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Citation: Jia-Richards, Oliver and Paulo Lozano et al. "Redundancy for Asteroid Detumbling via Staging." 2021 IEEE Aerospace Conference, March 2021, Big Sky Montana, Institute of Electrical and Electronics Engineers (IEEE), June 2021. © 2021 IEEE

As Published: <http://dx.doi.org/10.1109/aero50100.2021.9438201>

Publisher: Institute of Electrical and Electronics Engineers (IEEE)

Persistent URL: <https://hdl.handle.net/1721.1/131027>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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Redundancy for Asteroid Detumbling via Staging

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Abstract—This work analyzes the use of microfabricated electro-spray thrusters in a staged configuration during detumbling of small asteroids. For asteroid redirection missions, keeping the asteroid in a static and controllable orientation greatly simplifies the redirection process. In order to achieve this, spacecraft with propulsion systems need to be landed on the surface of the asteroid in order to detumble it. Prior work has studied the optimal landing locations of these detumbling spacecraft as well as suggested that small spacecraft, such as CubeSats, may be ideally suited for this task. However, small spacecraft suffer from component reliability issues, particularly in the propulsion system where redundancy is not typically provided. A potential solution is to use staging, analogous to launch vehicle staging, in order to provide propulsion system redundancy directly on each spacecraft. Staging has primarily been studied for enabling deep-space CubeSat missions with microfabricated electro-spray thrusters by bypassing the lifetime limitations of individual thrusters in order to increase the overall lifetime of the propulsion system, but it can also be used to provide redundancy. A small fleet of CubeSats, each equipped with a staged electro-spray propulsion system can detumble a small asteroid, all while providing redundancy in the event of a propulsion system failure. This work estimates the size of asteroid that can be detumbled with microfabricated electro-spray thrusters as well as the number of stages required in order to guarantee specified probabilities of mission success.

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1. INTRODUCTION

The redirection of near-Earth asteroids can be used to avoid potential impacts of the asteroid with Earth or to bring small asteroids to the vicinity of Earth for scientific study. As part of the redirection maneuver, detumbling of the asteroid may be a necessary first step; laser ablation and “tugboat” concepts both have improved performance for asteroids with lower rotation rates [1], [2]. While larger asteroids ($\gtrsim 100$ m) may have low enough rotation rates for these concepts to be effective, the small asteroids that have been observed tend to have relatively high rotation rates [3], [4]. This tendency could be caused by the bias against slowly-rotating asteroids in estimating rotation rates as well as the possibility that many small asteroids are monolithic and therefore do not have their rotation rates limited by gravitational attraction [4].

Small asteroids are favorable targets for redirection to the

vicinity of Earth as their relatively low mass means that they are easier to redirect. The detumbling of small asteroids through landing small spacecraft with low-thrust propulsion systems has been studied for its feasibility [5] and algorithms for determining the optimal landing locations of these detumbling spacecraft have been developed [6]. However, the ability to provide redundancy in the case of failure is still an open question. In particular, the ability to provide redundancy for propulsion system failures, which represent a large portion of all CubeSat system failures [7], is challenging as the restrictive form factor of CubeSats typically prevents redundancy from being embedded into the propulsion system itself. A previously proposed solution is to land additional detumbling spacecraft such that if one or more of them fail, the detumbling maneuver can still be completed [6], [8].

Landing additional spacecraft in order to provide propulsion system redundancy can dramatically increase the complexity of the detumbling maneuver. First, this solution requires more spacecraft to be manufactured as well as transported to the target asteroid. Second, landing the detumbling spacecraft onto the asteroid will itself carry significant risk. While quasi-analytical methodologies for landing on tumbling objects have been developed [9], they can be costly in terms of propellant and require accurate knowledge of the object’s spin state. Finally, the complexity of determining the optimal landing locations for the detumbling spacecraft increases with the number of spacecraft [6]. As such, it is desirable to minimize the number of spacecraft that need to be landed in order to successfully complete the detumbling maneuver.

