ROBUST ASTEROID IMPACT MITIGATION
by Viral Infection-Induced Exocytosis

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We review many of the main techniques proposed for technological mitigation of any threat posed by a near-Earth asteroid. Most of these methods require substantial warning times, the deployment of potential weapons of mass destruction and/or the launch of high mass assets to intercept the incoming asteroid. We present the idea that a self-replicating machine might pose an alternative solution in keeping the launch mass modest yet provide a mass amplification capability that could be exploited. We find that this is indeed the case, and that a 10 tonne self-replicating payload delivered to the surface of asteroid Bennu, a large asteroid of 0.5 km diameter, could consume the entire asteroid within 2.5 months or a 10 km diameter asteroid such as the KT impactor within 8.5 months (spanning over four orders of magnitude mass variation) imposing a very short warning time capability that grows only logarithmically with asteroid size.

Keywords: Asteroid impact mitigation, Electromagnetic launchers, Self-replicating machines

1 INTRODUCTION

Space situational awareness (SSA) is the term used to encompass the problem of natural hazards like near-Earth objects (NEO) and artificial hazards like space debris to operational spacecraft. SSA is a broad concept in characterising space threats to human activities in space and on Earth. Of these threats, the prospect of impact onto the Earth's surface by rogue Near-Earth Asteriods (NEAs) presents itself as particularly potentially catastrophic. Unlike any other natural disaster, such as supervolcano eruptions and/or basalt flooding, asteroid/comet impact can be mitigated against using current or near-current technology, in this case, space technology.

The main asteroid belt resides around two Jovian resonances at 5:1 (1.78 AU) and at 2:1 (3.28 AU). The asteroid size distribution is given by:

$$n = \frac{dN}{dD} = kD^{-\alpha} \quad (1)$$

where α = 2.3 for 0.4 km<D<5 km
= 4 for 5 km<D<20 km

NEAs leak from the main asteroid belt toward the Sun due to the Yarkovsky effect favouring smaller asteroid body migrations. Hence, NEO asteroids are typically smaller than average main belt asteroids (MBA) dominated by collision fragments making them difficult to observe except when they pass close to the Earth [1]. Furthermore, they are observable only over a short orbital arc making predictive orbital mechanics difficult - a minimum of three asteroid detections is required at different times to determine an asteroid's trajectory - particularly as gravitational encounters can alter this trajectory during close encounters through planetary orbit crossings. NEOs have low eccentricity ($0 \leq e \leq 0.4$), low inclination ($0 \leq I \leq 10°$) and perihelia under 1.3 AU and are classified into four types: (i) Atens are Earth-crossing with r_a>0.983 AU and a<1.0 AU; (ii) Apollos are Earth-crossing with r_p<1.017 AU and a>1.0 AU; (iii) Amors are not Earth-crossing with 1.017 AU<r_p<1.3 AU lying outside Earth's solar orbit; (iv) Atiras are not Earth-crossing with a<1 AU and r_a<0.983 AU lying inside Earth's solar orbit. Around 90% of NEOs comprise the Amor and Apollo populations. About 20% of NEOs can approach Earth's orbit within <0.05 AU of the Earth. Atens have the highest frequency of close encounters with the Earth with close encounters being 3.5 times more frequent than with Apollos. Because the Amors and Atiras are not Earth-crossing, they are ideal for technology testing missions without the prospect of Earth encounter. NEOs comprise primarily of near-Earth asteroids (NEA) supplemented by some extinct comets that approach or intersect Earth's heliocentric orbit [2]. The average lifetime of a NEA is around 30 My due to gravitational perturbations so their populations must be replenished continually. NEOs originate from the inner part of the main asteroid belt where their aphelia tend to reside (consistent with the dominance of S-type asteroids in the NEO population [3]) from Jovian resonances while the 6% comet nuclei population originate from the Edgeworth-Kuiper belt [4,5]. The largest NEOs are the spherical 35 km diameter 1036 Ganymed followed by the peanut-shaped 14 x 37 km 433 Eros, both being S-type asteroids dominated by pyroxene and olivine silicates. Most of the solar system's comet population originates from the spherical Oort cloud of ~10^{12} long period comets at $r \geq 10^4 – 10^5$ AU with an accumulated mass of around 1 Earth mass [6]. Trans-Neptunian icy objects (of which Pluto-Charon are members) originate from the Edgeworth-Kuiper belt of short period comets close to the ecliptic between 30-50 AU peaking at 41-46 AU. The Edgeworth-Kuiper belt

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has an estimated cumulative mass 20-200 times that of the asteroid belt at 5-20 lunar masses plus an additional scattered disk of 4-40 lunar masses. Comets are thus far more abundant than asteroids. Comet nuclei are inactive because they are mostly covered by an inactive dust layer which seals off the subsurface gases. This dust layer accumulates onto the surface of the comet nucleus rendering an asteroid-like veneer and suppressed outgassing. For example, comet Encke is evolving towards an asteroidal appearance.

There have been several recent missions undertaken to explore asteroids. The Galileo mission performed flybys of 951 Gaspra (1991) and 243 Ida-Dactyl (1993) but dedicated asteroid missions began with NEAR-Shoemaker (2001) which soft landed on the S-type 433 Eros (Amor group) following a flyby of the C-type 253 Mathilde (main belt group), both of which exhibited characteristic impact craters and regolith covering. Hyabusa (2005) landed on 25143 Itokawa and returned with samples to Earth. OSIRIS-REx (origins spectral interpretation resource identification security regolith explorer) is a NEA sample return mission to the 500 m diameter B-type carbonaceous chondrite 101955 Bennu (which will potentially pass through a keyhole of Earth in 2135 to impact sometime over the 2175-2196 timeframe) to return a sample in 2023. OSIRIS-REx results from its analysis of Bennu indicate that it is volatile-rich with hydrated silicates, phyllosilicates and rugged large boulders and a rubble pile porosity of 50% [7].

2 THE NEO THREAT

The Spaceguard Survey has been cataloguing an increasingly large population of Earth-crossing asteroids and is expected to discover 90% of the NEO population larger than 140 m in diameter by 2028 - a diameter of 140 m represents the smallest impact hazard with the potential for significant regional rather than global devastation [8]. We believe we have discovered around half of the asteroids capable of destroying a city (in 2020) yet we have failed to observe large asteroids in close flybys of Earth. By 2015, 12,800 NEOs have been catalogued of which 10% are larger than 1 km in diameter, 3300 have diameters between 300 m and 1 km, and it is estimated that there are 30,000-300,000 which are larger than 100 m in diameter (with an estimated frequency of one impact every 300 years). There are only three asteroids around 10 km in diameter, none of which pose a threat to Earth (with an estimated frequency of one impact every 50-100 My). On the assumption that a 1 km asteroid has a magnitude M of 17.75, the cumulative NEO population N by size (magnitude M) may be modelled as:

$$N = 10^{(0.35 \pm 0.02)M} \text{ for } 13<M<22 \tag{2}$$

This implies that the total population of NEOs is 29,400 ± 3600 for M<22. Although none of the detected 1 km diameter asteroids appear to present a threat to Earth, the same cannot be said for 100-150 m diameter asteroids which are much more populous. In 2018, NASA's Centre for Near Earth Object Studies identified 18,136 known NEAs of which 1900 were potentially hazardous of size exceeding 140 m passing within 0.05 AU of Earth [9].

Comets are potentially more destructive due to their large size (up to 100 km diameter) despite their lower density of 0.6 g/cm^3 compared with 2.6 g/cm^3 for a stony asteroid, and higher velocity of 30-40 km/s for short period comets and 50-60 km/s for long period comets compared to up to 20-25 km/s for asteroids [10] – this yields at least twice the impact energy for a comet compared with an asteroid of the same volume (depending on the asteroid composition). For example, a 100 m diameter asteroid impacting at 25 km/s generates a 1000 Mtonne yield; a 100 m diameter comet impacting at 50 km/s yields 4000 Mtonnes.

Cometary bodies commonly have diameters exceeding 5 km and rarely below 1 km – a typical cometary nucleus is 5 km in diameter with a low albedo (0.02-0.05 being typical), an axial ratios >1.5 and a slow rotation period ~10+ h, making such bodies difficult to detect before they get close to the Sun. Furthermore, comets' surface activity near perihelion tend to alter their trajectories due to outgassing. Comet nuclei are weak structures that are prone to fracture (such as the Shoemaker-Levy 9 comet) [11]. Comet 67P/Churyumov-Gerasimenko explored by the Rosetta probe showed extensive deposits of both water and carbon dioxide ice impregnated with silicate dust and organic material. The centaurs are giant comets originating from the trans-Neptunian region as short period comets <200 y transiting the inner solar system [12]. Such comets are difficult to track on longer period orbits than asteroids and consequently are difficult to predict – the second centaur Pholus to be discovered after Chiron was discovered in 1992 (as was the second trans-Neptunian object QB1 after Pluto). Since then, 100s of centaurs have been detected, all cometary bodies with 5 AU $<r_p<$28 AU. About 10% of these >100 km diameter centaurs enter Earth-crossing orbits but typically disintegrate into swarms of many comet fragments (such as the 2P/Encke fragments) over their 30,000 year residence time but still comprise around 100 times the integrated mass of NEAs. Even more difficult to detect, track and predict are long period comets >200 y injected into the inner solar system by galactic tides and stellar encounters with the Oort cloud at a>10,000 AU – they are not visible until they are inside Jupiter's orbit affording only 6-9 months warning. For a comet encountering Jupiter in circular orbit around the Sun, the Tisserand parameter T_p defines a conserved dynamic variable that is conserved before and after the encounter [13]:

$$T_p = \frac{a_p}{a} + 2\sqrt{(1-e^2)\frac{a}{a_p}}\cos i \tag{3}$$

where a_p = planet semi-major axis, (a, e, i) = semi-major axis, eccentricity and inclination of small body. The relative velocity between the comet and Jupiter during the encounter is given by:

$$v_r = v_p\sqrt{3 - T_p} \tag{4}$$

where v_p=Jupiter's orbital velocity around the Sun. A comet has Jupiter Tisserand parameter T_J<3 with short period comets with 2<T_J<3 and long period comets with T_J<2. It has been estimated that, for creating craters exceeding 10 km in diameter, the rate of comet impacts on Earth (once every 43 My) is less than 1% that of NEAs (once every 300,000 years) [14]. Thus, comets represent a reduced threat compared with NEAs.

There are 170 asteroid impact craters around the world varying between 1-140 km in diameter, most of them concentrated around the Baltic and Canadian Shields. The largest craters on Earth are the 2.02 Gy old 300 km diameter Vredefort crater in South Africa, the 1.85 Gy old 250 km diameter Sudbury crater in Canada and the 66 My old 150 km diameter Chicxulub crater in Mexico. However, the most common terrestrial craters are around 10 km in diameter indicative of 300 m diameter asteroid impacts assuming a typical impact velocity of 21 km/s and an asteroid density of 3650 kg/m^3. This is testament to the influence of the resultant mass extinctions events during the evolution of life on Earth. The rate at which Earth undergoes cratering events can be estimated from the age and size of craters on the Earth's land mass and has the form $N(D) = 5 \times 10^{10} D^{-2.0}/10^6$ km^2 though a lower exponent varying from 0.4-1.7 applies to larger craters from 2.5-100 km diameter [15]. Small bolides tend to fragment when interactions with shockwaves exceed their mechanical strength S (Table 1) – this occurs at a velocity given by [16]:

$$v = \sqrt{\frac{S}{\kappa(1+\alpha)\rho_0} exp\left(\frac{h+H}{H}\right)} \quad (5)$$

where ρ_0 = sea level air density, α = homogeneity factor = 0.12 for glacial till, $2<\kappa<6$ = amplification factor, h= airburst height, H = scale height. The minimum size to survive entry through the Earth's atmosphere to the ground is around 50 m diameter.

