Title:	In-Orbit Assembly of Cube Satellites with Novel Docking Techniques
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Organization:	Singapore University of Technology and Design
(x) We apply for Student Prize.	

I – Sustainability Development Goal:

1. Industry, Innovation and Infrastructure
2. Partnerships for the Goals

II – Needs:

Today's "New Space" companies are dominating the space industry with affordable small satellites, particularly 1U-sized cube satellites. Reduced launch costs accrue to the ability for cube satellites to "piggyback" on existing launch missions, given the small form and size. However, for variants larger than 1U-sized, they may not easily "piggyback" due to form-fitting and packing issues in the launch vehicle. One novel, often proposed approach would be to introduce modularity in spacecraft so that in-orbit assembly is made possible. A "system-of-systems" approach to modularity, much like the ISS, can reduce cost by allowing for flexible deployment of spacecraft by parts. Modularity also allows for developers to transcend weight limitations of launch vehicles; it opens up collaboration, motivates cost-sharing across teams working on different modules; finally, it provides common pool resources and technical economies of scale. Studies have shown that this reduces the cost of space access, barriers to entry, and empowers the sustainable growth of the "New Space" economy [1]. However, any in-orbit assembly requires a rendezvous mission and a docking mechanism. We look towards cube satellites as the basic "building block" for in-orbit assembly of larger variants greater than 1U size. At present, there are no established docking standard designs for 1U sized cube satellites. Thus, there is a need to design a docking mechanism for these cube satellites and a means for rendezvous, if we wish to enhance the sustainability of "New Space" economies via in-orbit assembly.

III – Mission Objectives

This will be a demonstration mission in LEO, to prove that a rendezvous and an in-orbit assembly of 2 cube satellites is possible using the proposed design. This will then be extended to a system of more than 2 cube satellites. We will assume the target satellite is inserted at 500km LEO. This mission demonstration's objectives are:

1. Have the interceptor perform a successful rendezvous using a single Hohmann transfer, with 7.5m/s of Delta-V budget.
2. Have the interceptor successfully launch docking tethers to grapple the target in one swift attempt.
3. Have the interceptor establish electrical connection through the docking modules' connection cables, with the target.

IV – Concept of Operations

In this mission report, we will perform a demonstration mission for rendezvous and docking. We begin by proposing an algorithm for orbit rendezvous using a single Hohmann transfer. We employ a MEMS based cold gas thruster, designed for cube satellites with baseline configuration having 60 g of butane in a tank under 2 to 5 bar pressure. Realistically, it can provide up to 15 m/s Delta-V [2]. We intend to use only 50% of the budget for the Hohmann transfer (rendezvous), keeping the rest as spare. Once rendezvous is completed, the docking mechanism initiates. The design is a modular, lightweight and space conscious docking system that is non androgynous in design. After rendezvous, an Arduino Nano controls a tether launch control system, where the tether functions as a magnetic grappling hook. It also houses a SparkFun MPU 6050 IMU for accurate position determination. In a nutshell, docking is achieved when the male docking face launches tethers from the interceptor to grapple the target's female docking face, and reels it in for docking. They may then conjoin and form larger variants via in-orbit assembly. A full breakdown of the in-orbit assembly is explained in Section VI.

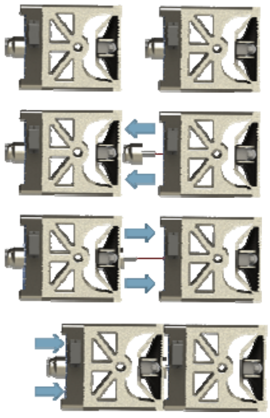


Fig 1: CubeSat docking illustration

V – Key Performance Parameters

1. The interceptor and target must both be launched at the same orbit inclination angle, as small satellites cannot afford the ΔV needed for orbit plane changes.
2. The interceptor satellite must be launched at an altitude that is within the range of 491.6km to 508.4km in order to close-in on the target in a single Hohmann transfer with using only 7.5m/s of ΔV (50% of total budget of 15m/s, 50% spare).
3. A final rendezvous distance of ~ 1 metre must be established between satellites.
4. The electromagnetic grapple of the interceptor's male docking end must launch successfully and grapple the target's female docking end in 1 attempt to establish a mating and an electrical wired connection.
5. The interceptor must successfully reel the target satellite in.

