied to space vehicles. Colonel Sands retired from the Air Force having been thrice decorated for single acts of combat heroism, and he maintains active clearances as a USN Civil Servant (professor). He formerly served as the spaceflight mission planner and piggybacks manager for the DOD Space Test Program in addition to the propulsion and reliability engineer of the Atlas medium launch vehicle family. His research doctorate was earned in astronautical engineering and led to the award of one U.S. patent for novel spacecraft attitude control and the prestigious Theodore von Kármán Award for the most outstanding contribution to national defense in the fields of science and engineering relating to aerospace activity. As a former Provost, Associate provost, Dean, and Associate dean at both military postgraduate universities, he will provide informal leadership ensuring smooth integration of the military universities with Cornell towards the mission research needs of Space Force and the Air Force. His technical role in this project is to lead novel research in very lightweight spacecraft robotic resupply and assembly supporting novel supply chain concepts, in addition to managing military aspects necessitating utilization of secured spaces and communications channels.

Co-I Reiman is an expert in logistics and supply chain management; order fulfillment network modeling, operational energy analysis and supply chain resilience. He is currently an Assistant Professor of Logistics and Supply Chain Management at the Air Force Institute of Technology. Reiman will assist the project team with defining network evaluation metrics, the overall network optimization, and ensuring that network implementation goals are in line with DoD priorities.

2.3.1. *Other Personnel.* Research Associate Andrew van Paridon will assist the Cornell project team in overall project management and execution of project tasks. In addition to the PhD students funded by the project, the Cornell team plans to recruit heavily from the undergraduate and Masters of Engineering (MEng) population in the Sibley School and broader college of engineering. The Cornell MAE MEng program has a significant research and design component, and students frequently work on externally funded research efforts as part of their degree work. All members of the Cornell team have significant experience with advising undergraduate and MEng students in project work, including flight projects. Most notably, Peck has advised multiple small satellite build projects, including three current projects selected for the NASA CubeSat launch initiative. Undergraduate and MEng students will work on the project for academic credit during the school year, and we have budgeted funds in each summer of the project to continue student involvement for up to 10 students. These summer funds can also go pay for additional PhD student summer time, which can be staffed by additional students from MAE, or other graduate programs at Cornell including Systems Engineering, and the Center for Applied Math.

2.3.2. *AFOSR and AFRL Engagement.* Space Force and Air Force POCs include Dr. Andy Sinclair, AFRL/RV expert in GNC with interest in control of large, flexible structures; Dr. Chris Petersen, a GNC specialist who has experience and interest in path planning for spacecraft; and Dr. George Boyarko, USSF Technical Lead for Wargaming, Space Security and Defense Program for transition of our developments into USSF wargames. AFOSR's Dr. Frederick Leve will be a POC regarding Cislunar and deep space domain awareness, and Dr. Mitat Birkan for propulsion and power in addition to Jean-Luc Cambier at OSD. Air University's Peter Garretson will also be kept informed of project status and results.

2.4. **Management and Work Plan.** The proposed work will take place over a period of three years, with planned activities for an extension period of two additional years, with a nominal start date of January 1, 2022. All work will be carried out at the Ithaca campus of Cornell University, at the Naval Postgraduate School (NPS) in Monterey, California, and at the Air Force Institute of Technology (AFIT) at Wright-Patterson Air Force Base, Ohio. The project work will be split into four concurrent research efforts:

(1) Network design and analysis
(2) Orbit design and analysis
(3) Subsystem design and analysis
(4) Spacecraft autonomy design and validation

Efforts 2 and 3 will be led by subteams at Cornell, led by Savransky and Petro/Peck, respectively. Effort 1 will be jointly led by Reiman at AFIT and Savransky at Cornell, while effort 4 will be led by Sands at NPS and Cornell. Each effort will be staffed by at least one associated graduate student and multiple undergraduate and MEng students in each year of work (see §2.3.1). Each subteam will have weekly progress meetings, and the full project team will have monthly status meetings. All senior project personnel have significant experience with managing large, geographically distributed teams. Funds have been budgeted for travel for in-person meetings in each year of work, as well as conference travel.