Larger asteroids survive to Earth impact. The Shoemaker crater scaling formula relates the initial impact crater diameter to energy [17]:

$$D = 0.01436\left(E\frac{\rho_i}{\rho_t}\right)^{1/3.4}\left(\frac{g_E}{g_t}\right)^{1/6}(\sin\alpha)^{2/3} \quad (6)$$

where E = impactor kinetic energy, $\rho_{i,t}$ = bulk density of impactor and target, $g_{E,t}$ = surface gravity of Earth and target, α = impact angle. The crater size however does not reflect the blast damage. The area of damage caused by the impact itself is given by:

$$A(km^2) = 100E^{2/3} \quad (7)$$

where $E = \frac{1}{2}mv^2 = \frac{2}{3}\pi\rho r^3 v^2$ = energy yield (Mtonnes where 1 Mtonne = 4.2 x 10^{15} J), ρ = density (g/cm^3) = 2.6 on average, r = radius (km), v = impact velocity (km/s). Impact energies between 10 and 10^4 Mtonnes (<100m diameter asteroid) would cause significant local damage similar to that by a natural disaster, e.g. Tunguska. Between 10^4 and 10^5 Mtonnes (~1 km diameter asteroid), catastrophic loss of life will occur but civilization survival is probable despite extensive regional damage. Above 10^5 Mtonnes (~2-3 km diameter asteroid), human civilization would be obliterated but human species survival is probable but at a sub-medieval level. Above 10^7 Mtonnes (5+ km diameter asteroid), human species survival is unlikely. Equation 7 quantifies the blast damage but it is the subsequent global winter resultant from levitated soot in the stratosphere that imposes mass extinctions. Furthermore, it has been estimated from the Gutenburg-Richter magnitude-energy relation that a bolide impact can initiate seismic events of magnitude M: $M = 0.67\log_{10} E - 5.87$ where E = impact energy. This suggests that a 30 m diameter asteroid impacting at 20 km/s would produce a seismic event with a Richter magnitude of M=4.8 causing moderate seismic damage. Devastation may be quantified through the Binzel scale of impact damage ranging from 0 (no threat) to 10 (complete civilisation destruction). Satellites have detected numerous flashes due to the explosion of 1-10 m diameter meteorites in the upper atmosphere. In 2008, a 5 m diameter object 2008TC3 exploded in the atmosphere over Sudan with an energy release of ~1 ktonne but did no damage - it is estimated that there are airbursts of up to 5 ktonne TNT once per year. The minimum impact energy on the ground is 10 Mtonne as smaller bodies do not survive atmospheric entry.

TABLE 1: Mechanical strength of celestial bodies

Celestial Body	Mechanical Strength S (MPa)
Comets	1
Carbonaceous chondrites	10
Stony asteroids	50
Iron asteroids	200

An impact event occurred at the Cretaceous-Tertiary geological boundary 66 My ago due to a 10 km diameter asteroid (of 1.3 x 10^{15} kg assuming a density of 2500 kg/m^3) impacting the Earth with ~10^{23} J creating the 180 km diameter Chicxulub Crater in the Yucatan peninsula of the Gulf of Mexico with the attendant (KT) mass extinction that eliminated 75% of all species [18]. In 1994, the 1.5 km diameter Shoemaker-Levy 9 comet fragmented into 22 smaller bodies (all less than 750 m in diameter) prior to impacting across Jupiter at 60 km/s generating impact plumes 6000 km in diameter erupting 3000 km above the atmosphere at hypersonic speed of 400 m/s. Post-impact effects continued for two years after impact. Such huge impacts are rare.

On Earth, there is evidence of more modest but still potentially devastating impacts. The 1.3 km diameter by 200 m deep Barringer Meteor Crater in Arizona was formed 50,000 years ago by a 3.5 Mtonne impact of a 40-60 m diameter NiFe asteroid. There have been several recent but more modest events. However, even a modest 35 m diameter asteroid could level an entire city. In 1908, the forested Tunguska region of Siberia including 80 M trees over 2000 km^2 (a similar area to that enclosed by the M25 motorway orbital around London) was obliterated by 15 Mtonne airburst at scale height (8.4 km altitude) of a 30-40 m diameter stony asteroid but it left no crater or debris [19,20]. This may be compared with 15 ktonne and 20 ktonne yields from the Hiroshima and Nagasaki atom bombs with attendant death tolls of 150,000 and 75,000 respectively – if the Tunguska bolide had struck 5 hours later, it would have destroyed St Petersburg. Of course, the Earth is more densely populated today than it has ever been in the past. There have been numerous incidents of close approaches to Earth. For example, the 100 m diameter asteroid 2002MN passed within 120,000 km of Earth (within the Moon's orbit of 385,000 km) in 2002. In 2003, Sudusudya village in India was burned down due to the impact of a fireball, killing one and injuring 20. In 2007, a 30 m diameter impact crater was created in Carancas village in Peru. In 2013, an 18 m diameter stony meteor of 10,000 tonnes airburst at 20 km altitude with an energy release of 400 ktonnes TNT over Chelyabinsk Russia, injuring 1600 people primarily from blasted windows and damaged buildings. It had been preceded by a 45 m diameter asteroid 2012DA14 of 190,000 tonnes that passed within 27,700 km of Earth at 7.8 km/s – this was closer than geostationary orbit at 36,000 km altitude.

In the future, it was estimated that the 270 m diameter 99942 Apophis (mass of 2 x 10^{10} kg with a density of 1990 kg/m^3) could pass through a 400 m wide keyhole trajectory in 2029 generating an impact on Earth in 2036. This was the first time that a NEO registered at level 4 on the Torino scale (albeit temporarily) [21]. If it impacted Earth, it would release an explosive energy of 1 Gtonne (compared with 20-30 Mtonne nuclear test explosions) creating a 4 km diameter crater on land and destroying everything within 1000-5000 km^2. A deflection prior to passing through the keyhole would require a Δv of only 10^{-6} m/s. A keyhole is a narrow region of space near Earth defining a resonant orbit through which an impactor must pass in order to impact the surface at a later date. The 2.7% probability of Earth impact from Apophis was subsequently revised down to 0.003% on further observations shrinking the error ellipse but it will pass within 39,000 km of the Earth's centre (within the geostationary ring) in 2029.

The threat is still potentially extant [22]. The frequency of impacts is dependent on the impact energy [23,24]:

$$f(/y) = \frac{3}{100} E^{-4/5} \quad (8)$$

where E = energy (Mtonne). Impacts by 50 m sized meteors with a 15-20 Mtonne yield are expected about once per 1500 years yielding blast damage over a 30 km diameter, enough to wipe out a large city such as most of Greater London; impacts by 300 m sized meteors with a 1000 Mtonne yield are expected about once per 50,000 years yielding blast damage over a 100 km diameter enough to wipe out two English counties. A 1.5 km diameter asteroid impacting the Earth has an estimated probability of 1 in 5000 within the next 100 years. The explosive energy of 500,000 Mtonnes would kill millions of people and destroy most of Britain. Following the devastation of the impact blast and shock waves, vast quantities of dust could blot out the sun globally for years. There is an estimated probability of 1 in 10,000 in the next 100 years that a 2 km asteroid or comet will impact Earth killing 1.5 billion people (20% of the Earth's population - the closest historical experience of such devastation is the Black Death (1347-1351) which killed 40% of medieval Europe). This is considered the threshold for civilization-destroying impacts. However, the risk of death for an individual over his or her lifetime due to asteroid impact has been revised downwards since the Spaceguard survey from the same risk of perishing in an aeroplane crash to the same risk of death by fireworks [25-27].

3 NEO MITIGATION PRECURSORS

Most effort to date has been the detection and cataloguing of NEOs through Spaceguard-type programmes. However, there have been a host of proposed NEO missions of an exploratory nature. A 200 kg spacecraft using a gridded ion engine such as two T5 thrusters can provide a Δv of 10-12 km/s to rendezvous with three NEAs consuming under 50 kg of propellant and 2.4 kW of power [28]. A solar sail propelled spacecraft has been proposed to explore NEOs for sample return – a 300 kg spacecraft payload propelled by a 70 x 70 m^2 solar sail (mass ~100 kg) can return a sample from an NEO within 10 years: reducing the spacecraft payload to 75 kg permits samples from three NEOs within 8 years; a larger solar sail of 140 x 140 m^2 may accomplish the same with the original spacecraft payload of 300 kg within 10 years [29]. To minimise propellant consumption, electric sails – spin-deployed long conducting tethers - exploit solar wind dynamic pressure for generating radial thrust have been proposed to reach 67% of over 1000 potentially hazardous asteroids within one year [30]. An electron gun fires an electron beam along the spin axis of the spacecraft that perturbs solar wind protons transferring momentum to the tethers radially. Differential potentials in the tethers introduced by resistors generate an asymmetric thrust.

We shall consider in some detail the ARM (asteroid redirect mission) that was planned for 2020 as it is insightful to the NEO mitigation quest. It would begin its mission as an 18 tonne LEO spacecraft with a 40 kW solar electric propulsion system. It was to land on a large NEA and deploy a robotic grapple mechanism to acquire a 4 m diameter boulder of up to 70 tonnes from the surface of an asteroid and return it to lunar orbit using its solar electric propulsion aided by a lunar gravity assist [31,32]. For comparison, the Hoba meteorite is 1 x 3 x 3 m in size with a mass of 60 tonnes of nickel-iron that landed in Namibia 80,000 years ago. ARM had adopted solar electric propulsion based on Hall thruster technology to test the gravity tractor technique. Bringing the asteroid boulder into a high Earth orbit was considered far too dangerous unless the diameter was under 3 m (which would burn up harmlessly in the Earth's atmosphere in the event of a miscalculation). However, insertion into a lunar orbit would provide ready access from a near rectilinear halo orbit (NRHO) around the Earth-Moon L2 libration point which has been targeted for the Lunar Gateway habitat and for any associated cislunar relays to Earth. The original notion was to deliver an entire 7 m diameter asteroid of 500 tonnes (assuming 2.8 g/cm^3 density) to high lunar orbit as a testbed for extraterrestrial mining by astronauts as a stepping-stone to sustainable human NEA missions [33]. A testbed setup has demonstrated the plausibility of bagging a 13 m diameter asteroid of <1000 tonnes using mechanically deployed tube booms rather than inflatables [34]. For the 4 m boulder, the capture mechanism was a 10 m long by 15 m wide cylindrical Kapton fabric bag deployed by inflatable arms connected by inflatable hoops that keep the bag open until they surround the boulder and then the bag is closed with tensioning cinch cables acting as drawstrings. Once the asteroid was bagged, the entire spacecraft and asteroid would be despun. The primary target was Bennu as carbonaceous chondrites are the most compositionally diverse asteroids yet constitute 20% of the NEA population. The ARM mission would have demonstrated some of the technologies required to deflect an asteroid threat. The mission was suspended in 2018.

To prevent asteroid impacts from occurring again on Earth, we must develop technological strategies to deflect any incident asteroid or comet. AIDA (asteroid impact and deflection assessment) is a planned mission that involves two spacecraft, NASA's DART (double asteroid redirection test) to impact the 150 m diameter Didymoon "moonlet" around Didymos at 10 km/s and ESA's AIM (asteroid impact monitor) to observe the impact and its effect on the parent asteroid 65803 Didymos [35]. NEOShield-2 is a subsequent European proposal to test NEO impact mitigation approaches [36]. An important constraint is that on discovery of an asteroid threat, an intercept mission would take at least three years from concept to launch to intercept (depending on its proximity to Earth).

4 REVIEW OF SOME NEO MITIGATION METHODS

The central idea behind asteroid impact avoidance is to divert a NEA on a collision course with Earth away from the Earth. The Earth acts to gravitationally focus asteroid/comet trajectories that increases the effective area of a planet and the velocity of impact defined by a capture radius (defined as the physical radius augmented by gravitational focussing). As the impactor approaches, the MOID (minimal orbital intersection distance) decreases within a month of the impact event to less than the Earth's capture radius [37]:

$$b = r_E \sqrt{1 + \frac{v_{esc}^2}{v_\infty^2}} \quad (9)$$

where r_E = Earth radius, $v_{esc} = \sqrt{2GM/r_E}$ = Earth escape velocity, v_∞ = asteroid velocity. This increases the Earth's effective cross-sectional area:

$$A_{eff} = \pi r_E^2 \sqrt{1 + \frac{v_{esc}^2}{v_\infty^2}} \quad (10)$$

For a NEO impact velocity of 21.0 km/s, the Earth's collisional cross-section is 7540 km compared to its equatorial radius of 6378 km. Any object approaching Earth within 0.05 AU constitutes a threat while deflection by 2.5RE (15,000 km) is sufficient to avoid collision. The minimum distance between Earth and the asteroid is given by [38]:

$$d_{min} = \frac{3\gamma a v_E}{\mu} t v \Delta v \quad (11)$$

where $\mu = GM_s$ = Sun's gravitational parameter, v_E = Earth's velocity at encounter, a = asteroid semi-major axis, v = asteroid velocity at encounter, t = time from initiation of deflection to impact, γ = encounter geometry parameter, Δv = amount of asteroid deflection. This yields the required minimum Δv to deflect the asteroid from Earth:

$$\Delta v = \frac{d_{min}\sqrt{\mu r}}{3t\gamma v_E} \frac{1}{\sqrt{a(2a - R_E)}} \quad (12)$$

where $\gamma = \frac{|v - v_E|}{v_E} sin\beta$, β = angle between Earth orbit and asteroid orbit at encounter. The requirement is to impart a velocity change of $\Delta v = 3.5 \times 10^{-2}/t$ m/s where t = warning time (y). The Earth is 12,750 km in diameter travelling at 30 km/s (one Earth diameter in 425 s) around the Sun. Due to the huge mass of any asteroid, this translates to a very high thrust requirement and/or a very long lead time at more modest continuous thrusting (typically 20 years). Continual monitoring of NEOs potentially affords a decade or more of warning time. With a warning time of a decade, a Δv of 0.01 m/s is sufficient to divert an asteroid from impacting the Earth [39]. However, such long warning times cannot always be guaranteed. It has been proposed that a system of space-based telescopes is capable of detecting smaller asteroids and more distant comets than ground-based telescopes [40]. A set of 3 m diameter UV/optical/IR telescopes with a diffraction-limited resolution of 0.06 arcsec could detect a 1 km diameter impactor at 5 AU giving a one-year warning or equivalently, a 50 m diameter impactor at a distance of 0.2 AU giving a few weeks warning [41].