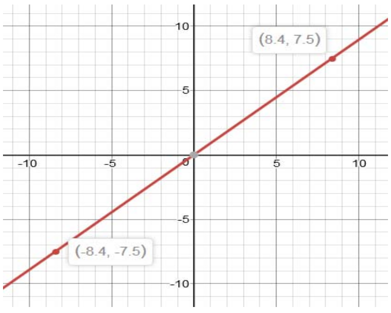


Fig 2: ΔV (m/s) budget against allowable altitude error tolerance

VI – Orbit Rendezvous Description

In this section, we address the rendezvous mission. It is a coplanar rendezvous done in a single manoeuvre. The target is assumed to fly at 500km LEO. We assume the interceptor satellite is (deliberately) injected into LEO at 491.60km altitude, circular orbit. This is the lowest possible altitude for the allowable ΔV of 7.5m/s for a realistic mono-propellant MEMS-based cold gas thruster. Using a well-timed Hohmann transfer, the target will cover both the altitude difference and catch-up to the true anomaly of the target in a single thruster burn. However, it will require very precise timing, possibly a long waiting time to get both satellites in the "right position" before firing thrusters, and accurate determination of the difference in the anomalies (α, β) between both satellites.

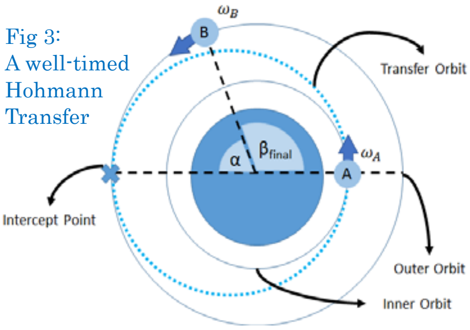
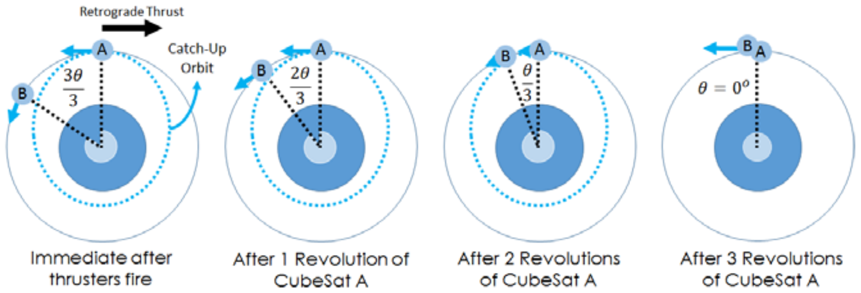


Fig 3: A well-timed Hohmann Transfer

Before the manoeuvre, both satellites have constant but unequal mean motions, and hence covers phase at different rates. The interceptor, which in our case is A, will perform an impulsive Hohmann transfer with a time of flight that is only dependent on the inner and outer orbital radii. In this time of flight, our interceptor satellite covers a phase of 'π', while our target satellite B must cover a phase of 'α'. This manoeuvre can only take place after waiting for the time where we know both satellites will intercept each other at the same point after the same time of flight. We know both orbital radii of target and interceptor, with Earth's mean radius being 6,371km. Thus, the transfer ellipse required has a semi-major axis of 6866.80km. Thus, knowing the semi-major axis allows us to calculate time-of-flight (TOF) using Kepler's Laws. T = 2831.56 sec. We now need to know what angle α is, to know when to time the fire of the Hohmann transfer. We have the TOF of A, thus angle α is simply the phase covered by B during this TOF. The mean motion (mean angular velocity) of B can be calculated since it is proportional to the inverse of B's orbital period. We calculate angle α = 179.8349431 degrees, which is the phase covered by B, during the time in which A covers a full 180.00 degrees. The waiting time, T_{wait}, is therefore the time in which both the target and interceptor are in the correct exact position required to perform this manoeuvre. This waiting time is dependent on the actual difference in orbital radii of both satellites, since that determines their mean motion. If both satellites have a small difference in altitude, then the mean motion relative to each other will also have a small magnitude and the time it takes for the target and interceptor to be in the same position with the desired final angle of 'ß' could be unreasonably long. Furthermore, the timing of execution in this manoeuvre is very critical and thus the margin for error is very small. If the rendezvous is not entirely successful (i.e. the interceptor is still lagging quite a bit behind the target), we will use the conserved 50% of ΔV budget to perform an in-orbit catch up. We illustrate how one might achieve this in the graphic below, assuming full rendezvous in 3 revolutions.

