Feasibility of Satellite Sabotage via TrojanCube

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***Abstract*—The U.S. military requires strategic capabilities in the space domain and viable solutions must avoid causing collisions while also avoiding detection. A new method for satellite sabotage is to deliberately impair the attitude (but not the orbit) of a target spacecraft via the direct attachment and thrust output of TrojanCube, a sabotage picosatellite using the CubeSat form factor. The small attitude perturbations created can be varied to mimic anomalies that preoccupy the target satellite ground systems team. This project utilized a demonstration model and simulated momentum build-up potential to showcase feasibility and found that TrojanCube is an effective method to sabotage spacecraft functions and operation.**

Keywords—Aerospace and electronic systems, Aerospace engineering, Attitude control, Low Earth orbit satellites, Military satellites

I. Introduction

As access to, and reliance on, space infrastructure continues to expand, Earth orbital space is becoming a more contested operational environment. Space Policy Directive-3 (SPD-3) of the National Space Traffic Management Policy highlights the fact that a congested space system presents challenges for the safety, stability, and sustainability of U.S. space operations. [1]. Since space is the ultimate high ground, the US military needs viable options to deceive, degrade, deny, disrupt, or destroy adversary access to assets in the space domain.

However, viable solutions must avoid causing fragmentation and scattering of orbital debris, which pose a threat to friendly assets and can impair overall domain access. Traditional kinetic weapons do not meet this constraint as evidenced by the results of the People's Republic of China's (PRC) 2007 direct ascent anti-satellite test as detailed in a 2007 congressional research report. The anti-satellite missile test resulted in a debris cloud. " This debris cloud (estimated at 950 pieces 4 inches or bigger plus thousands of smaller pieces) threatens space assets in LEO…" [3]. Deorbiting a space asset is likewise a suboptimal solution, as a lost satellite is typically replaced with a new upgraded satellite. A solution to the defined problem space is to suriptitiously and deliberately impair the attitude but not the orbit of a target spacecraft via the direct attachment and thrust output of TrojanCube, a sabotage cubesat. This impairs the ground operations and requires the adversary to continually adjust their Concept of Operations (ConOps) while keeping the space assets themselves intact, but less useable. This method of spacecraft attack provides the non-kinetic disablement/impairment of a target which prevents debris scattering and causes both acute and aggregate long term negative effects to its target.

The project described in this paper explored this idea by physically demonstrating the above concept, as well as a potential software solution, in a neutral buoyancy test environment. The physical demonstration produced thruster commands based on attitude sensor feedback to repeatedly disturb a model spacecraft's orientation. This physical demonstration was supplemented with more accurate computational simulation work to gauge likely real world effects and explored torque profiles for commercially available small form thrusters as well as momentum buildup potential. The result of this project was an analysis of achieved perturbations and their potential effects on a target's attitude as well as the resultant potential feasibility of this asset vulnerability.

The stage of the proposed solution that will be explored by this project depends on prerequisite technologies that are engineering challenges in their own right and must be acknowledged and addressed for future development of this system. Most critically, there must exist vulnerability windows or blind spots in which rapid deployment and maneuvering of the cube can deliver it to the intended target proximity without detection by the adversary or a third party. Next, timely selective deployment of the Trojan Cube system would likely require a "nested" approach where the cube, or cubes, is delivered to orbit by a larger space asset when required by mission. This secondary deployment of small form satellites is already beginning to raise post deployment identification and tracking concerns such as the case of Spaceflight's SSO-A mission (Figure 1) [4]. During deployment, the cube would need to be able to sense its target, intercept, match attitude, and attach to a surface. Finally, this project's stage of development exists at a proof on concept level and does not include design of the codependent subsystems of a fully integrated system. Generation of this weapon system would require a complete system design.