There are eight main approaches to NEO impact mitigation which may be classified into either asteroid destruction (which are rapidly effective against solid bodies but not rubble piles) or asteroid diversion (which require much longer times to be effective but work against rubble piles) approaches [42]: (i) kinetic impactor; (ii) nuclear detonation; (iii) gravity tractor; (iv) surface ablation by solar concentrators or lasers; (v) rocket engine emplacement such as chemical rocket, ion engine or electromagnetic launcher; (vi) ion beam deflection; (vii) albedo manipulation such as using white TiO2 particle coatings; (viii) tethers with ballast have been proposed to alter impact-threatening NEA trajectories by altering the NEO centre of mass [43]. In general, around 1000 times more energy is required to disrupt a 1 km diameter body (with the risk imposed by fragmentation) in comparison with moving it. However, it is easier to deliver large amounts of energy as a bomb rather than a controlled lower expenditure of energy. In general, these deflection strategies are best employed at perihelion for maximum efficiency but this may not always be feasible, particularly if warning times are short when terminal interception becomes necessary.

4.1 Destructive Approaches

Kinetic impact involves colliding a spacecraft with the asteroid solid body at high velocity >10 km/s to transfer momentum to the asteroid to nudge it off its catastrophic trajectory [44,45]. Conservation of linear momentum imparts a velocity change to the asteroid given by:

$$\Delta v = \beta \frac{m_{imp} v_{imp}}{m_{ast} + m_{imp}} \quad (13)$$

where β = momentum enhancement factor, m_{imp} =impactor spacecraft mass, m_{ast} = asteroid mass, v_{imp} = relative impact velocity. Asteroids approach Earth on a curved hyperbolic path for which there is an elliptical orbit that intercepts it at 90°. This is the ideal angle for a missile attack to deflect the asteroid – this would favour employing an array of space-based missile launchers at the Earth-Moon Lagrangian points L_1 and L_3 to minimise Δv manoeuvres with maximum orthogonal deflection [46]. The deflected hyperbolic orbit of the asteroid has a semimajor axis:

$$a_f = \frac{GM_E}{v_f^2 - 2GM_E/r} \quad (14)$$

where r= radius of asteroid intercept. Miss distance is given by the radius of perigee: (15)

$$r_p = \frac{\mu(e-1)}{2E} \quad (15)$$

where $E = \frac{v_{ast}^2}{\mu} - \frac{\mu}{r}$ = energy per unit mass, e = eccentricity. Kinetic impactors must be massive and/or high velocity to have a substantial effect on the target asteroid but most of the Δv imparted to the asteroid is in the form of kinetic energy of the debris from the explosion. The interceptor must blow off a much larger mass of debris from the asteroid in order to be effective. The Δv imparted to the asteroid is determined by the conservation of momentum:

$$\Delta v = \beta S \frac{m_{deb} v_{deb}}{m_{ast}} \quad (16)$$

where S = scattering factor, β= momentum enhancement factor, m_{ast} = asteroid mass, $v_{deb} = \sqrt{\frac{2\eta E}{m_{imp}}}$, $m_{deb} = A_r m_{imp}$ = debris mass, m_{imp} = exploded mass, $A_r = \frac{1}{2} - \frac{\sqrt{h}}{2}\frac{\sqrt{h+2r_{ast}}}{r_{ast}+h}$ = ratio of area of shockwave cross section intercepted by asteroid, η = conversion of explosive energy to kinetic energy, h = altitude of explosion. The mass of material ejected from an impact-generated crater is related to its energy by:

$$m_{eject} = \delta \alpha^2 E^\beta \quad (17)$$

where α = factor depending on the nature of the burst (groundburst for a kinetic impactor = 1.6×10^{-4}), β = factor depending on asteroid material ≈ 0.9, δ = fraction of input kinetic energy converted to output kinetic energy = 0.7 for 30% energy coupling, $E = \frac{1}{2} m_{sc} v^2$ = kinetic energy of impact, v = impact velocity. The distance by which the asteroid will miss the Earth is dependent on the range to Earth at which interception has occurred:

$$\Delta r = R\left(\frac{\Delta v}{\Delta v + v}\right) \quad (18)$$

where R = range to Earth, v = initial asteroid velocity. A variation on the kinetic impactor is to impact a small asteroid to divert it to deflect a larger incoming asteroid [47]. A variation on this notion is to capture an asteroid of 20-40 m diameter into a Sun-Earth L_1 or L_2 point and then direct it as a kinetic impactor against a larger incoming asteroid threat at least 500,000 km from Earth [48]. Δv thrusts of 50 m/s imparted by catapulting of scooped surface material can inject this small asteroid into the Sun-Earth Lagrange point within 10 years. Kinetic energy deflection is effective for asteroids of 70 m diameter or less at a distance of 1/30 AU or more.

NASA's Deep Impact mission collided the 370 kg spacecraft into the 5 km diameter comet Tempel-1 (2005) illustrating a small-scale demonstration of the kinetic impactor. The impact at 10 km/s released 2 x 10^{10} J creating a 20 m deep by 100 m wide crater with negligible deflection of the comet. Chemical explosives are too weak to yield a significant blow-off fraction so nuclear explosives are required. Nuclear detonation offers around 10,000 times the specific energy yield than a kinetic impactor – indeed, it is considered the only solution for large asteroids with closer engagements at less than 5 x 10^6 km or under 10-year warning times. Nuclear standoff deflection reduces the probability of asteroid fragmentation at a cost of interceptor mass. The nuclear explosive is required to provide sufficient specific impulse to deflect the asteroid [49]. The intercept range of the nuclear missile to the asteroid is given by:

$$R = R_l\left(1 - \frac{v_{ast}}{v_{ast}+v_f}\right) \tag{19}$$

where $v_f = gI_{sp}\ln\frac{m_i}{m_f}$ = interceptor velocity, v_{ast} = asteroid relative velocity, R_l = asteroid range at launch. The blow-off fraction f defines the fraction of explosive energy converted to kinetic energy:

$$f = \frac{m_{ex}}{m_i} \tag{20}$$

where $m_{ex} = \alpha^2 E^\beta$ = mass ejected by explosion, α = crater constant = 2 x 10^{-4}, β = crater exponent = 0.9 for most asteroids and comets, E = interceptor kinetic energy. The energy yield from a nuclear warhead is given by:

$$E = \phi m_{nuc} \tag{21}$$

where ϕ = specific yield = 1 ktonne/kg. The incremental velocity imparted to the asteroid by nuclear detonation is given by [50]:

$$\Delta v = \sqrt{\frac{8\times10^{15} fE}{m_{ast}}} \tag{22}$$

where E = explosive yield (Mtonne). For a 1 km diameter asteroid, this would require detonation of a 100 ktonne bomb to change its velocity by 10 cm/s, i.e. a 7-year lead time before impact. In nuclear explosions, the kinetic energy is dominated by radioactive expulsion. A standoff nuclear detonation generates energetic radiation – 2.45 MeV neutrons, 10 keV soft X-rays and 100 keV hard X-rays - which heats and ablates surface material which is ejected at high velocity and imparts thrust in the opposing direction. The deposited energy density is given by:

$$\epsilon = \frac{\eta Y}{4\pi d^2 \lambda_d} \tag{23}$$

where η = coupling efficiency, Y = yield over 4π steradians, d = distance between detonation source and NEO surface, λ_d = penetration depth at which fraction (1-1/e) of energy is deposited. The deposited energy density is up to 200 times that required to melt silica [51].

From nuclear detonation itself, ablated debris velocity is given by:

$$v_{ex} = \sqrt{2(\mu_0 E(z) - E_v)} \tag{24}$$

where $E(z) = E(0)e^{-\rho_0 \mu_0 z}$ = energy/area of impacting radiation with depth z, μ_0 = opacity (Table 2), $E(z)$ = energy per unit area at the asteroid surface, E_v = sublimation enthalpy = 5.03 kJ/g for forsterite. The Δv imparted by a nuclear explosion is given by [52]:

$$\Delta v = 3.4\frac{\sqrt{\sigma E/\rho}}{m_{ast}} \tag{25}$$

where σ = asteroid material strength (dyne/cm³), E = explosive yield (ktonne), ρ = material density (g/cm³). Standoff requires precision and multiple midcourse corrections to generate sufficient impulse yet prevent asteroid fragmentation.

TABLE 2: Opacity and kinetic energy associated with different radiations

X-ray	Neutron	Gamma ray	
Opacity μ	01.5 m²/kg	0.0044 m²/kg	0.005 m²/kg
Kinetic energy	10 keV	2 MeV	14 MeV

The buried nuclear explosive is the most efficient approach over surface and stand-off techniques. Nuclear penetrators (optimum depth of ~100 m) offer no advantage for deflection but are more suited to pulverization at short ranges. Subsurface detonation is preferred for efficient energy coupling to the asteroid. Penetrator impact velocities have been limited to 1.5 km/s to prevent destruction of the nuclear fusing mechanism which limits the depth of penetration to 3-5 m but impact velocities of 10-30 km/s can be tolerated with a split forebody-aftbody penetrator [53]. The aftbody carries the nuclear ordnance while the forebody creates the crater to penetrate beneath the surface. Subsurface detonation is more efficient (which increases α) but risks fracturing the object. Micromechanics-based material strength of asteroid materials have been analysed with reference to fragmentation [54]. A similar analysis has been performed for macroscopic-based material strength such as the Hoek-Brown power law model [55]. A fractured asteroid may cause more widespread damage on impacting the Earth – only if the fragments disperse at speeds in excess of the escape velocity of the asteroid can fragmentation be an effective solution. A 20-30 m standoff burst prevents disruption of rubble piles - most disaggregated objects re-accrete within days with the rubble pile retaining 98-99% of its original material [56]. Large fragmented bodies exhibit reduced ejection velocities to the extent that the fragments remain in place as "brick-piles" [57].

On average, the Δv imparted to an asteroid by nuclear detonation is around 30 m/s/ktonne in the direction of motion. The nuclear detonation approach requires only a few months lead time against a 50-500 m diameter object. A 1 Gtonne nuclear explosive of 25-30 tonnes imparts sufficient energy to vaporise a 1 km diameter asteroid or divert a 10 km diameter asteroid with only a few month's notice or even a 100 km diameter comet with one year's notice. However, the largest nuclear weapons on Earth were the US 25 Mtonne B41 and Russian 50 Mtonne Tsar bombs but neither exist today. A variation is to use a kinetic impact penetrator to create a crater which then acts as a rocket nozzle for subsequent nuclear detonations. The 2 km diameter asteroid 1997 XF11 had a very small probability of impacting the Earth on 26 October

2028 (which has subsequently been revised downwards). It was proposed that the launch of 10-15 interceptors in 2015, each carrying a 1 Mtonne yield 1 tonne mass neutron bomb warhead would mitigate against it [58]. Each warhead would provide a 1 cm/s velocity change, i.e. a total Δv of 10 cm/s equating to an alteration of its Earth rendezvous trajectory by at least 8 minutes (the time for Earth to move one Earth radius in its orbit). There are limits to the efficacy of nuclear detonation for smaller asteroids due to the tendency to fragment so kinetic impactors may be more appropriate at smaller sizes [59]. The 270 m diameter Apophis body is close to the boundary at which nuclear detonation becomes preferable. The chief problem against using kinetic and nuclear impactors is that they can be turned towards Earth by rogue states or even terrorists through cyber-intervention – this has been the primary rationale behind abandonment of nuclear breeder reactors on Earth because they require widespread proliferation of plutonium fuel. Furthermore, deflecting a smaller asteroid which would have local effects involves moving its impact point across the Earth's surface, potentially endangering different populations of people than originally threatened.

Kinetic impactors at 10 km/s will not work against ribble pile asteroid structures, e.g. Bennu has a porosity of 40%. Nuclear missile interception poses certain problems: (i) launch of nuclear weaponry into space is currently prohibited; (ii) resultant shrapnel from detonation will stay on course perhaps presenting a greater hazard by spreading destruction over a wide portion of the Earth.