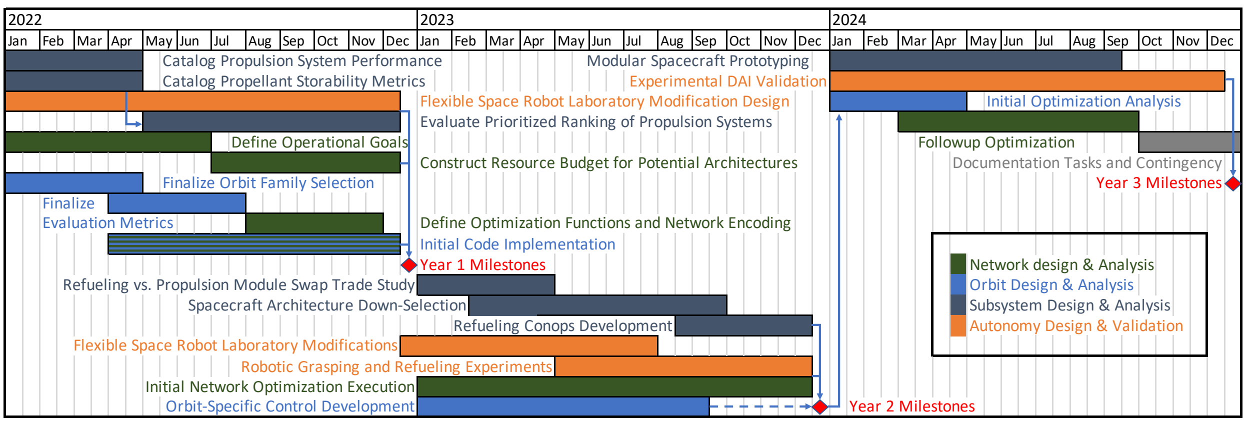


Figure 16. *Project plan for Years 1-3.*

2.4.1. *Years 1-3.* Figure 16 shows the project plan for Years 1-3, with major milestones listed in Table 2. Top-level year 1 goals include the definition of operational goals with our Air Force partners, and to build a detailed resource budget for various architectures that enable intercept and proximity operations anywhere in cislunar space. The orbital design team will complete the identification of all orbit families to be considered for network components and, in collaboration with the network design team, will generate final definition of all evaluation metrics and define and validate cost functions for network identification. A concurrent effort by these two teams will create initial implementations of optimization programs to be executed in year 2. The spacecraft design team will compile propulsion system performance parameters and catalog propellant storability metrics. This work will feed into an evaluation study resulting in a prioritized ranking of propulsion systems best suited to key network operations including (1) cargo delivery, (2) servicing (rendezvous and proximity operations), (and 3) orbit maintenance for key assets. The autonomy team's efforts will be focused on the design of necessary flexible space robot laboratory modifications, including installation of well-designed gripper hardware and software and equipment check-out evaluations. This will be followed by an evaluation of benchmark classical experiments to establish baselines for future comparison of proposed and to-be developed methods should be accomplished. We will also commence analytical development of D.A.I. for highly flexible space robotics.

Table 2. *Major project milestones. Sub-Teams match the effort list in §2.4.*

Year	**Sub-Team**	**Milestone**
1	1	Operational concept goals defined and resource budget completed. Initial cost functions defined.
	2	Orbit families selected, evaluation metrics encoded, and initial code implementation complete.
	3	Propulsion systems down-selected and ranked by network utility.
	4	Laboratory modification designs complete. Preliminary analytical development of D.A.I. complete.
2	1	Initial network optimization HPC runs complete.
	2	Orbit-specific control development complete.
	3	Refueling conops development complete.
	4	Lab validation experiments complete.
3	1	Followup optimization complete.
	2	Optimization analysis complete.
	3	Subsystem design and prototyping complete.
	4	D.A.I. experimental validation complete.