This work proposes the use of staging, analogous to launch vehicle staging, in order to provide propulsion system redundancy directly on each detumbling spacecraft. Figure 1 shows a concept image of staging on a 3U CubeSat. A stage-based system consists of a stack of propulsion system elements which could be just the thrusters themselves or thrusters and fuel tanks. If one element in the stack fails prematurely, it is ejected from the spacecraft thereby exposing a new element which can continue the mission. This solution is restrictive in that it requires a propulsion technology where multiple elements can be included without significantly increasing the mass and volume of the overall propulsion system. Fortunately, passively-fed microfabricated electro-spray thrusters [10] are ideally suited for such a system; their lack of propellant management systems (such as pumps and pressurized containment) means that the mass of a thruster and its fuel tank is small relative to other spacecraft systems.

The Ion Electro-spray Propulsion System (IEPS) under development at the Space Propulsion Laboratory at the Massachusetts Institute of Technology is a type of microfabricated electro-spray thruster that utilizes ionic liquid as its propellant [10]. A single thruster mounted on a propellant tank is shown in Figure 2. The thruster itself is a 13 x 12 x 2.4 mm chip and consists of an emitter array with 480 emitter tips, a gold-coated silicon extractor grid, and a silicon frame.

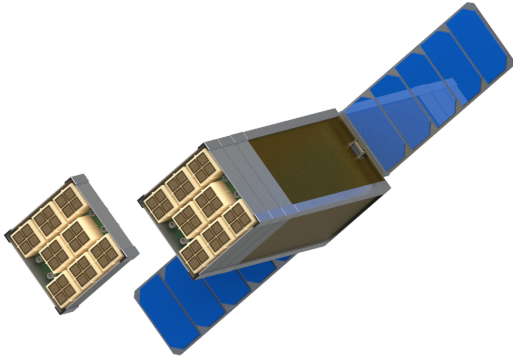


Figure 1. Concept image of staging on a 3U CubeSat.

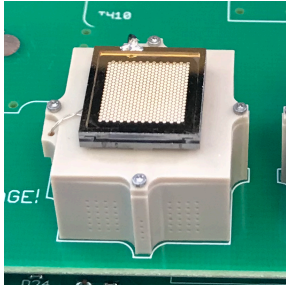


Figure 2. IEPS thruster mounted on a fuel tank.

Ionic liquid is passively fed from the fuel tank to the emitter array eliminating the need for any propellant management systems. In addition, since ionic liquids have negligible vapor pressure at the expected operational temperatures of a spacecraft [11], no form of pressurized containment is required. These advantages allow the thruster and propellant tank to be compact and ideally suited for propulsion of small spacecraft such as CubeSats.

Staging was originally analyzed as a method of reducing the overall mission time of lunar missions by approximately 10% [12]. Since the spacecraft ejects the dry mass of the thrusters and fuel tanks in addition to the propellant mass, the propulsive acceleration is substantially increased towards the end of the mission relative to a traditional, single-stage, propulsion system. Further studies have analyzed the feasibility of integrating a stage-based electro spray propulsion system based on IEPS thrusters into a CubeSat form factor for missions to near-Earth asteroids [13] and demonstrated the operation of a stage-based electro spray propulsion system in a vacuum environment [14]. For this work, staging is proposed in order to provide propulsion system redundancy throughout an asteroid detumbling maneuver. However, the implementation is similar and requires the same mechanisms that were developed in Ref. [15].

This paper analyzes the feasibility of detumbling a small asteroid with CubeSats equipped with electro spray thrusters and shows that staging can be used in order to provide propulsion system redundancy. The scenarios in this paper are not intended to be the full detumbling scenarios considered in [6], but rather simplistic scenarios from which an approximation of the detumbling time can be obtained. The example considers the asteroids 2006 RH₁₂₀ and 2011 MD which could be potential targets for asteroid redirection missions and shows that these asteroids could be detumbled with electro spray thrusters in times short relative to the redirection time. In

addition, if the use of staging in order to provide redundancy is required, the overall mass and volume of the propulsion systems are still expected to be quite small (~ 2 kg, ~ 0.8 U) with the majority of the mass being propellant.