4.2 Remote Deflection Approaches

Gravity tractors, attached rocket engines, solar sails and mass drivers require 10-20 years lead time to be effective. The gravity tractor is a variation on the tugboat concept (e.g. the FIMER concept could be adapted to this application [60] with freeflying robots and deployable tethers) in which one or more spacecraft are attached to the asteroid and pull it by applying thrust. Gravity tractor involves a large spacecraft station-keeping near the asteroid while thrusting gently to slightly gravitationally tug the asteroid. This is a slow process. It applies a very low constant thrust from a massive multi-tonne spacecraft hovering over a small 100-300 m diameter asteroid at an altitude of 0.5r to gravitationally tug it where r = asteroid radius [61]. The spacecraft and asteroid are gravitationally bound by an "imaginary tether" without docking or contact so the ion engine thrust pulls the asteroid-spacecraft centre of mass. The thrusters are angled at 20° to ensure that the thruster plume does not impact on the asteroid surface thereby negating the gravitation attraction. The gravitational force F_{grav} balances the vectored thrust F_{vt}:

$$F_{grav} = F_{vt} \tag{26}$$

where

$$F_{grav} = m_{ast}\frac{\Delta v}{\Delta t} = \frac{Gm_{ast}m_{sc}}{(r+h)^2}$$

$$F_{vt} = F\cos\left(\sin^{-1}\left(\frac{r}{r+h}\right) + \phi\right)$$

m_{ast} =asteroid mass, F = thrust, ϕ = half-angle of thrust cone = 20° typically, m_{sc} = spacecraft mass, r = asteroid radius, h = hover altitude. Mass of the gravity tractor is given by:

$$m_{sc} = \frac{6F(h+r)^2}{\pi G\rho d^3} \tag{27}$$

where d = asteroid diameter, ρ = asteroid density, h = 0.5r = minimum safe hovering height. The spacecraft mass evolves over time as:

$$m(t) = m_i exp\left(-\frac{Gm_{ast}(t-t_0)}{(r+h)^2\cos(\sin^{-1}(r/(r+h))+\phi)I_{sp}g}\right) \tag{28}$$

The acceleration imparted as the spacecraft mass evolves is given by:

$$a(t) = \frac{Gm(t)}{(h+r)^2} \tag{29}$$

The Δv imparted is ~2 x 10^{-3} m/s per year for a 200 m asteroid with a thrust of 1 N from a 20 tonne nuclear electric spacecraft hovering at 25 m altitude. For a velocity change of Δv = 3.5 x $10^{-2}/t$ m/s to deflect from Earth, t ≈ 20 years. The position change is given by:

$$\Delta x = \frac{3}{2}\frac{F_{grav}}{m_{ast}}t_a(2t_f - t_a) \tag{30}$$

where t_a = thrust time, t_f = time from thrust initiation to impact. Gravity tractors must be massive though smaller gravity tractors can be employed to prevent a gravitational keyhole which requires shifting by 500 m or so. Although such a technique requires years to be effective, it is effective against rapid rotators and rubble piles. Multiple gravity tractors may enhance the procedure [62]. However, it may be more efficient to impact mass onto the asteroid rather than tugging it [63].

A variation on the use of ion engines is to direct the ions into a collimated beam toward the asteroid near its surface to transfer momentum to it [64]. A second ion engine applies thrust to the spacecraft to compensate for the first engine. The Δv from an ion thruster is given by:

$$\Delta v = \frac{3F\Delta t}{\rho d^3} \tag{31}$$

where $F = \frac{1}{2}m_{prop}I_{sp}g/\Delta t$ = thrust, d = asteroid diameter, ρ = asteroid density, Δt = burn duration. Minimum fuel mass required to deflect the asteroid is given by:

$$m_{prop} = 2F\sqrt{\frac{2\alpha\Delta t}{\eta}} \tag{32}$$

where α = inverse specific power, η = ion propulsion efficiency. The ion beam shepherd is an order of magnitude more effective than the gravity tractor for asteroids under 200 m diameter but this factor decreases with increasing asteroid size until both approaches become comparable at a diameter of 2 km and greater (in fact, the gravity tractor becomes saturated at a maximum asteroid diameter of 2 km given certain reasonable assumptions).

Another contactless approach is to deflect the asteroid through surface ablation using focussed solar energy projected onto the asteroid surface to vaporise the material. This option is discussed in more detail later. A variation is to employ a two-sail solar-photon sail as a solar concentrator to generate a 9.5 x 10^5 W/m^2 at the hotspot which according to the Stefan-Boltzmann law equates to a temperature of 2000 K – this can vaporise ice to form an ablation jet but cannot generate ablative jets from silicates or iron [65, 66]. Another variation on solar concentrators is to use multiple orbiting lasers which permits the use of higher orbits due to their reduced energy propagation losses.

This reduces sputtering of ablated material onto the optics and the complexity of formation flying at a cost of reduced energy efficiency in lasers compared with solar concentrators. A 1 MW/m^2 laser will heat the surface over 2000 K to evaporate the surface material as ejecta. The Δv generated is given by:

$$\Delta v = \int_{ti}^{tf} \frac{F}{m(t)} dt \quad (33)$$

where $F = \lambda v \dot{m}$ = thrust due to sublimation, $m(t)$ = asteroid mass, $\dot{m} = \frac{1}{H}(P_o - Q_{rad} - Q_{cond})$ = mass flow rate, H = sublimation enthalpy of material, $Q_{cond} = (T_{sub} - T_0) A_{spot} \sqrt{\frac{c\rho\kappa}{\pi t}}$ = heat losses through conduction, $Q_{rad} = \sigma_{SB} \varepsilon A_{spot} (T_{sub}^4 - T_{amb}^4)$ = heat losses through radiation, T_{amb} = ambient temperature = 4 K, T_0 = asteroid core temperature = 298 K, c = asteroid heat capacity, ρ = asteroid density, κ = asteroid thermal conductivity, $t = \frac{\pi^2}{4}\left(\frac{T_{sub}\sqrt{c\rho\kappa}}{P_o}\right)^2$ = time to raise the temperature of material to sublimation temperature, $v = \sqrt{\frac{8k_b T_{sub}}{\pi M_a}}$ = ejecta average velocity, λ = scatter factor = 2/π, k_b = Boltzmann constant, T_{sub} = sublimation temperature, M_a = molar mass of ablated gas = 50 g/mole for olivine. Thermal power delivered by the laser is given by:

$$P_o = \frac{\tau(1 - \varepsilon\alpha) P_i}{A_{spot}} \quad (34)$$

where A_{spot} = laser spot area, $P_i = \eta_{sys} C_R \frac{S_0 A_{conc}}{R^2}$ = input power for the laser, η_{sys} = overall solar-laser efficiency ~ 5%, $\tau = e^{-2\alpha h}$ = plume absorption losses according to the Beer-Lambert law, α = ejecta absorptivity/unit length = 10^4/cm for olivine, ε = asteroid reflectivity = 0.2, α = asteroid albedo = 0.1-0.3, C_R = concentrator ratio, A_{conc} =solar concentrator spot area, S_0 = solar constant, R = distance to the Sun =1 AU for NEAs. Laser ablation still causes deposition of ejecta onto the laser optics but in fact was experimentally shown to be much reduced compared with theoretical models [67, 68]. The lasers would be powered by solar concentrator-based photovoltaic arrays rather than solar-pumped directly by solar concentrator onto the lasing medium for efficiency. A 100 MW laser (outputting 1000 kJ pulses at 10 Hz) generates the 2.5 x 10^4 GJ required over 30 days one year before impact to deflect a 0.2 km asteroid by 1 R_E. Laser ablation may also be exploited to control the rotation of an asteroid by pointing the laser off-barycentre [69]. However, these are marginal concepts.

4.3 Landed Asset Deflection Approaches

The installation of chemical rockets, ion thrusters or VASIMR engines on the surface of the asteroid requires high specific impulse fuels to be either carried with the engines or extracted from the asteroid [70]. For example, impulse from ion engines is given by:

$$I = \int_{t_0}^{t_f} F.dt = \int_{t_0}^{t_f} \frac{dm}{dt} v_{ex} dt = \frac{1}{2} F(t_f - t_0) = (m_i - m_f) v_{ex} \quad (35)$$

where F = ion engine thrust. Continuous thrust ion engines powered by solar energy or nuclear reactors may be used to deflect the asteroid if 10 years warning time were available. For continuous rather than impulsive thrusting, asteroid rotation must be dealt with first by despinning it from an average of 5.5 rev/day with an upper limit of 12 rev/day. Spin can be nullified by firing in a direction opposite to its spin and the engine re-aligned for the main thrust manoeuvre but the stability of asteroids to spin-down is not known. If the rotation is not nullified however, the timing of thrust must be restricted to one window per revolution such that: $\Delta t_{thrust} = \frac{\theta}{360} T$, where T = rotation period. Another use of ion engines is to spin up asteroids using tethers attached to ion engines to ensure their fragmentation [71]. However, ion engines require suitable propellant (nominally a noble gas).

Attaching large solar sails of aluminised plastic film onto the asteroid does not require fuel but affords very low impulse propulsion of 9.3 x 10^{-6} Pa requiring many years of operation. An alternative approach is to amplify the Yarkovsky effect which is applicable to smaller asteroids ~100 m in diameter [72]. Asteroid surface temperature is given by:

$$T = \left(\frac{(1-A)S_0}{16\varepsilon\pi r^2}\right)^{1/4} \quad (36)$$

where A = bolometric Bond albedo, S_0 = solar luminosity, ε = asteroid infrared emissivity = 0.9, σ = Stefan-Boltzmann constant, r = asteroid distance from sun. The Yarkovsky effect occurs when sunlight warms one face of a spinning asteroid more than the other – more heat is reradiated from the warmer "dusk" side over the cooler "dawn" side, generating thrust and a torque that alter the asteroid's trajectory and its spin rate respectively. The albedo of the asteroid may be altered via the Yarkovsky effect by painting it with white rutile (TiO_2) power or black carbon particles. The time required for this approach is far too long to be effective.

Similar arguments apply to the use of electromagnetic launchers (mass drivers). For example, the linear induction electromagnetic launcher is a variation on the electromagnetic coilgun based on the operation of the induction motor [73]. Linear induction motors are essentially rotary induction motors that have been opened out. Indeed, maglevs are also linear induction motors which is effectively an unrolled rotary induction motor [74]. The linear induction motor comprises stator rails similar to the rotary stator and a conducting plate which acts like a squirrel cage armature. The stator is a slotted lamination design (typically with stator teeth of 25 mm in size) forming the core around which coils are inserted in the slots. Polyphase excitation of the coils creates an electromagnetic wave which accelerates the rotor along the rails. The squirrel cage rotor of an iron core surrounded by aluminum bars is stretched out into a flat aluminium sheet with a steel backing. This may be rolled into a container to carry a payload within it. Induced currents in the armature interact with the magnetic field to generate propulsive forces on the armature. A 50 kg copper armature was accelerated to 45 m/s by a three-stage electromagnetic induction launcher of length 30 cm with electrical energy consumption of 216 kJ [75]. We consider the employment of electromagnetic launchers (mass drivers) in more detail in the next section.

4.4 Summary of Approaches

Several means of asteroid mitigation have been analysed under the assumption that the asteroid was not despun [76]. Laser sublimation was the least favoured approach in terms of performance followed by the ion beam and the gravity tractor. The mass ejector performed best but with an associated higher risk compared with the ion beam and the gravity tractor. Across multiple assessments, mass ejection proved to be the most consistent performer with the highest Δv capability. However, the application of Dempster-Shafer belief theory to characterise uncertainty in asteroid parameters due to lack of in-situ measurements suggests that the kinetic impactor offers a more robust solution over nuclear detonation or solar sublimation examined (mass ejection was not included) [77]. This correlates with another study that compared six different deflection strategies – kinetic impactor, nuclear interceptor, solar collector, mass driver, low thrust propulsion and gravity tractor - in terms of ease (miss distance quantified by MOID), cost (mass), complexity, technological readiness and response time [78]. The kinetic impactor is most appropriate for Apollos with short warning time while low thrust approaches are most appropriate for Atens with long warning times. Finally, comparison between the mass driver to the disperser concepts in which both employ solar energy collection and utilize asteroid material as reaction mass suggests that the dispenser has more favourable energy requirements and reduced complexity but the mass driver is favoured for its reduced transportation mass [79].