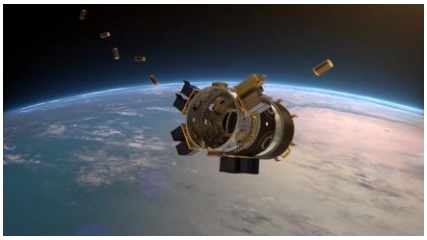


Fig. 1. "Spaceflight's SSO-A mission will deploy 64 satellites, raising concerns from some experts about the ability to accurately track and identify them after deployment." [4]

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The TrojanCube technology at its essence is designed as a targeted offensive sabotage capability. The intended employment of this technology should result in the disruption of the primary mission of a target spacecraft or the services it provides, the drain of resources and manpower, and the degraded capacity of the space asset in its entirety.

II. BACKGROUND

Commercial and military entities increasingly rely on space infrastructure, resulting in congested and contested orbital lanes. This need for maintaining US space superiority is laid out in the first doctrinal publication of the U.S. Spaceforce, Spacepower. "When warranted, offensive operations are designed to achieve a relative advantage by negating an adversary's ability to access, or exploit the space domain and are therefore essential to achieving space superiority."[2]. Spacepower goes on to define offensive operations as those which "target an adversary's space and counterspace capabilities, reducing the effectiveness and lethality of adversary forces across all domains."[2].This gives rise to the need for non-kinetic offensive capabilities in the space domain. Deliberate impairment to the attitude of a target spacecraft via the direct attachment and thrust output of a Trojan cubesat is a technological solution to this problem at efficient cost and a smaller scale than conventional 'space tug' proposals.

The most important and practical mitigation technique is actually the development of responsive, defensive technology solutions. We have seen this occur in other domains as well. For example, the development of chemical gas weapons drove advancements in soldier personal protective equipment. Similarly, in this particular case, responsive, defensive mitigation strategies would result in engineering solutions that would protect space assets from this particular sabotage vulnerability. In developing a new technology, one must necessarily understand how a system responds to the new technology which, in turn, exposes potential defensive mitigation strategies. Going through this process, which forces one to examine both the offensive capabilities of a new technology as well as the potential strategies to defend against that technology, is the single strongest argument for the advancement of national defense technologies.

Technological solutions must be explored once defined because if they are left unknown, someone else will inevitably explore them. By accepting responsibility to explore "harmful-by-nature" technologies, one also ensures exposure to the potential to design a shield from that harm should someone else develop it. The United States Department of Defense is charged with protecting the assets and interests of the State; that is their ethical obligation. As our reliance and dependence on space infrastructure and assets grows exponentially, so too will the necessity and urgency of defense capabilities. This ethical framework is, and will be, shared by all spacefaring entities past, present, and future. The right to defense is innate, expected, and the way that nations attempt to ensure their survival. Pragmatically, the question, "Is development of this technology ethical?", is shortsighted and misses the bigger picture that technology development fits into. Technology is just the relatively recent extension of a several billion-year-old evolutionary arms race. This kind of system of progress, at that kind of scale, is likely as innate and inevitable as can be. Therefore, not only is the development of this technology application ethical, but it is an eventuality.

III. DEMONSTRATION METHOD AND RESULTS

In order to physically demonstrate the capability of a TrojanCube to disturb the attitude of a spacecraft, and thus sabotage its mission functions and operation [7], we built a scaled physical model spacecraft and attached a motor and propeller to simulate the TrojanCube. The system architecture and test methodology for this model system is described below.

The demonstration model consisted of a 1/10th scale geometric approximation of an Iridium NEXT spacecraft. The model structure was built using a 1⁄2 inch PVC frame, an acrylic mounting sheet, and an acrylic watertight tackle box. The tackle box housed a Raspberry Pi 4, L298N motor driver, MPU-6050 accelerometer/gyroscope, and two battery banks. The tacklebox was affixed to the upper half of the frame to achieve positive buoyancy on the top of the model as a result of the air pocket within the compartment. To achieve negative buoyancy on the bottom of the model, sections of the frame were drilled to allow flooding while sections of pipe filled with gravel and sand were affixed to the bottom of the frame. Figure 2 presents a top down view of the completed model system.