2. DETUMBLING VIA ELECTROSPRAYS

The control law for detumbling a space object in minimum time with constraints on the maximum torque that can be applied is

$$\vec{\tau} = -\frac{\vec{h}}{\|\vec{h}\|} \tau_{\max} \quad (1)$$

where $\vec{\tau}$ is the applied torque, \vec{h} is the angular momentum vector of the object, and τ_{\max} is the maximum torque that can be applied [16]. This control law gives a convenient estimate for the time it would take to completely detumble an object with initial angular momentum of magnitude h_0 as

$$T = h_0 / \tau_{\max} \quad (2)$$

Assuming that the asteroid of interest is spherical with radius r and mass density ρ , then its mass can be approximated as

$$m = \frac{4}{3} \pi \rho r^3 \quad (3)$$

and its rotational inertia as

$$I = \frac{2}{5} m r^2 = \frac{8\pi}{15} \rho r^5 \quad (4)$$

where it is assumed that the detumbling spacecraft contribute negligibly to the overall rotational inertia. Therefore, for a given initial rotational velocity, ω , the asteroid has an initial angular momentum of

$$h_0 = I\omega = \frac{8\pi}{15} \omega \rho r^5 \quad (5)$$

Assuming that the detumbling spacecraft are placed on the equator of the asteroid, then the maximum torque that can be applied is given by

$$\tau_{\max} = r F_{\max} \quad (6)$$

where F_{\max} is the combined maximum thrust output of all detumbling spacecraft around a given axis. Substituting Eqs. 5 and 6 into Eq. 2 allows the detumbling time to be related to properties of the asteroid and propulsion system as

$$T = \frac{8\pi}{15} \frac{\omega \rho r^4}{F_{\max}} \quad (7)$$

Eq. 7 gives a rough estimate of the detumbling time for a given asteroid. It does not account for the possibility that the asteroid is non-spherical and may be tumbling rather than spinning around a primary axis. These effects are difficult to evaluate due to the limited data available for these objects. However, even if the asteroid is tumbling then the maximum torque that can be applied will still be similar to Eq. 6 but depend on exactly how the detumbling spacecraft are arranged on the asteroid's surface.

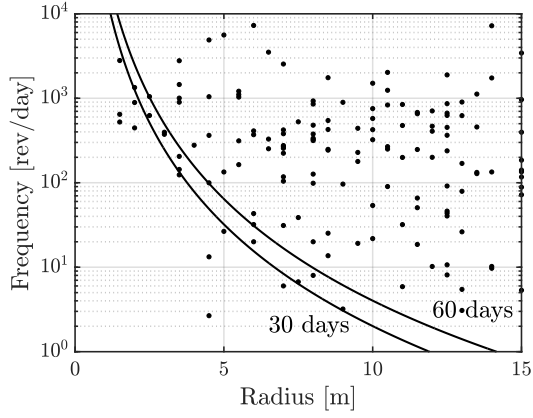


Figure 3. Asteroid rotational frequency versus radius. Lines indicate the boundary between asteroids that could feasibly be detumbled within 30 and 60 days assuming a usable thrust of 2.56 mN, that all asteroids are spherical with mass density equal to the average mass density of S-type asteroids (2.71 g/cm^3), and that the detumbling spacecraft are placed on the equator of the asteroid.