5 SELF-REPLICATION APPROACH

We propose that self-replication technology alters this analysis considerably in its favour. Most of the approaches to asteroid threat mitigation per se require considerable warning time and/or good knowledge of NEO parameters such as mass/inertia, material constitution, spin, porosity and Keplerian orbital elements. If we do not possess such information prior to the launch of the engineered solution, the design must have high adaptability to respond flexibly and rapidly to varying data on local conditions in-situ. Such adaptability is offered by self-replication technology in which a single general-purpose universal constructor factory is delivered to the NEO surface which then proceeds to construct the required productive capacity by initially building a number of copies of itself from in-situ resources. In this scenario, a single self-replicating machine [80] is sent to intercept the asteroid and land on it. With a self-replicating machine, it has been estimated that the mass of a self-replicating machine might be as much as 100 tonnes [81], 12 tonnes [82] or 5-10 tonnes [83] though more recent experiments [84] suggest that these estimates are conservatively high. Nevertheless, we shall take 10 tonnes as our baseline - a 15 tonne spacecraft can be launched into GTO by a full Falcon 9 or 66 tonnes into GTO by a Long March 9. Of course, such a machine does not have to be launched as a single package but may self-assemble in Earth orbit if necessary [85].

5.1 NEO Interception & Encounter

The first phase of any mitigation mission is to intercept the asteroid. Heliocentric orbital motion of an asteroid is given by [86]:

$$\frac{d^2r}{dt^2} = -\frac{\mu}{r^3}r + \sum_{k=1}^{n}\mu_k\left(\frac{r_k - r}{|r_k - r|^3} - \frac{r_k}{r_k^3}\right) + \ddot{e} \tag{37}$$

where n = number of perturbing bodies, μ = GM for the Sun, $\mu_k = Gm_k$, r_k = heliocentric location of body k, $\ddot{e}$ = perturbing accelerations such as solar radiation pressure. For interception of the asteroid, both solar electric and nuclear electric propulsion give similar performances with mission time dominated by the coast time [87]. Alternatively, a solar thermal propulsion system powered by parabolic mirrors with concentration ratios of 10,000 can generate temperatures of 2500 K to yield (a) propulsive thrust (using in-situ resourced water as fuel), (b) thermal energy for mineral processing and (c) electric power generation using a Stirling cycle engine [88]. We agree with the employment of solar concentrators for in-situ operations at the asteroid but propose the use of Fresnel lenses as we have for the Moon [80], solar power satellites [89] and solar shield spacecraft [90] in conjunction with thermionic conversion to electrical generation [91]. Such a power station may also be landed and mounted at the pole of the asteroid to generate power in-situ if the asteroid inclination permits.

Prior to the encounter, it will be essential to gain accurate data on the target object's ephemeris, its size, shape, mass distribution, albedo, outgassing, etc through sequences of ground-based observations and later by space-based observations prior to rendezvous [92]. There are certain fundamental parameters required by all mitigation techniques – mass, shape and rotational state – which can be estimated remotely prior to and during approach. Asteroid mass can be estimated from its absolute magnitude M [93]:

$$m = \frac{\pi}{6}\rho D^3 = \frac{\pi}{6}\rho\left(\frac{1.33\times10^6}{\sqrt{a}}10^{-M/5}\right)^3 \tag{38}$$

where a = albedo, ρ = density, D =diameter. Density varies from 1.0 g/cm^3 for carbonaceous chondrites to 8 g/cm^3 for solid NiFe metal, but most NEAs vary more narrowly in the range 1.9-3.8 g/cm^3 (average 2.8 g/cm^3), indicating that they have variable porosity and/or composition. Most NEAs have albedos in the range 0.09-0.36 – 0.03-0.09 for C-type asteroids and 0.1-0.18 for M-type asteroids – suggesting that diameter estimates from magnitude have uncertainties of ± 50%. The period of rotation T is also related the absolute magnitude M by:

$$T = e^{-0.509M+11.32} \tag{39}$$

Asteroid spin rates vary from 0.5-6.0 (usually 2.5-3.0) rev/day – large asteroids spin more slowly than smaller ones. The limit of material coherence of a spinning body against centrifugal force is given by a limiting angular velocity:

$$\Omega < \sqrt{\frac{GM}{R}} = \sqrt{\frac{4}{3}\pi G\rho} \tag{40}$$

Hence, the spin period <2.2 h when ρ = 2700 kg/m^3 (and accounting for spheroidal deformation) indicate rubble piles for diameters >150-200 m. Larger asteroids exceeding >150 m diameter have spin periods >2.2 hours in which the 2.2 h spin period represents the maximum limit for rubble piles. Rubble pile structures result from collisional breakup followed by gravitational reassembly [94]. Centrifugal forces must be less than the self-gravitating forces to keep the rubble pile together. Smaller asteroids spin faster implying that they must be coherent objects to withstand the higher centrifugal forces – small rocks ~m in diameter can rotate with as short a period as 10 min. For example, the Near-Earth Rendezvous (NEAR) Shoemaker spacecraft (1996) visited two contrastingly illustrative asteroids. 433 Eros is a S-type NEA with a cohesive peanut shape 32 km in length with a composition dominated by pyroxene and olivine. It is inclined at 10.8° to the ecliptic plane, has a perihelion distance of 1.13 AU outside Earth's orbit and an aphelion distance of 1.78 AU outside Mars' orbit with an orbital period of 1.76 years. Eros has a mean density of 2670 kg/m^3 with a cohesive integrity indicated by its rapid rotation period of 5.3 h. There are three major craters including the 7 km diameter Shoemaker and the 5.2 km diameter Psyche craters. 253 Mathilde is a 52 km diameter C-type main belt asteroid with a low density of 1.3 g/cm^3. It has a perihelion of 1.94 AU and aphelion of 3.35 AU, i.e. spanning the width of the main asteroid belt. It possesses five large craters exceeding 20 km in diameter – the largest is 30 km in diameter and 10 km deep. Its slow rotation period of 17.4 days suggests that Mathilde is in fact a large rubble pile weakly bound by gravity. It is possible that Mathilde is an extinct cometary nucleus which has spent its inventory of volatiles. Most asteroids (80%) are slow rotators with periods T>4-20 h, particularly larger asteroids. The transition size between rubble pile and monolithic bodies is ~100 m diameter. The spin rate thus informs about the nature of the asteroid body prior to an encounter. However, this is not hard and fast - there exist large fast rotators that are monolithic and there are small bodies that are not monolithic suggesting a taxonomic type dependence (which is not surprising as metal alloy has much higher cohesive strength than water ice, for instance). Intermediate asteroids >200 m in diameter are expected to be rubble piles with porosity ~40% but average porosity for most meteorites is ~10%. Further complications arise from the YORP (Yarkovsky-O'Keefe-Radzievskii-Paddock) effect that involves solar heating hot spots which re-radiate and cause spinning up of asteroids.

In proximity to a NEA, high capability autonomous navigation is required to cope with irregular shapes and tumbling of asteroids, the details of which can only be determined in proximity [95]. Although very large asteroids are near spherical, smaller asteroids are potato and dumbbell shaped generating irregular gravity fields around them. Around 15% of NEAs are binaries. Thus, stable orbits are not possible but station-keeping manoeuvres are feasible. Whilst asteroids generally spin near the principal axis of rotation, non-spherical shape can lead to J_2 effects; similarly, comets exhibit nutation and precession due to outgassing torques making landmark acquisition more challenging. The Jacobi constant provides a measure of the energy costs in coping with the complexity of the dynamics of the asteroid:

$$J \approx \frac{1}{a} + 2\sqrt{a(1-e^2)cosi} \tag{41}$$

Autonomous landing would involve approach along the spin axis of the lander, reducing the relative spacecraft spin error and relative surface velocity to zero. To achieve this, a LIDAR optical navigation system for altimetry with a supporting camera for proximity imaging will be essential. Cameras, attitude sensors and LIDAR provide measurements which may be fused to provide an estimate on the state of a spacecraft relative to the NEA and inertial space. The asteroid shape may be modelled as a superquadratic ellipsoid:

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2 = 1 \tag{42}$$

The gravitational field may be modelled as a spherical field with second order components. The second order terms may be modelled as process noise in a Kalman filter. For optimal state estimation, the unscented H∞ filter has been found to be superior to the unscented Kalman filter which in turn was superior to the extended Kalman filter in both cases due to the ability to handle non-Gaussian noise [96].

Asteroid exploration missions have flown several instruments to gain data concerning asteroid properties including near infrared spectrometers, laser altimeters, neutron spectrometers and ground penetrating radar to provide mineralogical data from orbit. Augmentation with surface penetrators would provide in-situ surface measurements [97]. Because most of the physical parameters necessary for a successful intervention will be a priori unknown from remote observation, such direct in-situ investigation will be necessary [98] – these parameters include surface/subsurface mechanical and thermal properties, internal stresses, etc. This requires the necessity to adapt to the local situation. In particular, physical interaction with the asteroid surface requires knowledge of the surface regolith. Small, high porosity (~20-70%) asteroids appear to be characterised by thin layers of regolith due to their low gravity in comparison with larger solid asteroids with ~cm deep regolith [99]. NEAs tend to be covered with coarser regolith than main belt asteroids due to impact fracturing. Eros with a density of 2.67 g/cm^3 (visited by NEAR-Shoemaker in 2000) possesses a 10-100 m layer of fine-grained regolith compared with the 320 m diameter Itokawa of density 1.9 g/cm^3 (visited by Hayabusa in 2005) with ~10 cm layer of gravel and pebbles – both are S-type NEAs with bulk density variations due to bulk porosity differences. Thus, large asteroids may have thick fine-grained regolith similar to the Moon but smaller asteroids tend to have thinner and coarser regolith which alters its cohesive and frictional properties. Prior to surface operations, the spacecraft would need to be anchored to the parent asteroid. Small asteroids may be captured using nets, grappling arms or airbag cushions. Anchorage options include using four counter-rotating augers such as proposed for ARM or winched harpoons but the latter failed to secure the Rosetta Philae lander on comet 67P/Churyumov-Gerasimenko.

A 100 m diameter asteroid has a mass of 1.6 x 10^6 tonnes with an escape of velocity of 0.07 m/s and an average spin rate of 4 rev/day (0.28 x 10^{-2} rpm). Pre-grappling manoeuvres will require determining the spin axis, manoeuvring along the spin axis and spinning up to match the asteroid spin to permit grappling. Once grappled, the spin may be negated. One approach is to wind a long cable through a series of pitons anchored around the equator and apply thrust at the end of the cable. Yo-yos or bolas are used in spacecraft for despinning spin-stabilised satellites - they may wrap opposing lengths of cable around the asteroid to which fragments of asteroid are attached at opposite ends to the anchored ends. Centrifugal force releases the cables and applies torque to the asteroid. At maximum deployment when the asteroid has despun, the cables are released from their anchors. For a 100 m diameter asteroid, each 6 km cable wraps around the asteroid 20 times each capped by a 20 tonne weight. Rather than weights, the bolas may be anchored to a rocker engine to apply thrust to nullify the asteroid's rotation at a cost of several tonnes of propellant. This is a small fraction of the asteroid mass if ejected by mass driver - a mass driver may use raw asteroid material as propellant (or waste gangue as propellant after valuable and/or useful materials have been extracted). Alternatively, a minimum of two reaction engines can be anchored onto the surface on opposing sides of the equator. A rocket thrust despin would require 30 tonnes of propellant. The mass driver would be a suitable reaction engine. Mechanically, this represents the simpler process than using yo-yos and bolas. Hence, the first task for the self-replicator payload would be to despin the asteroid using mass drivers.