$$T_{wait} = \frac{\beta_{final} - \beta_{initial}}{\omega_B - \omega_A}$$



Immediate after thrusters fire
After 1 Revolution of CubeSat A
After 2 Revolutions of CubeSat A
After 3 Revolutions of CubeSat A

Fig 4: In-Orbit Catch-Ups

This works by having the interceptor enter an elliptical transfer orbit by firing a retrograde thrust, allowing it to have higher mean motion in the trajectory indicated in the figure above. This allows A to cover phase at a higher rate than the leading target B. The target simply stays in its original orbit. This assumes the catch-up happens in an exact integer number of revolutions. After A has finally rendezvous with B, it will fire thrusters in prograde with the same magnitude of ΔV as the retrograde thrust, in order to re-circularise the orbit. In the figure above, we arbitrarily illustrated a catch-up in 3 orbits. It may not necessarily be 3 (could be more or less). If we want to save on the ΔV, we can reduce the ΔV thrust to enter another elliptical transfer with lower eccentricity, but with longer time-of-flight in transfer. The eccentricity of the ellipse and ΔV used here are all free parameters and thus is dependent on the nature of circumstances where the Hohmann transfer fails to perform a successful rendezvous. It is still constrained to 7.5m/s of remaining ΔV budget leftover however. Thus sufficient care and consideration must be taken as to how to allocate this budget.

VII – Space Segment Description

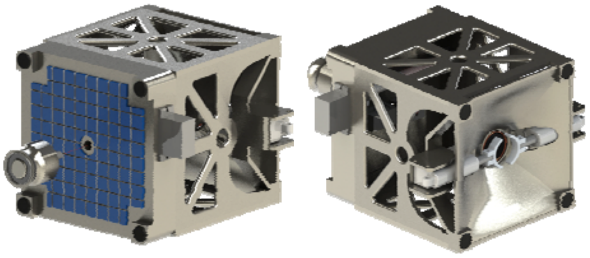


Fig 5: Male and female end of the MICRO-DOCK System

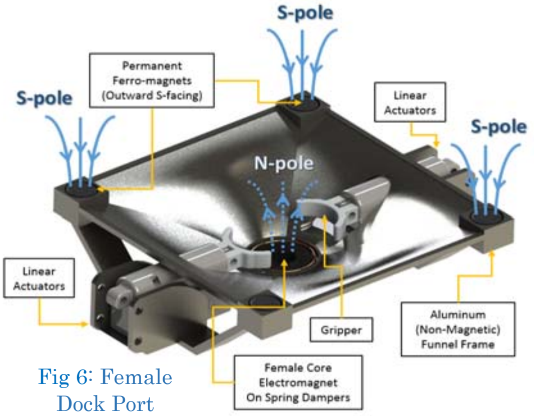


Fig 6: Female Dock Port

After rendezvous, we now introduce the docking designs, with full details and justifications of the design in the full text. Our design is called **MICRO-DOCK**: the **Modular Installation for CubeSat Rendezvous and Orbital Docking** – an extremely simple docking system with the size and simplicity suited for the generic 1U cube satellite. MICRO-DOCK is non-androgynous in design, and is meant to be extremely space-conscious. MICRO-DOCK takes up ~17.6% of a 1U cube satellite's volume (~200cm^2). The full details of how the mechanism works will be described in the full paper text.