The orbit and network teams will spend year 2 deploying, debugging, and executing the codes developed in year 1 on HPC resources (§6) to determine network features such as fleet size and composition, service depot positioning, orbits, and required resource resupply rates. The orbit team will also pursue a concurrent effort on generating and validating orbit-specific control techniques to maximize the efficiency of arbitrary transfers for network elements. The spacecraft design team will conduct a trade study on refueling vs. propulsion module swapping for small satellites, a concurrent overall space architecture down-select study, and, based on the results of these efforts, will develop an overall refueling concept of operations. The autonomy team will procure all necessary laboratory modifications and conduct an evaluation of whiplash compensation. We will also continue development, analysis, and numerical evaluation of D.A.I.

Year 3 will be focused on the analysis of year 2 computational results, executing additional optimizations to further explore aspects of the design space revealed by preliminary results, and the establishment of the Pareto frontier of network operations. The spacecraft team will work on prototyping and validating modular spacecraft designs, while the autonomy team focuses on experimental validation of D.A.I. methods. Q4 of year 3 is reserved as overall project time contingency and for documentation tasks and paper preparation.

We anticipate the submissions of at least three journal/conference papers in each year, covering the network and orbit design results, the propulsion system and overall spacecraft architecture design results, and the autonomy results. One or more of the last category of papers will be submitted as a potentially classified or Controlled Unclassified Information or higher category to the Journal of Defense Research and Engineering (JDRE). We will similarly consistently work to incorporate project methodologies and results into our teaching

(§2.6). In particular, in each year, we expect to update up to 25% of the courseware of the following courses to include newly developed material form this research effort: Aerospace Dynamics, Guidance and Control, Spacecraft Design (two courses), Space Robotics, Space Propulsion, and Adaptive and Learning Systems. These courses are all available by distance learning to DOD personnel.

2.4.2. *Years 4-5.* We expect similar levels of effort in years 4 and 5 of the project, with budgets mirroring the year 3 budget (with standard escalation at each institution). Year 4 project goals will be to incorporate industry partnerships to outline the commercial transition of both the modular spacecraft and the resource hubs, and to conduct additional network optimization studies factoring in the year 3 results from the spacecraft and autonomy teams. We will commence detailed plans for an on-orbit demonstration of newly developed autonomy concepts, including planning for utilization of Naval Postgraduate School and AFIT ground stations for command and control of on-orbit experiment operations, as well as detailed coordination with DOD Space Test Program. Year 5 work would culminate with the delivery of a full network design, including fully scored reference orbits for satellites and hubs, technology component designs for key spacecraft subsystems, and deailed roadmaps for on-orbit demonstrations and continued concept maturation.

2.5. **Reporting and Technology Transfer.** In addition to the required annual and final performance reports, we plan to widely disseminate our work via peer-reviewed publications, conference presentations, and public talks. We have budget funds in each year for page charges as well as conference travel for all affiliated team members (including all graduate students. Furthermore, our team members at AFIT and NPS provide us with the opportunity to provide direct reports to DoD over secure channels, as needed.

DoD-specific reporting and transition efforts will follow four lines of action: 1) integration into USSF wargaming, 2) USSF-sponsored spaceflight demonstration through the DOD Space Test Program, 3) publications in DOD secured-journals, and 4) regular periodic coordination with USSF and USAF technical points of contacts (POCs).

Periodic reporting will be provided to identified POC's as requested in addition to annual publication (to include classified articles as appropriate) through the Defense Technical Information Center's (DTIC) Journal of Defense Research and Engineering (JDRE). Space Force and Air Force POC's include Dr. Andy Sinclair, AFRL/RV expert in GNC with interest in control of large, flexible structures; Dr. Chris Petersen, a GNC specialist who has experience and interest in path planning for spacecraft; and Dr. George Boyarko, USSF Technical Lead for Wargaming, Space Security and Defense Program for transition of our developments into USSF wargames. To further facilitate transition, validating spaceflight experiments will be pursued through the DOD Space Test Program necessitating prior detailed coordination with offices in Space Force and the Air Force to sponsor the effort through the space experiments review board (SERB) process.