5.2 Electromagnetic Launcher (Mass Driver)

We initially consider a single electromagnetic launcher on the surface of the asteroid. The electromagnetic launcher must be anchored to the asteroid together with a raw material mining system to extract the reaction mass. The installation of an electromagnetic launcher on the asteroid surface which extracts and ejects local material as propellant to impart thrust (mass driver) offers a versatile approach to asteroid thrusting. It operates through the Lorentz J x B force, $F = \int J \times B . dV$, to accelerate an armature. The electromagnetic driver has many favoured characteristics including that the propellant is provided by the asteroid itself (surface ablation offers the same advantage) and high ejection velocities of ~km/s are achievable. We suggest that both are suitable as part of a self-replication facility as both are derivative from our self-replication scheme. While thermal ablation does not require landing on the asteroid surface like the electromagnetic launcher, it does require precision orbit and station-keeping. Furthermore, surface ablation by solar concentrators is limited to the solar facing side of the asteroid while the electromagnetic launcher is more versatile and offers greater controllability. The electromagnetic launcher offers a versatile solution to convert a potential catastrophe into a boon. The electromagnetic launcher offers a high degree of controllability to the trajectory of the asteroid enabling it to be redirected at will. In fact, this was the rationale behind the Asteroid Redirect Mission (ARM) to capture a small asteroid and direct it into a high cislunar orbit. In any electromagnetic machine, there is a minimum amount of structural mass required to store magnetic energy due to internal hoop stress given by the virial theorem: where E =magnetic energy, ρ =mass density, σ =yield strength, m_t = mass under tension, m_c =mass under compression. This may be cast into an alternative form:

$$\frac{\sigma}{\rho} = \frac{E}{m_t - m_c} \tag{43}$$

where m_T = total mass, k = topological factor ≈ 1/3 for toroid/solenoid configurations.

$$k\frac{\sigma}{\rho} = \frac{E}{m_T} \tag{44}$$

There are two main configurations of electromagnetic launcher (mass driver) – railguns and coilguns. A railgun is a linear DC motor. Railguns accelerate projectiles by passing a high current through an armature which has physical sliding contact (brushes) with two flanking parallel current-carrying rails (linear stators). The armature closes the current loop between the two rails. High current passing through the armature coil from the rails interacts with a magnetic field generated by the rail currents which accelerates the armature along the rails. The force on the armature is given by:

$$F = BIl \tag{45}$$

where l = distance between rails. The Δv imparted is given by:

$$\Delta v = \frac{\dot{m}_{prop}}{m_{ast}} v_{ex} \tag{46}$$

where $m_{prop} = \frac{2Pt_{thrust}}{v_{ex}^2}$ = propellant mass, $P = \eta\frac{m_{pow}}{\tau}$, t_{thrust} = thrusting time, v_{ex} = exhaust velocity, η =power efficiency = 0.3, τ = mass/power ratio = 25 kg/kW. The chief disadvantage is the rapid wearing of the physical contact brushes with the rails at high armature currents. To decrease the rail current to reduce wear requires the addition of an augmented magnetic field source using external coils [100]. It is reckoned that the railgun is limited to payloads under 50 kg.

Coilguns use electromagnetic Lorenz interaction to accelerate a conducting armature. A series of sequential stator coils induce acceleration in a conducting armature. Energising a coil generates an induced circular current in the armature that interacts with the stator coil magnetic field. The series of coils are energized sequentially by electronic switches and capacitors. Magnetic coupling between the armature current and the stator coils eliminates the requirement for physical contact. Payloads may be attached to the armature and released when the armature is decelerated by reversing the magnetic polarity. Coilguns may be comprised of many modular stator coils stacked end-to-end to form a barrel. Power must be supplied through high density electric discharges – high voltage capacitors or flywheels are suitable. Each module may be fed by an independent electrical power supply of flywheel generators. The flywheel is imposed by the requirement for energy storage with rapid discharge during power switching of the electromagnetic launcher. The flywheel permanent magnet motor should have low inductance and low resistance in the stator windings but provide high frequency stator currents [101]. Each stator coil's current pulse must be synchronised sequentially to create a travelling stator magnetic pulse to accelerate the armature down the barrel. Each successive coil must be energised at higher frequency to compensate for the voltage drop. The stator coil current pulses must be slightly faster than the armature speed to ensure slip - in induction motors, peak thrust occurs at small slip (synchronous motors require an induction motor for startup). Active feedback of the armature position is essential to control energising of the coils to compensate for deviations in armature speed. In particular, the field coils should be switched off when the armature is in the middle of the coil. The stator coil currents induce currents in the armature conductors which interact with the stator magnetic field (F = J x B). Magnetic pressure generates thrust on the armature:

$$P_B = \frac{B^2}{2\mu_0} \tag{47}$$

where B = magnetic field, e.g. a superconducting magnet generating 10 T yields close to 40 MPa which on a 1 m diameter armature generates 30 MN thrust. Higher exit velocities are generated by higher magnetic pressure. High stresses are induced in the supporting structure of the coil drives due to magnetic interaction between the coils:

$$F = i_b i_d \frac{dM}{dx} \tag{48}$$

where i_b =constant bucket current, i_d = variable drive coil current, dM/dx = mutual inductance variation between drive and bucket coils. Temperatures due to Joule heating which increases with B^2 must not exceed the armature magnetic stress limits. Further constraints on the armature are that eddy current skin depth δ due to magnetic penetration must be less than the armature diameter:

$$\delta \sim \sqrt{\frac{\rho_r t}{\mu_0}} \tag{49}$$

where ρ = armature resistivity, t = time (typically <1 s). A large electromagnetic coil gun launcher has demonstrated acceleration at 30,900g of a 10 kg mass to 11 km/s [102]. Currents of 1.72 MA were generated in each stator coil module at high voltage 10-30 kV to generate a magnetic force down the 200 m long launcher accelerating an armature by inducing a current in the armature coil. The force on the armature was 3 MN over 0.036s. The flywheel generator for each coil module was a 7.4 tonne rotor of radius 1.24 m with an iron core of flux density 1.6 T storing 60 MJ. We adopt a more modest example of a coilgun [103]. The power requirement is given by:

$$P = IV = \frac{\pi}{2}\frac{mv^2 l_c v}{\eta l_s l_a} \tag{50}$$

where I =peak stator coil current, V = applied voltage, η = electrical conversion efficiency, v = armature velocity at the coil, l_c = coil module length, l_s = stator barrel length, l_a = armature length. The voltage per coil turn is fixed:

$$\frac{V}{n} = \frac{\pi v}{l_a}\sqrt{\frac{\frac{1}{2}\mu_0 r_c^2 k_L (1-k_a^2)(1+k_c) m v^2}{2\eta l_s}} \tag{51}$$

where $n \le \frac{1}{4}\frac{\Delta v^2}{at}$ = number of stator coil turns, t =pole pitch, r_c = coil radius, k_L = self-inductance, k_a = magnetic coupling to armature, k_c = magnetic coupling to adjacent stator coil. From the voltage selection, peak current can be determined:

$$I = \frac{1}{2}\frac{\pi m v^2 l_c v}{\eta l_s l_a (1+k_a) V} \tag{52}$$

The kinetic energy of a flywheel power storage system is given by:

$$E = \frac{1}{2} I w^2 = \frac{1}{4}\rho \pi r^4 h (2\pi n)^2 = \frac{1}{2}\frac{m v^2}{\eta \eta_t \eta_r} \tag{53}$$

where η = motor efficiency, η_t = transfer efficiency, η_r =flywheel energy recovery efficiency.

$$\Delta v = \frac{n.m_{pellet}}{m_{ast}(t)} v_{ex} \tag{54}$$

where $m_{ast}^{(t)}$ = asteroid mass, n = number of pellets, $m_{pellet} = \frac{2P\Delta t}{v_{ex}^2}$ where Δt=time between pellets.

Optimisation of 11 design parameters of a coilgun to maximise energy efficiency is possible [104]. Rather than using coils for the armature, a ferromagnetic container may used [105] which makes the manufacture of the projectile considerably simpler than an armature coil. This is subject to magnetic saturation limits of 1.5 T. It is plausible that high temperature superconducting magnets of REBCO (rare earth barium copper oxide) tapes for higher magnetic fields of up to 12 T [106] may be realisable from asteroid in-situ resources but ferromagnetic material is a more readily accessible resource. Accelerated asteroid material is ejected from a mass driver as reaction mass offering low-thrust but high specific impulse (I_{sp}~800-1500s with T/W~10^{-4}) performance.

5.3 Deployment of Solar Energy

For our self-replication scenario, we assume a baseline coilgun [104] with a 40 kV total coil voltage and two 0.03 m long coils of 21 kV per turn with a peak current of 490 kA accelerating a 20 kg armature of length 0.085 m to 2.5 km/s along a 15 m long coilgun of radius 0.155 m with 30% efficiency and 60% armature coupling and 56% stator coil coupling (eq 51-55). The power supply of almost 20 GW represents a 200 MJ discharge over 0.012 s (with acceleration of 200 km/s^2). In fact, the electromagnetic launcher will not be the dominant structure because its 9 tonnes (assuming 400 kg/m [107] with a 50% margin) will be dwarfed by its power supply. Solar concentrators are required to provide thermal and electrical power - they can be manufactured as mirrors through vapour deposition from aluminium powder feedstock and built from modular sections. A 1 km diameter aluminium parabolic reflector of thickness 0.5 μm has a mass of 1 tonne at 1 AU from the sun (assuming a mass/area ratio of 0.1 kg/m^2 typical of inflatable structures) [108]. A 1 km^2 reflector generates 1.2 GW thermally at 1 AU (assuming a solar constant of 1360 W/m^2 and a reflectivity of 0.9). Power generation for mining and manufacturing requires the construction of solar concentrators (nominally Fresnel lenses) to provide high-intensity thermal sources for smelting.

Solar concentrators may be co-opted to provide surface ablation (to vaporise rather than melt material) to supplement the electromagnetic launchers. The advantage of surface ablation using focused solar energy to vaporize material is that it is controllable, avoids catastrophic fragmentation of the asteroid and does not require tactile interaction with the asteroid. A large solar concentrator such as mirror or Fresnel lens is mounted onto a spacecraft which directs concentrated solar energy onto a small area of the asteroid surface. Ablating surface material requires large structures of up to 10 km in diameter in a low orbit around an irregular gravity field of the asteroid. Such large structures suffer from significant light pressure perturbations which must be compensated for through active station-keeping. The solar concentrators may be multiple mirrors that ablate the asteroid surface creating a jet of gas and dust which applies thrust [109]. Concentrated solar energy thermally ablates asteroid surface material to generate continuous thrust on the asteroid. Sublimation of icy material is far easier than vaporization of silicates or metals. It is plausible to vary these parameters, e.g. longer driver, higher thrust, higher throughput, higher exit velocities but these will have implications for the power demands. Solar power focussed onto the asteroid is given by:

$$P = \eta \frac{S_0}{R_{sun}^2} A(1-a) \tag{55}$$

where η = reflective efficiency = 0.9, S_0 =solar constant, R_{sun} = distance to the sun, A = reflective cross section, a = albedo of asteroid = 0.2 for an S-type asteroid. A solar concentration ratio of 2500 is nominal to yield a surface temperature of 1800°C to evaporate forsterite. The distance to the asteroid h is dependent on the concentration ratio $C = A/A_{hotspot}$ of the mirrors:

$$A_{hotspot} = \frac{1}{4}\pi (h\alpha)^2 \tag{56}$$

where α = Sun's angular diameter (radians). In a Fresnel lens, the concentration ratio is determined by the design of the lens and its focus. Mass flow rate is given by:

$$\dot{m} = 2v_r \int_{t_0}^{t_f} \frac{1}{E}\left((P_{in} - Q_{rad}) - \left(\sqrt{\frac{CK\rho}{\pi}} (T_{sub} - T_0) \right) \sqrt{\frac{1}{t}} \right) dt \tag{57}$$

For a 100 m diameter mirror (almost 0.008 km^2), mass flow rate is ~1 kg/s. Induced acceleration is given by:

$$a = \frac{S\dot{m}v}{m_{ast}(t)} \tag{58}$$

where $S = \frac{2}{\pi}$ = scattering effect, $v = \sqrt{\frac{8kT_{sub}}{\pi \mu_r}}$, μ_r = molar mass of forsterite = 0.141 kg, T_{sub} = sublimation temperature = 2000 K. The acceleration generated on the asteroid is very small ~6 x 10^{-21} m/s^2 – adopting multiple mirrors to increase the mass flow rate does little to reduce the requirement for many decades of operation. The solar concentrator is also prone to accumulate deposition of the ablated material over time which degrades the optics following a Beer-Lambert law. This is a critical problem. Rather than a single large structure, a set of smaller solar concentrators may be employed in a formation undergoing continuous station-keeping or mounted as a configuration onto the asteroid surface. Each individual solar concentrator would be focussed on a single point to ensure ablation. This approach does little to alter the poor performance of this technique.

Solar power however is essential which may be generated using such solar concentrators to provide hot thermal sources. This permits thermionic conversion of solar power into electrical energy which is typically 15% efficient yielding 0.18 GW per 1 tonne reflector [91,110]. Each electromagnetic launcher requires 110 reflectors to generate the near 20 GW requirement, massing at 100 tonnes. The capacity of the electromagnetic launcher is determined by its loading rate which must match its full capacity of 20 kg at 80 Hz (1600 kg/s) using a bucket wheel excavator. The carbonaceous asteroid Bennu with a diameter of almost 500 m has a mass of 7 x 10^{10} kg.

With a single electromagnetic launcher, it would impart a Δv of 5.7 x 10^{-5} m/s giving a required warning time of over 560 years. Clearly, this is not an effective solution.