Figure 3 shows rotational frequency versus radius for asteroids with radii on the range 0–15 m cataloged in the asteroid lightcurve database [17]. The lines correspond to contours of Eq. 7 for detumbling times of 30 and 60 days. The asteroid mass density was selected to be the average mass density of S-type asteroids (2.71 g/cm^3 [18]) as the vast majority of the asteroids in this radius range of the asteroid lightcurve database are S-type. The apparent dearth of C-type asteroids, which are the largest family of asteroids in the solar system, may be due to their low albedo, relative to S-type asteroids, which when combined with the small size of the asteroids surveyed here makes them difficult to observe [19]. The maximum thrust was selected to be 2.56 mN, which is the expected thrust for two 3U CubeSats each equipped with an electro spray thruster system similar to the one shown in Figure 1. Asteroids below each line can be detumbled within the specified time frame for the assumed asteroid and propulsion system parameters. Although this corresponds to a small fraction of the asteroids in the lightcurve database, there are still 10 asteroids that could be detumbled in under 30 days and likely many more that have yet to be observed.

Figure 4 shows the number of asteroids in the lightcurve database that can be detumbled versus the allotted detumble time. The asteroid mass density is still assumed to equal to the average mass density of S-type asteroids and the total thrust of the propulsion system is still assumed to be 2.56 mN. There are 4 observed asteroids that could potentially be detumbled in under 10 days demonstrating that electro spray thrusters could be used to detumble small asteroids in relatively short time scales. The asteroids that could be detumbled in under 10 days are quite small in size, but it is exactly this size of asteroid that has been considered as targets for potential asteroid redirect missions [20].

3. REDUNDANCY VIA STAGING

A stage-based approach, as shown in Figure 1, could be used to provide propulsion system redundancy throughout the detumbling maneuver. The analysis in this work starts at the probability density function for the lifetime of a given stage.

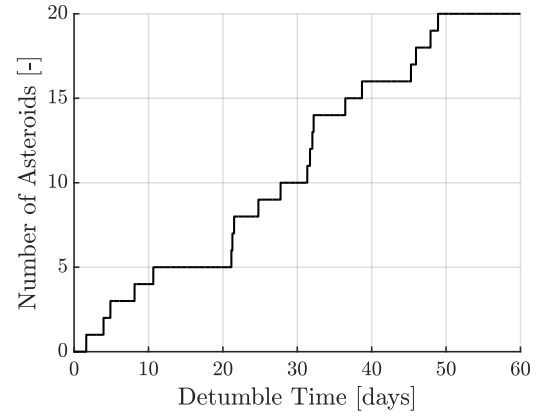


Figure 4. Number of observed asteroids that can be detumbled within a given time. Assumes a usable thrust of 2.56 mN, that all asteroids are spherical with mass density equal to the average mass density of S-type asteroids (2.71 g/cm^3), and that the detumbling spacecraft are placed on the equator of the asteroid.

In reality, the analysis should probably start at the probability density function for the lifetime of a given thruster or even individual emitters on each thruster. However, these functions are completely unknown and there is currently not much value gained by starting the analysis at that level of depth. In addition, the lifetime of different stages are expected to be independent from each other whereas the lifetime between different thrusters or emitters will be dependent. Finally, there exists an ambiguity on how to determine the lifetime of a stage based on the lifetime of the individual thrusters; the lifetime of a stage could be taken as the lifetime of the shortest-lived thruster on the stage, or a more nuanced approach could be taken where the lifetime is defined as a balance between maximizing total impulse output of the stage and maximizing the overall thrust (in order to minimize mission time) as is considered in Ref. [21].

The overall lifetime of the propulsion system is then just the sum of the individual lifetimes of the stages. In the particular case that the lifetime of each stage, L_s , is drawn from a normal distribution with mean μ_L and standard deviation σ_L

$$L_s \sim \mathcal{N}(\mu_L, \sigma_L^2) \quad (8)$$

then the lifetime of the overall propulsion system, L_p , is also drawn from a normal distribution

$$L_p \sim \mathcal{N}(n\mu_L, n\sigma_L^2) \quad (9)$$

where n is the number of stages. In general, the probability density function for the lifetime of the propulsion system will have to be approximated numerically through Monte Carlo analysis. However, since computing the overall propulsion system lifetime given individual stage lifetimes is a trivial computation, a large number of samples can be used in the Monte Carlo analysis in order to determine the propulsion system lifetime distribution to high precision.