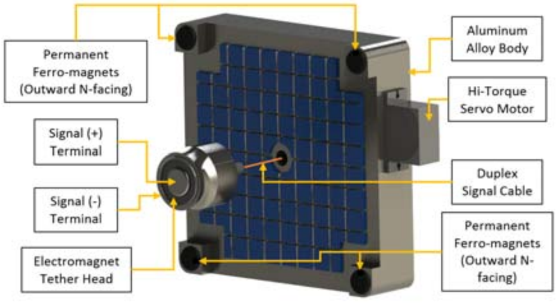


Fig 7: Front face of the male docking end

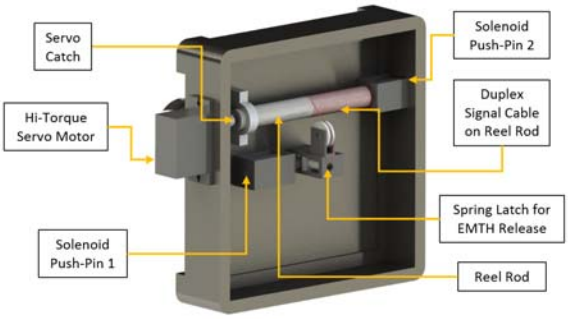


Fig 8: Internal face of the male docking end

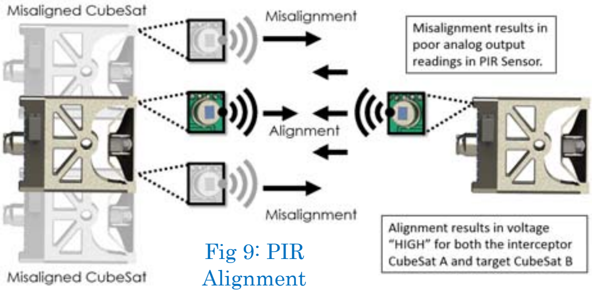


Fig 9: PIR Alignment

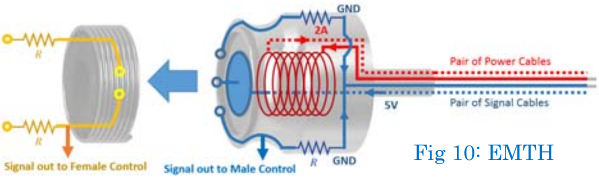


Fig 10: EMTH

On the male end of the adaptor (Fig 7, 8), there is an electromagnetic tether head (EMTH). It is a standard COTS Type 58 electromagnet of 20mm diameter (Fig 10). The tether itself is a bundled set of electrical cables, one pair providing 24VDC and GND to power the EMTH, and another set of cables for wired communications between each 1U Cube-Sat 'block' as they begin in-orbit assembly. The tether cables are neatly twined around a reel rod in the interceptor's housing. When a passive infrared transceiver (PIR) on both the target's female end and the interceptor's male end reads, it indicates a collinear alignment. A simple microcontroller such as the Arduino Nano 3.0 would be able to trigger the relay to the power supply for the EMTH the moment the PIR readings indicate that the satellites are aligned (Fig 9). This will also be confirmed with the use of an MPU-6050 Inertial Measurement Unit to ascertain the position of the cube satellite. Once they are aligned and close enough, the Arduino activates a solenoid push-pin that is holding a spring-release catch that launches the EMTH. As the EMTH is launched out of a spring-release catch from the male end of the interceptor cube satellite (details of the design in the full text), it gets attracted and clamps onto the female end of the target satellite. An arrangement of permanent N52 Neodymium magnets on the female face of the target's docking module provides a guide to magnetically "funnel" the incoming launched EMTH from the interceptor. Once both the electromagnets from the target's female end, and the interceptor's male end, have made electrical contact, it triggers a simple logic circuit that outputs a "HIGH" signal to both the target and the interceptor (Fig 11). The logic circuit from Fig 10 is shown in Fig 11.