2.6. **Infusion into Teaching.** All senior members of the project team have teaching duties at their respective institutions, and **all of us plan to incorporate the ongoing project work into our teaching**. The rationale for this is three-fold: First, it will allow us to more efficiently balance our teaching and research duties. Second, it will make it easier to recruit and train students for the project work (see §2.3.1). Finally, teaching topics related to the proposed research will provide training for current students in exactly those areas highlighted by the DoD as high priority for future development efforts.

The results of this research will immediately augment the education of officers from the Space Force, Air Force, Naval Space Cadre, and Army FA40 in the following graduate courses offered by the military postgraduate university partners: Aerospace Dynamics, Guidance and Control, Spacecraft Design (two courses), Space Robotics, and Adaptive and Learning Systems, where these courses are available by distance learning to DOD personnel. Classified content in these courses is possible upon request where the courses would then be taught and broadcast from secured facilities. Professional development of military space personnel will be enhanced through the following graduate certificates available by distance learning: Space Control, Tactics, and Operations; Space Systems Fundamentals; Space Systems Design; and Space Nuclear Command, Control & Communications.

At Cornell, Savransky, Peck, Petro, and Sands are primarily responsible for nearly 100% of the space-focused teaching. Existing courses within which new content generated by our research efforts can be integrated include undergraduate level courses such as Introduction to Spaceflight Mechanics, Spacecraft Technology and Systems Architecture, Aerospace Propulsion, and graduate level courses including Spacecraft Attitude Dynamics, Estimation, and Control, Advanced Astrodynamics and Celestial Mechanics, and Astronautic Optimization.

3. Principal Investigator (PI) and Senior Personnel Time

3.1. **Savransky.** Savransky has a standard teaching load of one course per academic semester, with a balance of 50% of time devoted to research activities in the 9 month academic year (AY), plus 3 summer months available for research efforts. He will devote 2 months per year of time to this project, nominally split as one month AY and one month summer, but adjustable based on the outcome of currently pending proposals. As detailed in the current & pending document, Savransky currently has funding obligating 3 months of research efforts during the proposed funded work period for this project in year 1, and up to 4 months of research effort obligated by pending proposals. There are no significant project overlaps in any current or pending investigations, and even in the event of the successful outcome of every currently pending proposal, Savransky will be able to devote the requested amount of time to this work. Savransky plans to take a sabbatical during year 2 of the project work, but will continue with his duties in the project, and manage his team remotely, as needed.

3.2. **Peck.** Peck also has a standard teaching load of one course per academic semester, with a balance of 50% of time devoted to research activities in the 9 month academic year (AY), plus 3 summer months available for research efforts. He will devote 2 months per year of time to this project, nominally split as one month AY and one month summer, but adjustable based on the outcome of currently pending proposals. There are no significant project overlaps in any current or pending investigations, nor are there overlaps with anticipated consulting activities.

3.3. **Petro.** Petro has a standard teaching load of one course per academic semester, with a balance of 50% of time devoted to research activities in the 9 month academic year (AY), plus 3 summer months available for research efforts. She will devote 2 months per year of time to this project, nominally split as one month AY and one month summer, but adjustable based on the outcome of currently pending proposals. As detailed in the current & pending document, Petro currently has funding obligating 2 months of research efforts during the proposed funded work period for this project in year 1, and up to 3 months of research effort obligated by pending proposals. There are no significant project overlaps in any current or pending investigations, and even in the event of the successful outcome of every currently pending proposal, Petro will be able to devote the requested amount of time to this work.

3.4. **Sands.** In the first year (adjustable in subsequent years) sixty-two percent will be devoted to related teaching with the remaining thirty eight percent devoted to research, where this project will be the top priority, dominating research efforts 2022-2025 (potentially 2027). Research on this project will occupy a portion of each week throughout the year, where the university operates on a four-quarter system with only two-week breaks for Christmas and Independence Day. Daily work occurs in unsecured spaces as appropriate (on a military base not openly accessible), remaining sensitive to operational security and management of controlled unclassified information.