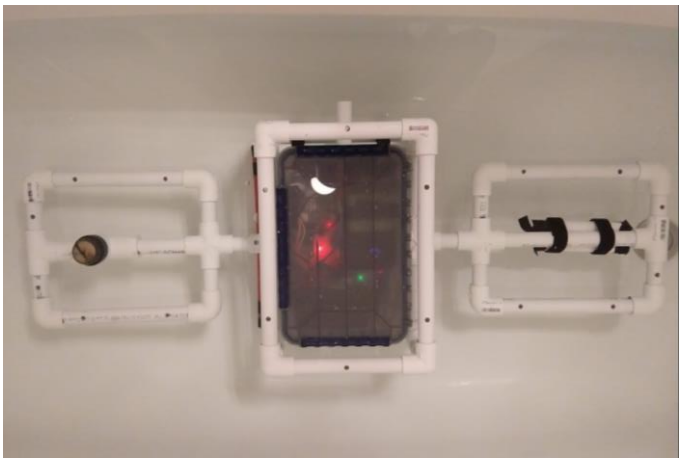


Fig. 2. Early controlled system functionality testing with the completed model spacecraft submerged in a bathtub (Top-down view).

This combined structural arrangement had the effect of a relatively neutrally buoyant overall frame with clear positive and negative buoyant poles. This effect was intentional and allowed for the test rig to right itself passively and was meant to function as a passive attitude and control system. To simulate a Trojan Cube attached to a solar panel of the Iridium NEXT spacecraft, a small waterproof DC motor with a 3D printed propeller protruded from the PVC piping of the model spacecraft to roughly represent a 1/10th scale 6U cubesat. DC power was delivered to the motor via a cable routed through the PVC frame. This allowed for the ability to provide repeatable force at the Trojan attachment point. The model was connected to a physical stand via a floating wooden dowel inserted into the PVC frame. This allowed for freedom of rotation in a single axis as a result of applied thruster force. Areas intended to remain dry were sealed

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with plumbers wax and marine sealant to avoid unwanted water exposure.

A test routine program was written in Python to allow autonomous operation of the thruster while the entire test rig was submerged in a pool. After a time delay, the program began sampling the MPU-6050 at a rate of 10x per second and compared each successive sample to the last. If the variance between samples was within a defined tolerance, a static counter incremented. At 20 seconds of static movement, which simulated the target operating nominally, the thruster would fire. The counter would then reset and wait for the target to again resume nominal operating orientation for 20 seconds before the next thruster fire. Sampled attitude data during the test runtime was stored in CSV files and saved onboard the Pi. After completion of the test routine, the CSV files were run through a post-process filter to determine the target's roll in the X-axis over test duration. In addition to the stored sensor data, a high-definition video camera was used to record the test iterations for future demonstration and comparison to the stored data. Video snapshots from the recorded test runs are shown in Figure 3.

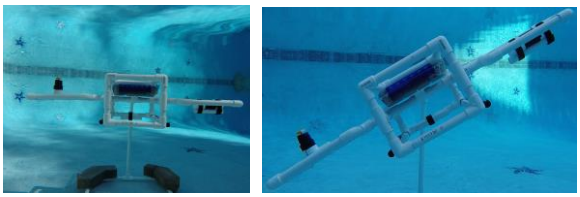
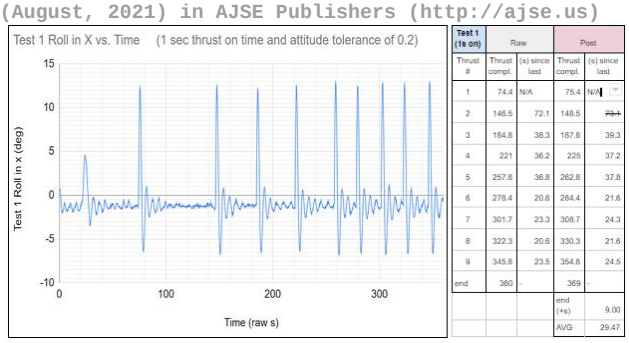


Fig. 3. (Top) Model and test rig submerged in a pool at approximately nominal orientation. (Bottom) Model and test rig submerged in a pool with significant attitude disturbance after thruster fire, which manifested as a +X roll in the model's frame.