With the probability density function for the lifetime of a staged propulsion system, $f_L(l)$, the mission success criteria can be defined based on the lifetime of every spacecraft's propulsion system being greater than the required detumbling time. Therefore, the probability of mission success for N

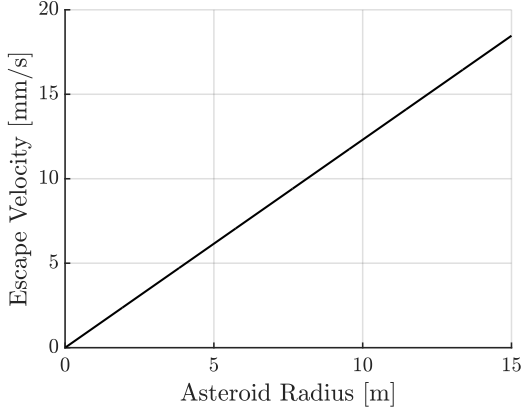


Figure 5. Estimated escape velocity around asteroids of various radii. Assumes that all asteroids are spherical with mass density equal to the average mass density of S-type asteroids (2.71 g/cm^3). This is the velocity that the ejection mechanism needs to provide to ejected stages throughout the detumbling maneuver in order to avoid potential collisions between ejected stages and detumbling spacecraft.

spacecraft can be calculated from

$$\mathbb{P}(\text{success}) = \left(\int_T^\infty f_L(t) dt \right)^N \quad (10)$$

where it is assumed that the lifetime of the propulsion systems between spacecraft are independent and identically distributed. This analysis is conservative in that it requires the lifetime of every spacecraft to be greater than the detumbling time where in reality it is possible for the asteroid to be detumbled even if a few spacecraft fail. However it requires only the computation of the probability of a single spacecraft's lifetime being above the detumble time in order to calculate the overall mission success probability.

Beyond solving for the appropriate number of stages, another concern about using staging in order to provide redundancy might be what happens to the ejected stages. Ideally, the ejected stages escape the asteroid otherwise there is a possibility that they might collide with one of the detumbling spacecraft. Figure 5 shows the escape velocity at the surface of spherical asteroids of various radii with an assumed mass density equal to the average mass density of S-type asteroids (2.71 g/cm^3 [18]). In order to ensure that all ejected stages escape the asteroid, the ejection mechanism needs to be able to impart this velocity to each ejected stage. Even for the largest asteroids considered in this work, the escape velocity is under 2 cm/s - a velocity that is easily achievable with a spring-based ejection mechanism such as the once considered in Ref. [15].

4. EXAMPLE

As examples, consider the asteroids 2006 RH₁₂₀ and 2011 MD. Both of these asteroids are identified as easily-retrievable objects [20] which could be brought to the L₁ or L₂ Lagrange points of the Sun-Earth system at low- ΔV cost, and both appear in the asteroid lightcurve database [17]. Data from observations of these asteroids are available [22], [23], including elongation and approximate mass density, allowing for a more-accurate assessment of the required detumbling

Table 1. Physical properties of 2006 RH₁₂₀ and 2011 MD.

	2006 RH ₁₂₀	2011 MD
Size	3 m	7 m
Rotational Period	2.7 min	11.6 min
Elongation	1.4	2.5
Density	N/A	1.1 g/cm^3

time beyond the spherical approximation.