3.5. **Reiman.** 40 percent of my time will be dedicated to research, 50 percent to teaching and 10 percent to service. Of the 40 percent dedicated to research, this project will occupy a quarter. I am responsible for advising 10 graduate students annually. I am currently in the process of seeking funding for a SAF/IEN project using stereoscopic vision for automated load planning of cargo, but the proposal has not yet been submitted.

4. Facilities

4.1. **Cornell.** The Cornell team consists of three research groups, each with their own existing facilities, detailed below. In addition to these, all members of the Cornell team will have access to the resources available to all members of the Cornell community, including the Cornell Libraries (granting access to online journals and databases), the Center for Advanced Computing and the campus IT infrastructure, and the eCommons digital data archive, which members of the proposing team have previously used for long term preservation of digital research products, and plan to use as part of their data management for this work.

Cornell also hosts a Center for the Integration of Research, Teaching, and Learning (CIRTL), which prepares graduate students and postdoctoral scholars to excel as teachers, researchers, and mentors, working through a rich network of faculty, staff, and students brought together by shared ideas about the importance of evidence-based and inclusive teaching and mentoring practices. Through their participation in the national CIRTL Network (21 universities), the university contributes and provides access to online seminars, courses, and training guides for interest students, faculty, and staff. In addition, a particular focus of the CU-CIRTL program is on research mentor training, enabling graduate students and postdocs to effectively mentor undergraduate researchers from diverse backgrounds and eventually supervise their own graduate students, postdocs, and research technicians. The CIRTL Network represents 22% of the national STEM PhD production. Cornell has been an active member of CIRTL since 2011. The CIRTL Network is funded by the National Science Foundation (DUE #: 1231286), the Sloan Foundation, and the Great Lakes Higher Education Guaranty Corporation. The affiliated graduate students will have the opportunity to work with CIRTL to present a seminar on the integration of graduate and undergraduate instruction with work on cutting-edge research projects, targeted for the "preparing future faculty" audience.

4.1.1. *SIOSlab Facilities.* The proposed work, and especially the prototyping phase of the computational effort, will make extensive use of the PI's existing computational infrastructure, which includes two general purpose computing servers (total 100 cores with 768 Gb of memory and 55 Tb of local storage in RAID-5 arrays with backup redundancy). These servers run a broad range of software, including full licenses for MATLAB as well as multiple open source toolchains, which will all be used in prototyping and debugging all high performance software that will be implemented as part of the project tasks (see §2.4 and §6).

Figure 17. *SIOSlab laboratory facility showing the optical table (with enclosure removed) and control computer.*

In addition, SIOSlab facilities include a 300' dark room facility for visible light optical experiments (Figure 17), with a vibration isolated optical table, enclosure, and standard optomechanical components, parts, and tools for optical assembly and testing, including a variety of motorized stages including two- and three-axis translation stages, tip/tilt stages and rotational stages. This facility will be available to provide support to the work being executed primarily at the NPS facilities (§4.2).

Figure 18. *ASTRAlab vacuum chamber*

4.1.2. *ASTRAlab Facilities.* Cornell's research and development activities related to electric propulsion system development and integration will be carried out in the ASTRAlab facilities. The Cornell ASTRAlab is a brand new roughly 800 square foot facility located on the Cornell University campus within the Mechanical and Aerospace Engineering Department. The lab is equipped with two vacuum chambers which will be available for the SURI research program. The 500 L instrumentation chamber (shown right) is fitted with over 30 ports that will be used to heavily instrument the environment with QCMs, Langmuir

Probes, a mass spectrometer, and several spatially-distributed pressure sensors. The chamber is fitted with a turbomolecular pump andcapable of reaching high vacuum (<10-6 torr base pressure).

In addition to hardware facilities, the lab is equipped with several simulation platforms (COMSOL multiphysics, LSP/Vsim particle-in-cell), and computing facilities several 8 core windows PCs, Intel quad core with Tesla GPU) along with access to Cornell's University Center for Advanced Computing, all of which can be leveraged to perform simulations to accompany the characterization experiments.