The physical demonstration yielded 4 successful test runs, each greater than 6 minutes in length. Each run produced raw sensor data from the MPU-6050 and a text file with test event readouts. The sensor data was then able to be used to compile a data visualization for roll in the model's X-axis that coincides with the underwater video of the test runs. The TrojanCube concept was clearly demonstrated and the thruster disturbance properly executed every time the program recognized that the target had returned to a static attitude. Average time between thrusts was greater than the static limit imposed for all test runs, confirming that a notable attitude perturbation was induced.

After successful test runs were recorded, the sensor data was run through a filter to provide the relative roll in the model's X-axis. This data was then compiled in a spreadsheet and graphed with raw test time to provide a visual representation of the roll over time. The visual representation of the first of the four recorded successful test runs can be seen in Figure 4. The largest consistent spikes in the disturbance of the model's X-axis represent thruster actuation and can be differentiated from the early smaller spike that resulted from the test conductor physically handling the model.



Test 1 (1s on)	Raw		Post	
Thrust #	Thrust compl.	(s) since last	Thrust compl.	(s) since last
1	74.4	N/A	75.4	N/A
2	146.5	72.1	148.5	~~73.1~~
3	164.8	38.3	187.8	39.3
4	221	36.2	225	37.2
5	257.8	36.8	262.8	37.8
6	278.4	20.6	284.4	21.6
7	301.7	23.3	308.7	24.3
8	322.3	20.6	330.3	21.6
9	345.8	23.5	354.8	24.5
end	360		369	
			end (+s)	9.00
			AVG	29.47

Fig. 4. Roll in X (deg) versus test time (raw s) for the first test run. Test run 1 had a one second thrust setting as well as an attitude tolerance of 0.2. Raw thrust complete times and thruster fire spacing is displayed in the center "Raw" columns with corrected values under the "Post" columns. The bottom two cells represent the collective test time creep and the average time between thruster firings.

Beyond the initial successful test run, risk of water intrusion and the frigid water temperatures for the test conductor resulted in test iterations being rapid and chaotic. This resulted in the tolerance variable being incremented between tests in the wrong direction and was discovered later in post-test analysis. It was wrongly assumed that perceived delays between thruster firings was due to too restrictive of a tolerance when, in fact, it was actually due to a timing anomaly. This anomaly was a coding oversight, which presented as test time gain relative to thruster on-time. It was discovered that the test timer was not incrementing, nor were sensor readings being recorded, during thruster on-time. There were other variables in the test environment not originally accounted for, which presented in the data to include wind effects on surface water, sun versus shade temperature differences, and currents from the test conductor's physical entry and exit of the pool; however, these variables did not functionally affect the intended demonstration and proof of the concept.

Four test runs were completed and the aggregate data was plotted. The combined graph (Figure 5) shows the roll in X for the last 160 raw test seconds for each test run. With each successive test, as the thruster on-time was increased, the amplitude of the roll in X likewise increased.