Data for both asteroids are shown in Table 1. Both the size (approximate diameter) and rotational period are taken from the asteroid lightcurve database [17]. In the case of 2006 RH₁₂₀, an elongation (ratio of the major axis to minor axes of a triaxial ellipsoid) of at least 1.4 is estimated in Ref. [22]. For 2011 MD, the elongation is estimated at 2.5 and the mass density is estimated at 1.1 g/cm^3 [23]. In neither case were observations conclusive regarding if the asteroid is tumbling or not. The time scale at which the tumbling motion of an asteroid will be damped to principal-axis rotation can be estimated [24] and is approximately 2 MYr for 2006 RH₁₂₀ and 30 MYr for 2011 MD. The time scale between collisions that alter the angular momentum of an asteroid can also be estimated [25] and is approximately 2 MYr for both 2006 RH₁₂₀ and 2011 MD. One caveat is that the estimate using the method in [25] is for asteroids in the asteroid belt. Although both 2006 RH₁₂₀ and 2011 MD are near-Earth asteroids with orbital elements similar to those of Earth, it is assumed that the time scales between collisions that alter their angular momentums are of the same order. It is therefore unclear if 2006 RH₁₂₀ would be tumbling but it certainly seems as though 2011 MD might be. However, in the absence of data regarding the tumbling motion of either asteroid, it is assumed that both asteroids rotate around their principal axis and any tumbling motion would not significantly impact the detumbling time estimate.

To account for the elongation, it is assumed that both asteroids are triaxial ellipsoids with axis ratios of $(\gamma, 1, 1)$ where γ is the elongation. The volume of the triaxial ellipsoid is assumed to be equal to a sphere with diameter equal to the size given in Table 1. This means that the minor axes of the ellipsoid, b , will be given by

$$b = D/2\gamma^{1/3} \quad (11)$$

where D is the diameter of the equivalent sphere, and the major axis, a , is given by

$$a = D\gamma^{2/3}/2 \quad (12)$$

The mass of the asteroid is then

$$m = \frac{4}{3}\pi\rho ab^2 = \frac{1}{6}\pi\rho D^3 \quad (13)$$

and assuming that both asteroids are rotating around their principal axes, then their rotational inertias are given by

$$I = \frac{1}{5}m(a^2 + b^2) = \frac{1}{120}\pi\rho D^5 \left(\frac{\gamma^2 + 1}{\gamma^{2/3}} \right) \quad (14)$$

The time to detumble the asteroids is then given by Eq. 2. It is assumed that the detumbling spacecraft are placed along the major axis of the asteroid giving a maximum torque of

$$\tau_{\max} = aF_{\max} \quad (15)$$

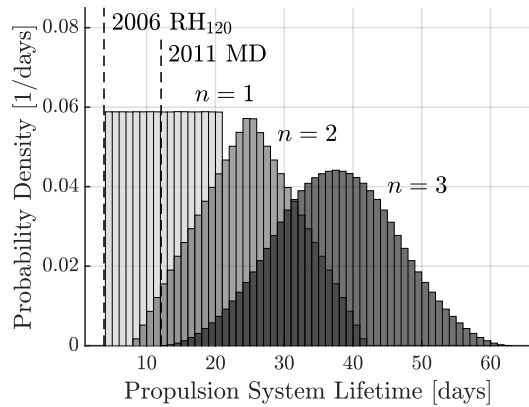


Figure 6. Probability density of the overall propulsion system lifetime for 1–3 stages assuming that the lifetime of each stage is drawn from a uniform distribution on the range 4–21 days. Vertical dashed lines show the estimated detumbling time for asteroids 2006 RH₁₂₀ (3.8 days) and 2011 MD (12.1 days).

Using the asteroid data from Table 1 and assuming a two spacecraft configuration with a maximum combined detumbling thrust of 2.56 mN, 2006 RH₁₂₀ could be detumbled in 3.8 days and 2011 MD could be detumbled in 12.1 days. Since no estimate of the mass density of 2006 RH₁₂₀ was provided in [22], it was assumed to be equal to the average mass density of S-type asteroids (2.71 g/cm³ [18]). These detumbling times are much shorter than time it would take to redirect the asteroid to the Sun-Earth L₁ and L₂ Lagrange points, so they should not noticeably effect the overall mission planning.