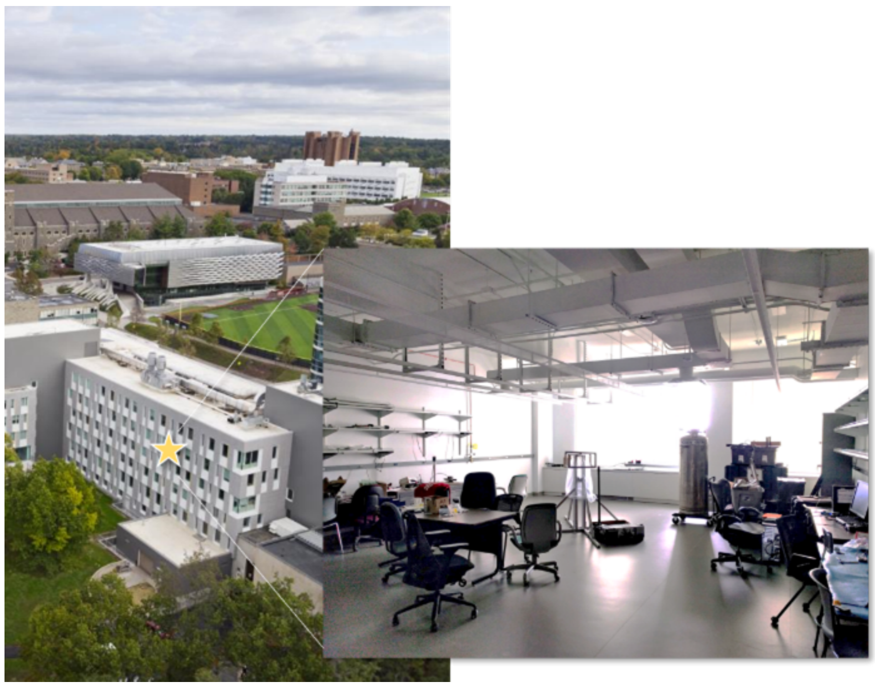


Figure 19. *ASTRAlab facility*

4.1.3. *SSDS Facilities.* The Space Systems Design Studio at Cornell University represents 3000 sf of spacecraft fabrication and test facilities, including a class 10,000 clean room and a mission-operations center. Cornell's Space Systems Design Studio has undertaken TRL1 – TRL7 development for the past 17 years for small spacecraft in collaboration with NASA, USAF, DARPA, and many US spacecraft prime contractors. This work has resulted in multiple small-spacecraft flight experiments and related mission operations. This grounding in flight programs is expected to inform the practical aspects of systems engineering for this research, a key discriminator for the systems-engineering aspects of the proposed study. Although we do not propose to undertake flight-hardware development during the effort described in this proposal, we expect to collaborate among one another to inform design choices based on this flight-system experience. Accordingly, some of Cornell's resources available for this project include

- Professional staff dedicated to design, fabrication, and test of spacecraft hardware.
- Three dedicated ground stations capable of send/receive in the 70 cm band.

- Mission Control Center with Orbital Sciences' In Control software, to coordinate data from various sites, voice network, displays, and computer facilities for subsystem experts to operate the spacecraft.
- The Emerson machine shop, available without charge to members of the university community. It includes CNC machines and most of the equipment found in professional machine shops.
- 1.5 m^3 Thermal vacuum chamber for testing and bake-out of spacecraft hardware.
- Two class-1000 clean rooms and one class-10000 clean room (total of roughly 500 sq. ft.).
- Xenon lamp from Spectra Physics Lasers for power testing.
- Ground station with heritage in multiple CubeSat programs since 2006
- Electronics tools such as oscilloscopes, spectrum analyzers and logic analyzers.
- Lab infrastructure with ESD-controlled electronics assembly areas, access-controlled storage of flight hardware, and computers for CAD, dynamics simulation, structural modeling, and other analyses.