5.4 Viral Infection-Induced Exocytosis

The power of self-replication lies in its inherent multiplier effect that can grow exponentially to amplify the Δv imparted by mass drivers:

$$t(y) = \frac{3.2\times10^{-2}}{\eta\Delta v} \quad (59)$$

where $\Delta v = \frac{m_{prop}}{m_{ast}} v_{ex}$ and $n = \sum_{i=1}^{p}(1+r)^i$ = population, r = number of offspring/generation = 2 nominally, p = number of generations. This expression does not account for the change in asteroid mass over time which will reduce the thrusting time to achieve a given Δv (we shall see later that this is unimportant). We shall use the reference time of one year to define the required number of generations to impart the necessary Δv:

$$n = \frac{3.2\times10^{-2}}{5.7\times10^{-5}} = 561 \quad (60)$$

This requires over 5 generations (n = 363) but under 6 generations (n = 1092). A full 6 generations brings the warning time down to 6 months. However, this timescale is dwarfed by the rate of consumption of the asteroid. In a time much less than this, the entire asteroid has been ejected as reaction mass, i.e. the entire asteroid has been consumed – this is exocytosis. The critical issue will be the generation time for the construction of 2 offspring per generation (120 tonnes each) – this assumes each 10 tonne self-replicator also builds the 100 tonnes of power generation and 10 tonnes of mass driver. We assume a throughput rate defined by a 2 m^3 bucket of 3000 kg/m^3 material using a JCB every 30 s yielding a throughput of 200 kg/s. A useful ore recovery rate of 0.1% (this is a worst case scenario as most terrestrial mines excavate 100 tonnes of ore to yield 1 tonne of metal) yields a construction rate of 0.2 kg/s and so a generation time of 14 days (for two offspring of 120 tonnes each). One significant time constraint is the growth of artificial crystals of quartz for piezoelectric sensors which takes 40-80 days (average 60 days). The most obvious way to eliminate this time constraint is to transport pre-manufactured quartz crystals as required. We assume the 14-day generation time remains valid. The total warning time is given by:

$$t = t_{prep} + t_{cons} \quad (61)$$

where $t_{prep} = pt_{gen}$ = preparation time and $t_{cons} = \frac{m_{ast}}{\dot{m}n}$, $n = \frac{3.2\times10^{-2}}{t(y)\Delta v}$ = consumption time. Now, $n = \sum_{i=1}^{p}(1+r)^i \sim (1+r)^p$ because the total population is dominated by the final generation, so $p \approx \frac{ln(n)}{ln(1+r)} \approx 6$ rounded up to nearest integer in this case of r = 2 and n = 561. Hence, 6 generations involve a construction time over 3 months (84 days). Without self-replication, the consumption time is over 500 days which is comparable to other methods. With self-replication, this reduced to under a single day. Hence, consumption time can be ignored as negligible:

$$t \approx \frac{ln(n)}{ln(r+1)} t_{gen} \quad (62)$$

The warning time necessary is determined by the number of generations required and the generation period. While the generation time required grows arithmetically with population, the Δv output grows geometrically with population. Nevertheless, we can explore trading off preparation time and consumption time. When preparation time equates to consumption time:

$$t_{prep} = t_{cons} \quad (63)$$

$$\frac{ln(n)}{ln(r+1)} t_{gen} = \frac{m_{ast}}{\dot{m}n} \quad (64)$$

The solution $nln(n) = \frac{m_{ast} ln(r+1)}{\dot{m} t_{gen}}$ = 40 (with a mass flow rate of 1667 kg/s) in this case which requires n = 15 or just under 3 generations. This yields an optimal preparation (42 days) and consumption time (34 days) of 76 days (2.5 months). This is a significantly short warning time for a sizeable asteroid. We have ignored the mass of the manufactured structures of 15 x 120 tonnes = 1.8 x 10^6 kg representing ~ 0.002% of the 7 x 10^{10} kg mass of the asteroid. We can generalise this to any mass of asteroid *ceteris paribus* (all other things being equal). Assuming that the 0.5 km diameter Bennu resides at the lower end of the asteroid threat, we may consider a 10 km diameter KT-like impactor of 1 x 10^{15} kg asteroid at the top end. This yields $nln(n)$ = 544,382. Since $ln(n)$ plateaus to ~10 for large numbers around n =50,000, this gives a reasonable estimate for n. This yields 10 generations which rounds to 59,049 modules. This gives a preparation time of 140 days plus consumption time of 118 days yielding a total warning time of 258 days, i.e. under 8.5 months. The warning time capability grows only logarithmically with asteroid size – this is an entirely general result that illustrates the power of self-replication in generating exponential growth in productive capacity from a modest initial mass investment. We submit that it constitutes the only practical (i.e. of modest cost) approach to dealing with asteroid threats.

These parameters can be adjusted after arrival at the asteroid to accommodate local conditions and circumstances. Once the required capacity has been attained, the universal constructor factories are then programmed to construct in parallel the requisite number of modules required for a given set of electromagnetic launchers on the basis that each mass driver comprises a linear sequence of identical modules forming a linear motor. These mass drivers, operating in parallel, continually launch material gangue from the in-situ mining and manufacturing of the universal constructors and mass drivers and further asteroid material to impart the required Δv manoeuvres to divert the NEO trajectory from Earth – this is the exocytosis process. As a byproduct of this process, the asteroid is entirely consumed. This resembles the autophagus spacecraft concept based on a polymer composite structure that can be converted into solid fuel for burning with an oxidizer (such as nitrogen tetroxide) [111]. Suitable structural fuels have low pyrolysis temperature for low thermal energy requirement though the specific fuels were not named. The structure may be reinforced with carbon fibre and impregnated with internal passages for the conveyance of oxidizer fluid.

As a variation on this concept, capturing a NEA into an impulsive patched conic manoeuvre into Earth orbit [112] or to a Sun-Earth Lagrangian point through continuous thrust propulsion attached to the asteroid [113] offers an attractive prospect for exploitation. The orbital manoeuvres would involve a ballistic trajectory that intersects a periodic orbit around the Sun-Earth L_1 or L_2 Lagrangian point. Over 1000 NEAs have a diameter exceeding 1 km, i.e. > 2 x 10^9 tonnes (comprising 30 x 10^6 tonnes Ni, 1.5 x 10^6 tonnes Co and 7.5 x 10^3 tonnes Pt). A 1 km^3 M-type asteroid could supply Earth with Fe for 10 years and Ni for 1000 years. However, supply to Earth requires atmospheric entry, deceleration and landing of cargo which is costly as well as producing of ozone-depleting NO_x due to shock heating. However, the import of the much rarer platinum group metals (PGM) in much smaller quantities would have a negligible effect on atmospheric NO_x production. However, despite this, we do not anticipate returning material to Earth. More usefully, NEOs may act as resource depots in useful orbits. Returning a NEO to Earth orbit may employ a lunar gravity assist into high Earth orbit with a Δv saving of 0.5 km/s to 2 km/s. There are 12 NEAs in the range 2-20 m in diameter which could be manoeuvred into an Earth orbit with a Δv of less than 0.5 km/s using in-situ mass drivers. The asteroid might be hollowed out as a potential shielded habitat and the extracted materials exploited using self-replicating machines.

6 CONCLUSIONS

The closest analogue to a self-replicating concept of asteroid mitigation is the League of Extraordinary Machines that proposed a distributed approach of using many small spacecraft to intercept the threatening bolide, land on it, and each to use mass drivers to deflect its orbit [114]. The 40 kW nuclear reactor powered 1600 kg MADMEN (modular asteroid deflection mission ejector node) spacecraft anchored to the asteroid surface would provide power. It mounted a 14 m long mass driver ejecting mass at 100-200 m/s assuming 1 kg per single shot per minute. This required it to drill out material at 100 kg/h. 200 MADMEN (320 tonnes) were required to impart a 1 m/s deflection on a 100 m diameter asteroid over 60 days (assuming 50% failure rate). This is far more sedate yet far more massive than the self-replicating machine proposal presented here.

Self-replication offers a superior means of asteroid mitigation that can accommodate any warning time sufficient to implement generational population growth. Self-replication technology offers the prospect for controlled redirection of the NEO which can be tested through an ARM II-type technology demonstrator mission on more threat-representative NEOs than is currently envisaged through ARM I. We contend that such self-replicating machines provide the most adaptable and robust solution to NEO mitigation without the need for legally-controversial destructive solutions or unrealistic long-term solutions that are unlikely to be acted upon in a timely fashion (to wit, human response to long-term climate change). Once self-replication technology has been mastered, asteroid threat prevention does not require a concerted international government effort to implement, rather it requires one or more privateers willing to turn a potential disaster into a lucrative opportunity.

REFERENCES

1. D. Lupishko & M. Di Martino "Physical properties of Near-Earth asteroids" *Planetary & Space Science*, Vol 46 (1), pp 47-74, 1998.
2. S. Ipatov, & J. Mather, "Comet and asteroid hazard to the terrestrial planets" *Advances in Space Research*, Vol 33, pp 1524-1533, 2004.
3. R. Binzel, D. Lupishko, M. Di Martino, R. Whiteley, G. Hahn, "Physical properties of near-Earth objects" in *Asteroids III*, (ed. W. Bottke, A. Cellino, P. Paolicchi, R. Binzel), University of Arizona Press, pp 255-271, 2002.
4. A. Morbidelli, W. Bottke, C. Froeschle, P. Michel, "Origin and evolution of near-Earth objects" in *Asteroids III*, (ed. W. Bottke, A. Cellino, P. Paolicchi, R. Binzel), University of Arizona Press, pp 409-422, 2002.
5. I. Williams, "Exploring the solar system beyond Neptune," *JBIS*, Vol 60, pp 387-388, 2007.
6. H. Spinrad "Comets and their composition," *Annual Reviews Astrophysics*, Vol 25, pp 231-269, 1987.
7. D. Lauretta & the OSIRIS-Rex Team, "Unexpected surface of asteroid (101955) Bennu," *Nature* Vol 568, pp 55-59, 2019.
8. D. Morrison, "Defending the Earth against asteroids: the case for a global response" *Science & Global Security*, Vol 13, pp 87-103, 2005.
9. J. West, "Space security index 2018," Spacesecurityindex.org, 2018.
10. B. Napier, & D. Asher, "Tunguska impact event and beyond," *Astronomy & Geophysics,* Vol 50, pp 1.18-1.26, 2009.
11. F. Whipple, "Note on the structure of comet nuclei," *Planetary & Space Science* Vol 47, pp 301-304, 1999.
12. B. Napier, D. Asher, M. Bailey, D. Steel, "Centaurs as a hazard to civilisation," *Astronomy & Geophysics*, Vol 56 (Dec), pp 6.24-630, 2015.
13. E. Asphaug "Growth and evolution of asteroids," *Annual Reviews Earth & Planetary Science*, Vol 37, pp 413-448, 2009.
14. D. Yeomans, A. Chamberlin. "Comparing the Earth impact flux from comets and near-Earth asteroids," *Acta Astronautica*, Vol 90, pp 3-5, 2013.
15. Hughes D "Cratering rate of planet Earth", *JBIS* Vol 52, pp 83-94, 1999
16. L. Foschini, "On the atmospheric fragmentation of small asteroids," *Astronomy & Astrophysics*, Vol 365, 612-621, 2001.
17. J. Stuart & R. Binzel, "Bias-corrected population, size distribution and impact hazard for the near-Earth objects," *Icarus*, Vol 170, pp 295-311, 2004.
18. S. Yabushita & A. Allen, "On the impact vs GMC model of the K/T boundary event", *Astronomy & Geophysics*, Vol 39, pp 3.28-3.29, 1998.
19. D. Steel, "Tunguska at 200," *Nature,* Vol 453, pp 1157-1159, 2008.
20. C. Chyba, P. Thomas, Zahnle K "1908 Tunguska explosion: atmospheric disruption of a stony asteroid" *Nature* Vol 361, pp 40-44, 1993.
21. E. Cartlidge, "Threat from above," *Physics World*, (Mar), pp 27-29, 2006.
22. D. Steel, "Our asteroid pelted planet," *Nature*, Vol 354, pp 265-267, 1991.
23. S. Chesley, P. Choads, A. Milani, G. Valsecchi, D. Yeomans, "Quantifying the risk posed by potential Earth impacts," *Icarus*, Vol 159, pp 423-432, 2002.
24. M. Bailey & W. Napier, "Fluctuating population of Earth impactors", *JBIS*, Vol 52, pp 185-194, 1999.
25. C. Chapman, D. Morrison, "Impacts on the Earth by asteroids and comets: assessing the hazards," *Nature*, Vol 367, pp 33-40, 1994.
26. C. Chapman, "Hazard of near-Earth asteroid impacts on Earth," *Earth & Planetary Science Letters*, Vol 222, pp 1-15, 2004.
27. A. Harris, "What Spaceguard did", *Nature*, Vol 453, pp 1178-1179, 2008.
28. S. Clark, D. Fearn, "Impact of advanced platform and ion propulsion technology on small, low-cost interplanetary spacecraft," *Proc 5th IAA Int Conf Low-Cost Planetary Missions* (ESA SP-542), ESTEC, Noordwijk, 279-288, 2003.
29. B. Dachwald, W. Sebolt, L. Richter, "Multiple rendezvous and sample return missions to near-Earth objects using solar sailcraft," *Proc 5th IAA Conf Low-Cost Planetary Missions* (ESA SP-542), ESTEC, Noordwijk, pp 351-358, 2003.
30. A. Quarta, G. Mengali, "Electric sail missions to potentially hazardous asteroids," *Acta Astronautica*, Vol 66, pp 1506-1519, 2010.
31. D. Mazanek, R. Merrill, J. Brophy, R. Mueller "Asteroid redirect mission concept: a bold approach for utilising space resources," *Acta Astronautica*, Vol 117, pp 163-171, 2015.
32. N. Strange, D. Landau, T. McElrath, G. Lantoine, T. Lam, M. McGuire, L. Burke, M. Martini, J. Dankanich, "Overview of mission design for NASA asteroid redirect robotic mission concept," *Proc 33rd Int Electric Propulsion Conf, Washington DC*, IEPC-2013-321, 2013.
33. A. Ellery, "Invited Commentary: Asteroid Ho!", *JBIS*, Vol 65 (2/3), pp 1-2, 2012.
34. B. Wilcox, M. San Martin, L. Girsch, S. Howe S, F. Grip, R. Nayeri, T. Litwin, J. Carlson, N. Shekels, A. Jain, C. Lim, S. Mint, J. Dunkle, A. Sirota A, C. Fuller, "Testbed for studying the capture of a small, free-flying asteroid in space," *Proc AIAA Space Conf & Exposition, Pasadena, CA, 2015.*
35. A. Cheng, J. Atchison, B. Kantsiper, A. Rivkin, A. Stickle, C. Reed, A. Galvez, I. Carnelli, P. Michel, S. Ulamec, "Asteroid impact and deflection assessment mission," *Acta Astronautica*, Vol 115, pp 262-269, 2015.
36. A. Harris, M. Barucci, J. Cano, A. FitzSimmons, M. Fulchignoni, S. Green, D. Hestroffer, V. Lappas, W. Work, P. Michel, D. Morrison, D. Payson, F. Schafer, "European Union funded NEOShield project: a global approach to near-Earth object impact threat mitigation," *Acta Astronautica*, Vol 90, pp 80-84, 2013.
37. A. Carusi, G. Vaksecchi, G. D'Abramo, A. Boattini, "Deflecting NEOs in route of collision with the Earth," *Icarus*, Vol 159, pp 417-422, 2002.
38. D. Izzo, C. de Negueruela, F. Ongaro, R. Walker, "Strategies for near Earth object impact hazard mitigation," *Acta Futura*, Vol 1, pp 61-67, 2005.
39. T. Ahrens & A. Harris, "Deflection and fragmentation of near-Earth asteroids," *Nature*, Vol 360, pp 429-433, 1992.
40. D. Mazanek, C. Roithmayr, J. Antol, L. Kay-Bunnell, M. Werner, S-Y Park, R. Kumar, "Comet/asteroid protection system (CAPS): a space-based system concept for revolutionizing Earth protection and utilization of Near-Earth objects," *Proc 53rd International Astronautics Congress, Houston, TX*, paper no IAC-02-IAA.13.4/Q.5.1.01, 2002.
41. C. Chapman, D. Durda, R. Gold, "Comet/asteroid impact hazard: a systems approach," *Southwest Research Institute White Paper,* 2001.
42. G. Paterson, G. Radice, J-P Sanchez, "Asteroid control and resource utilisation," *JBIS,* Vol 66, pp 155-160, 2013.
43. M. Mashayekhi, A. Misra, "Tether assisted near Earth object diversion," *Acta Astronautica*