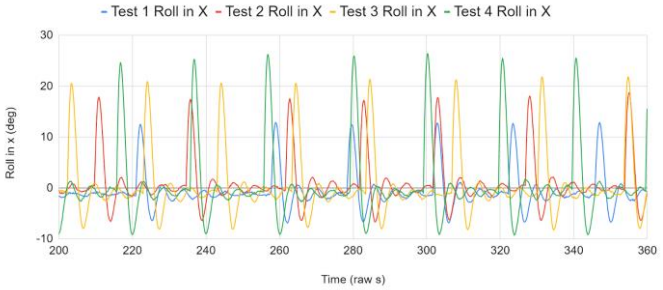


Fig. 5. Aggregate visual representation of the roll in X over the test period from 200 seconds to 360 seconds for four separate test runs. Test 1 used a 1 second thrust on-time and attitude tolerance of 0.2. Test 2 used a 1.5 second thrust on-time and attitude tolerance of 0.5. Test 3 used a 2 second thrust on-time and attitude tolerance of 1. Test 4 used a 3 second thrust on-time and attitude tolerance of 1.

This paper asserts that attitude disorientation of a spacecraft is an effective method of spacecraft sabotage. The degree of disorientation would be dependent on some mission specific tolerance to be deemed meaningful enough to adequately disturb the spacecraft. Here, the first test case used a tolerance of 0.2 difference between subsequent raw sensor readings. Since activation of the

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thruster is dependent on the sensor determining a static state, meaningful perturbation was determined because the time between thruster activations was greater than the static time limit.

As shown in Figure 6, the response of the target satellite to the Trojan perturbation was linear with the range tested; doubling the duration of the applied force roughly doubled the induced deviation in the satellite movement. These measurements were expected and parallel results from simulations. This validates the concept that a small TrojanCube using low impulse microthrusters can provide a meddlesome perturbation to the larger target satellite. The linear response also makes for easier design of perturbation profiles so that the TrojanCube can produce its choice of steady, erratic, or itinerant perturbation in order to confuse ground operations as to the source of the deviations.

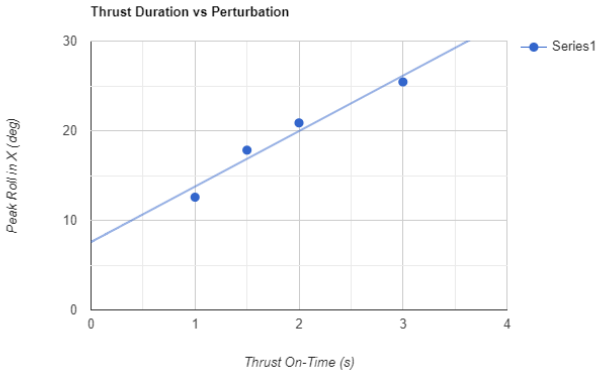


Fig. 6. Thrust duration versus perturbation. Vertical axis defined by peak average disturbance per test run. Horizontal axis defined by test run 1-4 thruster on-times.

IV. Simulation Method and Results

In parallel with the physical demonstration, we also created a simulation wherein the target Iridium NEXT and Trojan models are represented by basic geometric shapes with uniform density. As with the physical model, the moment of inertia changed when the TorjanCube was attached, which also changed the disturbance torque to the target from the Trojan thruster. We modeled both the disturbance momentum build up and the approximate fuel required to handle momentum dumping. We simulated the attitude perturbation potential of a target satellite as a result of a TrojanCube's thrust output, which required calculations of: the moment of inertia changes due to attachment of the TrojanCube, achievable disturbance torque to the target from the Trojan thruster, momentum build up over an orbit, and potential fuel required to handle momentum dumping. The program Matlab and its corresponding language were used to write scripts, which performed these calculations. Each script used a set of user-defined initial conditions, took into account certain general assumptions, and stepped through the required calculations. Figure 7 depicts the system inputs, assumptions, and script functions for the disturbance torque modelling.