4.2. **NPS.** The Naval Postgraduate School operates on an annual budget of merely 98 million dollars, yet earns around 110 million dollars in research awards each year supporting world class space laboratories including an operating FLTSATCOM spacecraft and a scaled segmented mirror spacecraft like the James Webb space telescope, both in clean rooms amongst other space labs like the SmallSat Lab. Most applicable to this proposal are the flexible spacecraft simulator and the orbital robotics laboratories which are both committed to this effort, respectively view-able at https://nps.edu/web/srdc/laboratories and at https://nps.edu/web/srl. The university also operates the Mobile CubeSat Command and Control (MC3) ground station network supporting DoD Space efforts in the emerging field of very small satellites. The MC3 lab is described further here: https://nps.edu/-/nps-students-tackle-key-challenges-of-the-mobile-cubesat-network.

The university has a long history with the DoD Space Test Program (STP) having flown several experimental space missions through the STP in support of military graduate space education. Secured facilities are also available and envisioned to be useful to aid discussions towards transitioning the research products into Space Force programs of record.

4.3. **AFIT.** AFIT has extensive laboratories available to conduct experimental research. Lab facilities at AFIT that could potentially be used in this research include the Aerospace Material Test lab and the Spacecraft Design, Test, Build and Fly lab. A major advantage of AFIT being located at WPAFB is that this research has access to some of the world's finest research facilities at the Air Force Research Laboratory (AFRL). AFIT also has research centers to provide research excellence concentrations that allow cross collaboration between departments. The centers most applicable to this research include the Autonomy and Navigation Center and the Center for Space Research and Assurance. AFIT also provides access to advanced additive manufacturing equipment and the DoD High Performance Computing (HPC) Center's Network which might have the potential to be used for this research.

5. Government Furnished Equipment

Other than the NPS and AFIT facilities detailed above, and the planned use of DoD high performance computing (detailed in §6), this project will not require the use of any government furnished equipment.

6. High Performance Computing Requirements

The numerical explorations described in §2.2 require significant amounts of computational time. For context, the evaluation of individual transfers takes minutes to evaluate as a single-threaded process. The full set of evaluation metrics in §2.2.1 can take several hours as a single-threaded process. The Poincaré map and associated visualizations in Figure 4 were evaluated over the course of 12 hours (again on a single CPU). All of these initial reference implementations are uncompiled and un-optimized, and of course specific wall times are strictly functions of the hardware used (and concurrent utilization of the system), but these times are indicative to what scaling these efforts to thousands of orbits will entail. The proposing team does not directly control sufficient computer resources to execute all of this computation within the span of the project, although we do have access to smaller-scale, high performance hardware, equivalent to approximately 2 Centennial (ARL DSRC)-class standard nodes, which will enable us to do all of the required code development, testing and debugging locally.

For execution of the proposed overall optimization program, we will require access to DoD High Performance Computing. We expect the bulk of initial computational work to be carried out in project years 2 and 3 (see §2.4), with access in year 1 limited to HPC Interactive Environment (HIE) single-node access for initial code deployment and debugging. Our projected computational needs are on the order of 180 Centennial-class nodes ($\sim$150 Gaffney/Mustang/Koehr nodes) for 4,368 hours/year (i.e., 26 maximum wall clock time normal priority user jobs). These estimates are based on existing code benchmarked on our local systems, with a standard parallelization penalty factor (it should be noted, however, that the majority of tasks described here have relatively high granularity, with low communications overheads, allowing for efficient asynchronous execution).

Code to be executed on HPC resources will consist of free and open source, publicly available codes (i.e., REBOUND, OR-Tools), code licensed for academic use (CPLEX, SNOPT), and dedicated codes written by the proposing team. All software will be CPU-only, with no GPU node requirements.

7. Disclosure of Foreign National and Dual Citizenship Personnel

Research Associate Andrew van Paridon is an Australian national, born May 8, 1988 in Auchenflower, Queensland, Australia, and is authorized to work in the United States under a J1 visa (issued 08/16/19, expiring 05/31/22). His green card application is pending.