For determining the required number of stages, it is assumed that the stage lifetime is given by a uniform distribution on the range 4–21 days

$$L_s \sim \mathcal{U}(4, 21) \text{ days} \quad (16)$$

which ranges from the published lifetimes of IEPS thrusters (~ 4 days [10]) to the expected current lifetimes (~ 21 days). Figure 6 shows histograms for the probability density for the lifetime of each spacecraft’s propulsion system for 1–3 stages. The distributions were generated with Monte Carlo analysis with 10^8 samples for each number of stages. The two vertical lines show the estimated detumbling time for 2006 RH₁₂₀ and 2011 MD. Only a single stage is required to detumble 2006 RH₁₂₀ as the minimum value of the stage lifetime is greater than the detumbling time. However, for 2011 MD multiple stages are required. When requiring that the lifetime of the propulsion systems for both spacecraft need to be above the detumbling time, the probability of mission success is estimated at 27% for $n = 1$, 94% for $n = 2$, and 100% for $n = 3$. The actual probability of mission success for 2011 MD with 3 stages is slightly lower than 100%. However, mission failure would require that the lifetime of all three stages be extremely close to their minimum possible value and therefore has a near-zero probability of occurring. Using importance sampling, the probability of mission failure when detumbling 2011 MD with a 3-stage system can be estimated at 6.8×10^{-8} .

5. CONCLUSION

This work shows that electro spray thrusters could be used to detumble small asteroids for potential asteroid redirection maneuvers, including asteroids such as 2006 RH₁₂₀ and 2011 MD which could be brought to the neighborhood of Earth at low ΔV cost. In addition, the use of staging is proposed in order to provide propulsion system redundancy throughout the detumbling maneuver as opposed to previously considered methods [6], [8] that require the landing of extra spacecraft.

Staging leverages the low mass and volume of electro spray thrusters in order to allow propulsion systems consisting of multiple stages to be created without exceeding the mass and volume constraints of small spacecraft such as CubeSats. While staging does provide redundancy for the propulsion system, other spacecraft systems, such as the solar panels, may still suffer from component reliability issues. In this case, additional spacecraft will still need to be landed on the asteroid according to the methods presented in Ref. [8]. However, because the additional spacecraft do not need to provide propulsion system redundancy, the number of additional spacecraft will be reduced.

In order to more accurately assess the number of stages required to ensure a particular probability of mission success, the distribution of stage lifetimes needs to be determined. This in turn requires the determination of the distribution of lifetimes for thrusters and potentially for individual emitters on each thruster array. The lifetime of emitters on an array are likely heavily dependent on each other. Non-uniformity of the emitted current on an array can lead to certain emitters being overly stressed [26], potentially reducing their lifetime. As stressed emitters deteriorate, other emitters on the array may then be stressed in order to maintain an overall current output of the thruster thereby coupling the deterioration of emitters on a given array. The lifetime can also be impacted by human factors, such as the misalignment of the extractor grid with the emitter array leading to excessive plume impingement on the extractor grid.

Without any knowledge on the distribution of lifetimes for a stage, a uniform distribution is used in order to cover the published lifetimes and the expected current lifetimes of IEPS thrusters. Under the assumed distribution and requiring a mission success probability close to 100%, asteroid 2006 RH₁₂₀ could be detumbled in 3.8 days with a single stage while asteroid 2011 MD could be detumbled in 12.1 days with three stages. In both cases the detumbling time is short relative to the time it would take to redirect the asteroid to the vicinity of Earth. In addition the number of required stages is quite low. Estimates of the mass and volume for a three-stage system are 2.2 kg and 0.82 U respectively, including the power processing unit [13]. The majority of the propulsion system mass ($\sim 64\%$) is propellant.

ACKNOWLEDGMENTS

Funding for this work was provided by the NASA Space Technology Mission Directorate through the Small Spacecraft Technology Program under grant 80NSSC18M0045 and through a NASA Space Technology Research Fellowship under grant 80NSSC18K1186. In addition, Paulo Lozano would like to thank the Miguel Alemán-Velasco foundation for its support.

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