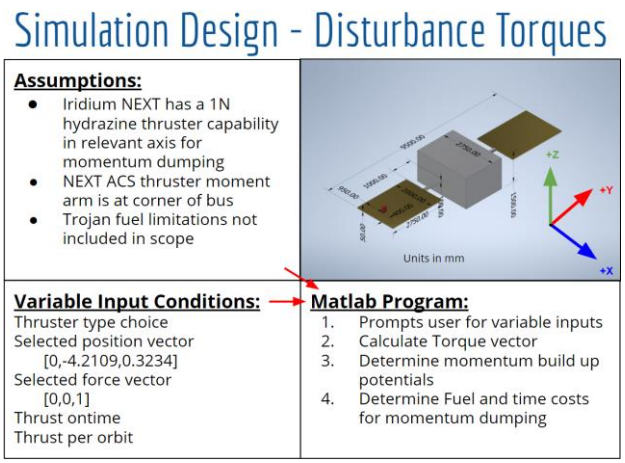


Fig. 7. Overview of disturbance torque script architecture and functions.

In calculating the moment of inertia changes, it was assumed that all components had uniform density, were cuboid in shape, and existed in the same reference frame. The script first determined individual component mass using an estimated total mass and percentage of total volume for each component. Next, the individual moments of inertia were calculated using the standard derivation for a cuboid moment. The center of mass of the model was defined, from an arbitrary reference point, as were the offsets from center of mass for each individual component. Then, the parallel axis theorem was used to move the moments to the center of mass. Next, the combined moment at the center of mass was found. Finally, the TrojanCube model was included in the system and a new center of mass was determined. Each of the prior steps was then repeated to find the new combined moment of inertia.

For the torque and momentum calculations, it was assumed that the Iridium NEXT had a 1N hydrazine thruster capability in the relevant axis for momentum dumping [8], the NEXT's thruster moment arm was at the corner of the spacecraft bus, and TrojanCube's fuel limitations would not be considered in the project scope. To achieve these calculations, the Matlab script prompted the user for a set of variable input conditions. First, it prompted the user to select a Trojan thruster from a set of commercially available small satellite thrusters. Second, it asked the user to provide the attachment point or position vector of the Trojan thruster, as well as the force vector. Last, it requested input of the thrust on-time and frequency of thruster firings per orbit. The Matlab script took these inputs and determined the resultant torque applied. From this torque calculation, momentum build up was also calculated for portions of an orbit over multiple orbits, as well as fuel requirements to dump the gained momentum under the simulated configuration. The table in Table 1 displays the relationship between thruster type selection, the "as-configured" torque applied by the thruster, and the selected thruster on-time per orbit. Since thruster force varied so widely by type, the thrust on-times were selected in order to constrain the momentum buildup outputs so that they were more visually comparable. It is, however, worth noting that the actual thrust on-time in a real-world mission setting would be dictated by the mission target and fuel constraints [9].

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Thruster	Applied Torque (Nm)	Thrust Time Per Orbit
EPSS-C1 1N BOL to 0.22N EOL (0.61N AVG)	-2.5686 0 0 X Y Z	1 sec
Regulus EPS 0.55mN nominal Plasma thruster	-0.0023 0 0 X Y Z	20 min
Halo 4-34mN (19mN AVG) hall-effect thruster	-0.0800 0 0 X Y Z	30 sec
PM200 0.5N nominal bi-propellent thruster	-2.1054 0 0 X Y Z	1 sec
IFM Nano Thruster 350uN nominal FEEP thruster	-0.0015 0 0 X Y Z	20 min

TABLE I. Table displays thruster type selection, the "as-configured" torque applied by the thruster, and the selected thruster on-time per orbit.

The script output graphs showing momentum buildup and responsive fuel mass required to handle momentum unloading over multiple orbits for each thruster selection; these graphs are included below. The first graph shows that in every thruster configuration, significant momentum build up can be reached with limited thruster on-time over a small number of orbits relative to a standard mission duration. As applied to a real-world TrojanCube mission, significant disturbances can be induced over a relatively short period of overall target mission time because the TrojanCube would likely be employed in low Earth orbit, which means that the orbital period would consequently be constrained to between 84 and 127 minutes.