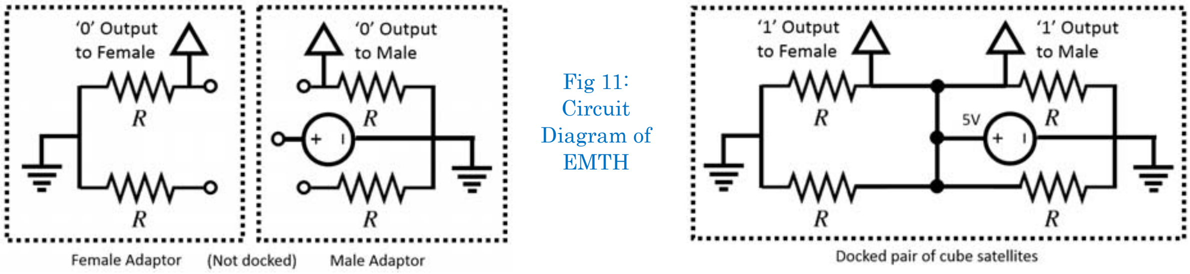


Fig 11: Circuit Diagram of EMTH

Initially, both signals out to the female microcontroller and male microcontroller are at voltage 'LOW'. Once they impact, the metallic conductive face of the EMTH bridges the circuit for both and we will see a signal change to voltage 'HIGH' as a signal out to both male and female (Fig 11). The now-triggered 'HIGH' signal will prompt the female adaptor to activate linear actuators and clamp onto the waist of the EMTH (Fig 12, 13), and the male adaptor will begin to reel in the EMTH by activating the servo motor on the male adaptor. We use PQ12 Actuonix Linear Actuators in our CAD model – they provide sufficient force and they are small enough to be refitted onto a cube satellite structure.

Fig 12: EMTH strikes the female adaptor’s EM!

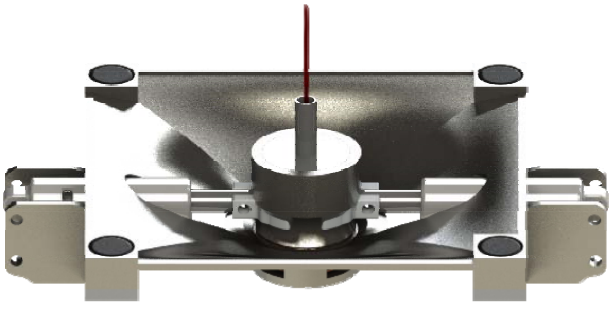
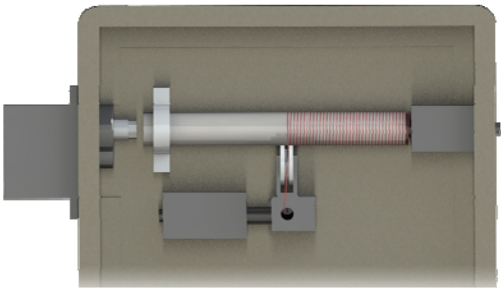


Fig 13: Circuit closes, and actuates the clamps linearly

At this point, since the EMTH is held together by the clamps, a preliminary “dock” is somewhat achieved. To save power, the signal also cuts off the 2A current to the solenoid of the EMTH. So far, in this stage of the docking procedure, recall that the reel rod has been free-wheeling all along (Fig 8). Now, we wish to make the reel rod rigid and well-controlled by the servo motor such that the motor can rotate the rod in reverse to reel back the docked satellite. The signal ‘HIGH’ caused by the closure of the signal circuit in the male adaptor triggers solenoid push-pin 2, which jerks the reel rod forward this time and locks it into place with the servo motor (Fig 14). The reel rod then engages with the servo motor directly.



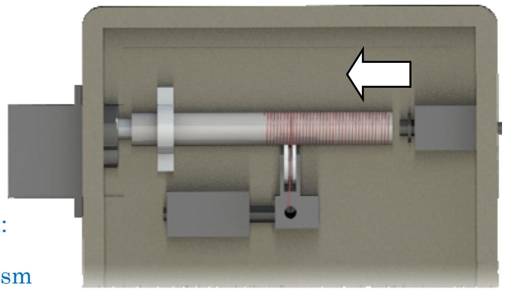


Fig 14: Servo mechanism

At Signal ‘0’, before the EMTH struck, the reel rod on the male adaptor is free-wheeling with little friction.

At signal ‘1’, solenoid push-pin 2 jerks the reel rod into the servo motor, pushing it into place.