The second graph below (Figure 8) shows that the fuel mass expenditure required of the target to handle the applied disturbance is minimal. For context, Iridium NEXT carries 141 Kg of Hydrazine monopropellant [9]; yet, the graph shows that the "as-configured" fuel mass expenditure never rises above 0.025 Kg, even after 30 orbits. This means that the fuel expenditure incurred on the target is acutely insignificant. Given the likely scale difference between fuel reserves for a cubesat versus a larger spacecraft, fuel expenditure can likely be deemed an ineffective vulnerability vector. However, given the precise pointing requirements imposed on a typical spacecraft mission, even slight disturbance to attitude will have immediate negative effects imposed on the target.

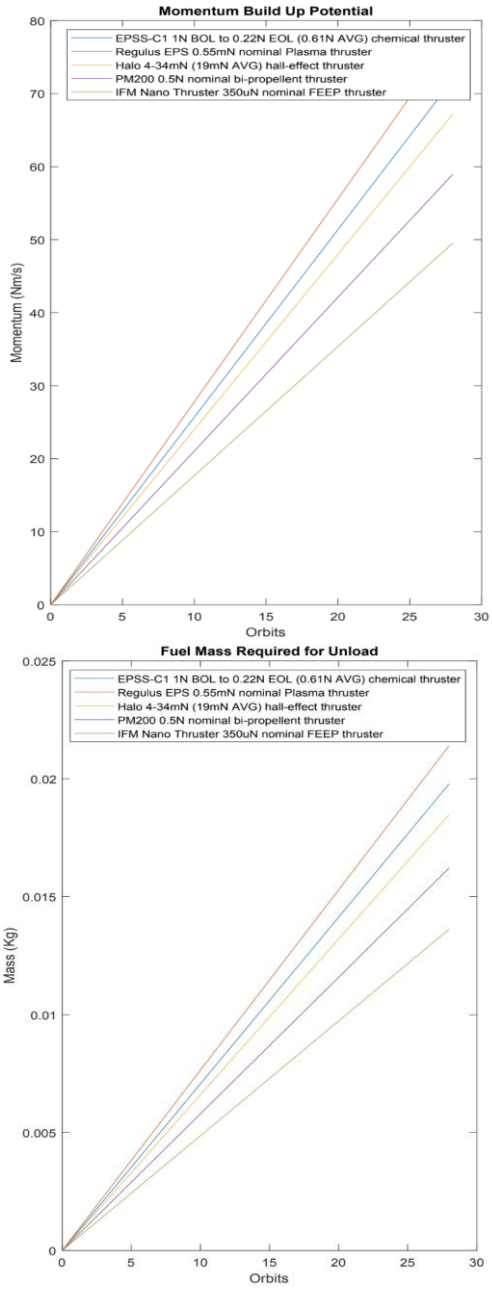


Fig. 8. Script output graphs of momentum (Top) and responsive fuel mass requirement (Bottom) over multiple orbits for each thruster selection.

Additionally, as one would expect, the simulation showed that higher-force thrusters provided higher torques and took less time to accumulate substantial momentum buildup. The lower-force, Ion-type thrusters had to run for longer; although, given more time, they could achieve the same momentum buildup. In all thruster cases, however, appreciable torques can be induced quite rapidly, resulting in disruption of the primary function of the target spacecraft.

Based on the resulting simulation data, it is apparent that the TrojanCube method is a viable option for spacecraft sabotage.

V. Ethical Concerns

As with any technology, this new idea for satellite sabotage raises certain ethical concerns regarding its

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intended uses, its unintended uses, and how this technology fits in with humanity. We establish that this technology's intended effect of sabotaging spacecraft is harmful by nature, but argues that its ethicality should be judged on how it achieves its desired goals — by minimizing the effect on orbital crowding and debris risk — and not merely on its harmful nature. Here, the technology is designed to incapacitate a spacecraft, yet it does so without adding to the orbital debris problem, thus achieving its goal in an ethical way. Since this method employs the use of cubesats, which tend to be inexpensive, this could easily be scalable and repeatable.