The servo motor then begins to reel in the target satellite into the interceptor satellite, with the female docking face of the former facing the male docking face of the latter. As the target gets reeled into the interceptor, the permanent ferromagnets on the perimeters of the docking modules naturally attract, fastening them into place. Electrical connectivity between each 1U sized piece has been established (if not the servos and push pins would not have been activated), and thus modules can begin communicating and transferring data to each other. With successful docking using a modular male-female add-on in the MICRO-DOCK system, we can easily see how this may extend to a system of two or more cube satellites. Using the blue to represent the male end, and orange to represent the female end, we may view this in different configurations:

Fig 15A: Linear Configuration

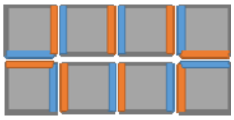


Fig 15B: Flat Configuration

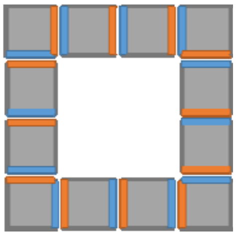


Fig 15C: Torus Configuration

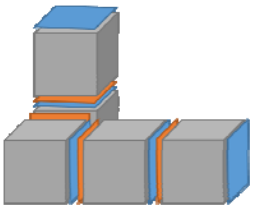
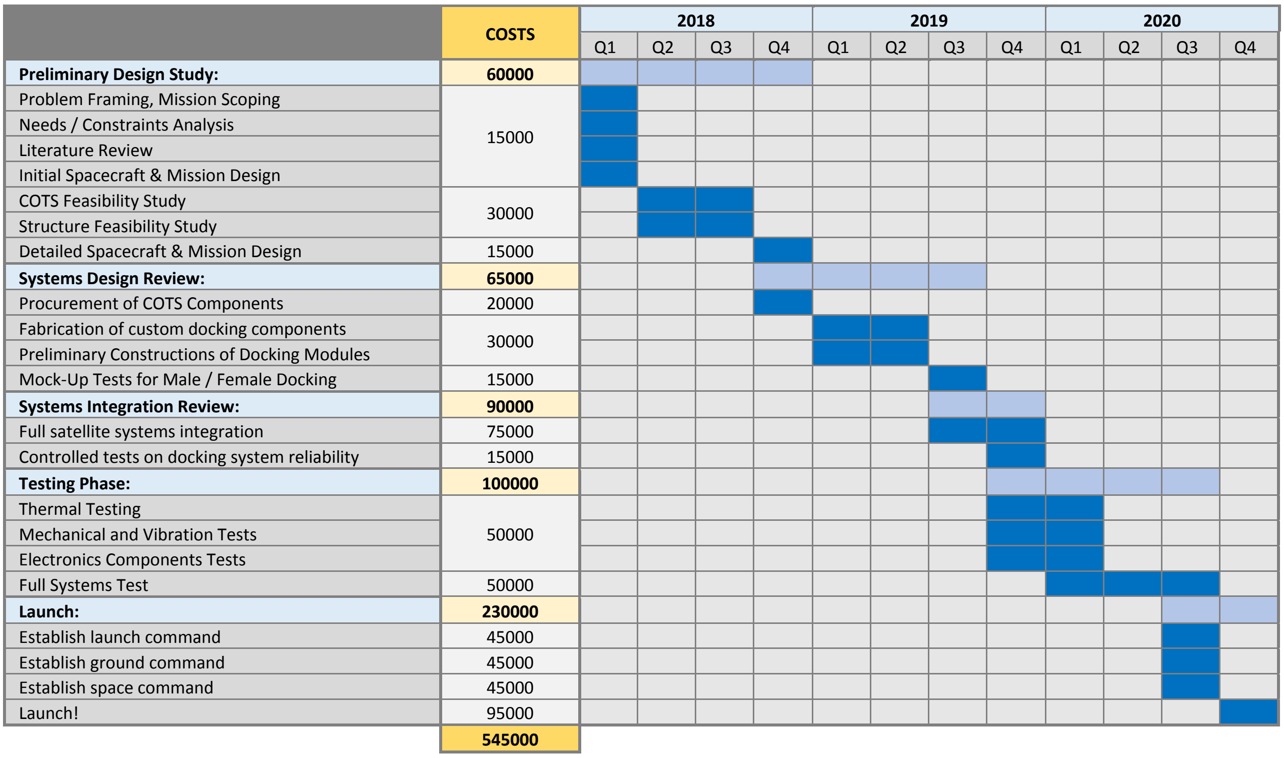


Fig 15D: 3D Configuration

VIII – Implementation Plan

Possible stakeholders for an in-orbit assembly mission for spacecraft would be small satellite developers aiming to reduce costs of development by launching space systems in parts, and researchers interested in pursuing joint projects with other space science and research agencies. Examples include Singapore’s DSO National Laboratories, DSTA, the Ministry of Defence, and private entities like MicroSpace. This is because the purpose of developing a docking method for cube satellites was to engage in cost-reduction by enabling in-orbit assembly of spacecraft, using the 1U cube satellite as a building block, and to enable joint efforts for small satellite “system of systems”, similar to the international efforts for the ISS.