Because this method of attack affects the attitude and orbit of a victim spacecraft, it is conceivable that it could also be used to deliberately steer that spacecraft into situations where a collision has a greater likelihood. Although unintentional, the collision of Iridium 33 and Cosmos 2251 produced greater than 1800 new orbital debris in low Earth orbit (LEO)[5]. By misusing the technology, a bad actor could intentionally congest orbital lanes with more debris, which could threaten and potentially cut-off access to critical space infrastructure through a runaway process known as Kessler Syndrome [6]. This is precisely the opposite effect of the problem for which this technology attempts to provide a solution. Due to the potential for this misuse, the question again must be asked: is this technology ethical to pursue? The potential for misuse exists with every tool man has ever created and, in fact, often serves as the driving force behind new technological problems that need answers. Developing creative solutions to address these problems can, in turn, push our technological horizon forward.

VI. Conclusions

Weapons development often comes with a large price tag, however, cubesats have a much lower barrier to entry than larger missions [10]. While numbers can vary wildly for putting a satellite into orbit, there is, on average, several orders of magnitude in difference between the price of a satellite and a cubesat. The average cost to put a cubesat into orbit is on the order of 10s to 100s of thousands of dollars ($US), while the average cost to put up a larger satellite is 10s to 100s of millions of dollars ($US). As an additional comparison, space-based-interceptor missile systems were estimated to have costs in the billions [11]. However, cubesats by nature have both low development and production costs. Their relative size and low mass constrains both the physical resource requirement per cube and the complexity of systems that can be included due to available space. The use of standardized design and commercially available off-the-shelf parts can allow for rapid mass production. This means that procurement of this weapon system would be both highly scalable and economically viable.

The physical and simulation demonstrations of our project also show that the TrojanCube is a realistic option for spacecraft sabotage. The project set out to explore the concept of deliberately impairing the attitude and orbit of a target spacecraft via the direct attachment and thrust output of a Trojan cubesat. Our physical model produced thruster commands based on attitude sensor feedback, repeatedly disturbing orientation, which demonstrated the overall concept and a potential software solution in a neutral buoyancy test environment. It also showed that this method can be executed autonomously. Additionally, we successfully modeled simulations of attitude perturbations of a target Iridium NEXT model as a result of a TrojanCube's thrust output. We found that appreciable torques and subsequent momentum build up can be applied to a target by a range of commercially available small-form thrusters in a short period of time. The overall project demonstrated that a TrojanCube can quite easily disrupt the primary mission function of a target spacecraft due to the precision pointing required for many instruments, high gain antennas, and solar panel facings.

Although scalable, economically viable, and physically realistic, the operation of this potential weapon system also raises a set of considerations. First, deployment of the system is dependent on delivery to orbit and subsequent maneuvering by the cube to the target. There are several options to examine when considering how to employ the TrojanCube method of attack. For example, one option is to deploy multiple TrojanCubes as a primary payload, delivering them in batches to multiple orbits where they lay dormant, awaiting activation from the ground; while another option is for a singular TrojanCube to hitch a ride as a secretive secondary to an alternative primary mission that, when activated, separates and redirects towards its intended target. Another consideration that must be addressed is that international space and arms laws may present a barrier to development and deployment of this system and would require thought before real development work could proceed. Finally, one must consider the issue of how to conduct functional in situ system testing economically. Because there is no shortage of defunct materials and spacecraft in orbit, assessment of intended effects of the weapon system could be conducted against any of these potential targets or a friendly asset that has reached, or is approaching, end of life.

While deployment of the TrojanCube system and in situ assessment raise unique considerations, the provided solutions address those concerns and furnish unique opportunities for creative development. Additionally, given the low individual cost and high scalability potential, a TrojanCube should be considered an extremely likely and economical weapon system. The demonstration model and simulated momentum build-up potential also showcased the potential effectiveness and feasibility of the TrojanCube in the space domain and found that TrojanCube is an effective method to sabotage spacecraft functions and operation.

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