	COSTS	2018				2019				2020			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Preliminary Design Study:	**60000**	▨	▨	▨	▨								
Problem Framing, Mission Scoping	15000	■											
Needs / Constraints Analysis		■											
Literature Review		■											
Initial Spacecraft & Mission Design		■											
COTS Feasibility Study	30000		■	■									
Structure Feasibility Study			■	■									
Detailed Spacecraft & Mission Design	15000				■								
Systems Design Review:	**65000**				▨	▨	▨	▨					
Procurement of COTS Components	20000				■								
Fabrication of custom docking components	30000					■	■						
Preliminary Constructions of Docking Modules						■	■						
Mock-Up Tests for Male / Female Docking	15000							■					
Systems Integration Review:	**90000**							▨	▨				
Full satellite systems integration	75000							■	■				
Controlled tests on docking system reliability	15000								■				
Testing Phase:	**100000**								▨	▨	▨	▨	
Thermal Testing	50000								■	■			
Mechanical and Vibration Tests									■	■			
Electronics Components Tests									■	■			
Full Systems Test	50000									■	■	■	
Launch:	**230000**											▨	▨
Establish launch command	45000											■	
Establish ground command	45000											■	
Establish space command	45000											■	
Launch!	95000												■
	545000												

We scale the project with the assumption of a joint assembly of 2 cube satellites, with a small team of 5 engineers – an electrical, mechanical, thermal engineer, an astrodynamicist, and a project lead. We include the costs of engineering salaries in Singapore, plus costs of facilities and resources, and using the average launch costs of cube satellites in 2018.

Rendezvous and docking technology is still extremely risky as re-attempts are often difficult when docking fails in-orbit. We shortlist the most crucial risks in the order starting with the highest:

1. Insufficient ΔV to perform rendezvous because of launch errors (insertion error in altitude, or different orbital plane).
2. Failure of the PIR sensors to get an alignment "lock" between small satellites.
3. Insufficient power to power on the electromagnets in the target and interceptor.
4. Failure of the spring-release catch to fire the EMTH out of the interceptor to target.
5. Failure of the servo-reel mechanism to reel back the target satellite (mechanical failure).

IX – References

[1] Gralla, E. L. and De Weck, O. L. (2007). "*Strategies for On-Orbit Assembly of Modular Spacecraft*", MIT, AeroAstro Dept.
[2] U. Kvell, M. Puusepp, F. Kaminski, J.E. Past, K. Palmer, T.A. Gronland, M. Noorma (2014). "*Nanosatellite orbit control using MEMS cold gas thrusters*". Estonian Academy of Sciences
[3] Larson, W.J. and Wertz, J.R. (1999). "*Space Mission Analysis and Design, 3rd Edition*".
[4] Gobetz, F.W. and Doll, J.R. (May 1969). "*A Survey of Impulsive Trajectories*". AIAA Journal.
[5] Chao, C.C. (2005). "*Applied Orbit Perturbation and Maintenance*", American Institute of Aeronautics and Astronautics.
[6] Howard; Nathan, Nguyen; Hai D (Jan 2006). "*Magnetic Capture Docking System*", NASA, U.S. Patent 7,815,149.
[7] Cal Poly State University. "*1U-3U CubeSat Design Specifications*". http://www.cubesat.org/. Retrieved 01-03-2018.
[8] MIT SSL. "*The SPHERES Program*". http://ssl.mit.edu/spheres/index.html. Retrieved 01-03-2018.
[9] NASA (Aug 2017). "*SPHERES Universal Docking Port*", https://www.nasa.gov/content/universal-docking-port-udp
[10] SpaceWorks (2014). "Nano/Micro Satellite Market Assessment". Retrieved 21-04-2018.