Vol 75, pp 71-77, 2012.

44. J. Solem, "Interception of comets and asteroids on collision course with Earth," *J Spacecraft & Rockets*, Vol 30 (2), pp 222-228, 1993.

45. J-S Chern, "Optimal thrust programme for deviating an Earth-pointing asteroid," *Acta Astronautica*, Vol 44 (7-12), pp 809-814, 1999.

46. C. Maccone, "Planetary defence from space: part 1 – Keplerian theory," *Acta Astronautica*, Vol 55, pp 991-1006, 2004.

47. Y. Akiyama, M. Bando, S. Hokamoto, "On the possibility of using small asteroids for deflecting near-Earth asteroids," *Advances in Space Research*, Vol 57, pp 1820-1831, 2016.

48. D. Massonnet, B. Meyssignac, "Captured asteroid: our David's stone for shielding earth and providing the cheapest extraterrestrial material," *Acta Astronautica*, Vol 59, pp 77-83, 2006.

49. J. Solem, "Nuclear explosive propelled interceptor for deflecting objects on collision course with Earth" *J Spacecraft*, Vol 31 (4), pp 707-709, 1993.

50. G. Matloff, "Near-Earth asteroids: our next interplanetary destinations", *JBIS*, Vol 51, pp 267-274, 1998.

51. K. Howley, R. Managan, J. Wasem, "Blow-off momentum from melt and vapour in nuclear deflection scenarios," *Acta Astronautica*, Vol 103, pp 376-381, 2014.

52. C. Hall & I. Ross, "Dynamics and control problems in the deflection of near-Earth objects," *AAS* 97-640, 1997.

53. B. Wie, "Hypervelocity nuclear interceptors for asteroid disruption," *Acta Astronautica*, Vol 90, pp 146-155, 2013.

54. K. Ramesh, J. Hogan, J. Kimberley, A. Stickle, "Review of mechanisms and models for dynamic failure, strength and fragmentation." *Planetary & Space Science*. Vol 107, pp 10-23, 2015.

55. K. Holsapple, "On the strength of the small bodies of the solar system: a review of strength theories and their implementation for analyses of impact disruptions," *Planetary & Space Science*, Vol 57, pp 127-141, 2009.

56. D. Korycansky, C. Plesko, "Effects of stand-off bursts on rubble-pile targets: evaluation of a hazardous asteroid mitigation strategy," *Acta Astronautica*, Vol 73, pp 10-22, 2012.

57. K. Housen, "Cumulative damage in strength-dominated collisions of rocky asteroids: rubble piles and brick piles," *Planetary & Space Science*, Vol 57, pp 142-153, 2009.

58. N. Peter, A. Barton, D. Robinson, J. Salotti, "Charting response options for threatening near-Earth objects," *Acta Astronautica*, Vol 55, pp 325-334, 2004.

59. B. Syal, D. Dearborn, P. Schultz, "Limits on the use of nuclear explosives for asteroid deflection" *Acta Astronautica* Vol 90, pp 103-111, 2013.

60. W-M. Shen, P. Will, B. Khoshnevis, "Self-assembly in space via self-reconfigurable robots" *Proc IEEE Int Conf Robotics & Automation*, pp. 2516-2521, 2003.

61. E. Lu, S. Love, "Gravitational tractor for towing asteroids," *Nature*, Vol 438, pp 177-178, 2005.

62. C. Foster, J. Bellerose, D. Mauro, B. Jaroux, "Mission concepts and operations for asteroid mitigation involving multiple gravity tractors," *Acta Astronautica*, Vol 90, pp 112-118, 2013.

63. D. Izzo, "Optimisation of interplanetary trajectories for impulsive and continuous asteroid deflection," *J Guidance, Control & Dynamics*, Vol 30 (2), pp 401-408, 2007.

64. C. Bombardelli, H. Urrutxua, M. Merino, J. Pelaez, E. Ahedo, "Ion beam shepherd: a new concept for asteroid deflection," *Acta Astronautica*, Vol 90, pp 98-102, 2013.

65. G. Matloff, "Solar collector and near-Earth object deflection," *Acta Astronautica*, Vol 62, pp 334-337, 2008.

66. G. Matloff, "Deflecting earth-threatening asteroids using the solar collector: an improved model," *Acta Astronautica*, Vol 82, pp 209-214, 2013.

67. A. Gibbings, M. Vasile, I. Watson, J-M Hopkins, D. Burns, "Experimental analysis of laser ablated plumes for asteroid deflection and exploitation," *Acta Astronautica*, Vol 90, pp 85-97, 2013.

68. M. Vasile, A. Gibbings, I. Watson, J-M Hopkins, "Improved laser ablation model for asteroid deflection," *Acta Astronautica*, Vol 103, pp 382-394, 2014.

69. M. Vetrisano, C. Colombo, M. Vasile, "Asteroid rotation and orbit control via laser ablation," *Advances in Space Research*, Vol 57, pp 1762-1782, 2016.

70. V. Ivashkin & V. Smirnov, "Analysis of some methods of asteroid hazard mitigation for the Earth," *Planetary & Space Science,* Vol 43 (6), pp 821-825, 1995.

72. C. Bombardelli, "Artificial spin-up and fragmentation of sub-kilometre asteroids," *Acta Astronautica*, Vol 65, pp 1162-1167, 2009.

71. J-Y Prado, A. Perret, O. Boisard, "Deflecting Apophis with a flotilla of solar shields," *Advances in Space Research*, Vol 48, pp 1911-1916, 2011.

73. A. Balikci, "High velocity linear induction launchers," *Int J Impact Engineering*, Vol 35, pp 1405-1409, 2008.

74. R. Thornton, "Magnetic levitation and propulsion 1975," *IEEE Trans Magnetics,* Vol 11 (4), pp 981-995, 1975.

75. D. Kawk, B. Kim, S. Kim, C. Cho, K-S Tang, S-H Kim, B-H Lee, S An, Y-H Lee, H. Yoon, S. Koo, G. Baik, S. Jin, "Modelling of three-stage electromagnetic induction launcher." *J Magnetics*. Vol 20, pp 394-399, 2015.

76. M. Bazzocchi, R. Emami, "Comparative analysis of redirection methods for asteroid resource exploitation," *Acta Astronautica,* Vol 120, pp 1-19, 2016.

77. Y. Sugimoto, G. Radice, J. Sanchez, "Effects of NEO composition on deflection methodologies," *Acta Astronautica*, Vol 90, pp 14-21, 2013.

78. J. Sanchez, C. Colombo, M. Vasile, G. Radice, "Multi-criteria comparison among several mitigation strategies for dangerous near-Earth objects," *J Guidance Control & Dynamics*, Vol 32 (1), pp 121-142, 2009.

79. G. Friedman, "Comparing mass driver and disperser concepts for non-nuclear mitigation of asteroid threats", *JBIS*, Vol 58, pp 310-315, 2005.

80. A. Ellery, "Are self-replicating machines feasible?" *AIAA J Spacecraft & Rockets*, Vol 53 (2), pp 317-327, 2016.

81. R. Freitas, W. Gilbreath, *Advanced Automation for Space Missions*, NASA CP- 2255, 1980.

82. P. Metzger, A, Muscatello, R. Mueller, J. Mantovani, "Affordable, rapid bootstrapping of space industry and solar system civilization," *ASCE Journal of Aerospace Engineering*, Vol 26 (1), pp 18-29, 2013.

83. G. Chirikjian, Y. Zhou, J. Suthakorn, "Self-replicating robots for lunar development" *IEEE/ASME Transactions on Mechatronics*, Vol 7 (4), pp 462-472, 2002.

84. R. Jones, P. Haufe, E. Sells, P. Iravani, V. Olliver, C. Palmer, A. Bowyer, "RepRap – the replicating rapid prototype",, *Robotica*, Vol 29 (1), pp 177-191, 2011.

85. W-M Shen, P. Will, B. Khoshnevis, "Self-assembly in space via self-reconfigurable robots," *Proc IEEE Int Conf Robotics & Automation*, pp 2516-2521, 2003.

86. G. Vardaxis, B. Wie, "Near-Earth object intercept trajectory design for planetary defense," *Acta Astronautica*, Vol 101, pp 1-15, 2014.

87. R. Walker, D. Izzo, C. De Negueruela, L. Summerer, M. Ayre, M. Vasile, "Concepts for near-Earth asteroid deflection using spacecraft with advanced nuclear and solar propulsion systems," *JBIS*, Vol 58, pp 268-278, 2005.

88. K. Zacny, P. Chu, J. Craft, M. Cohen, W. James, B. Hilscher B "Asteroid mining", *AIAA Space Conference & Exposition, San Diego, CA*, AIAA 2013-530, 2013.

89. A. Ellery, "Exponential populations of solar power satellites tending to zero specific cost," *Proc. 69th Int. Astronautics Congress, Adelaide, Australia,* IAC-17-C3.1.8x38036, 2017.

90. A. Ellery, "Low-cost space-based geoengineering – a necessary albeit unwelcome solution to climate change," *Proc IAF Global Space Exploration Conf (GLEX), Beijing, China, 2017*.

91. A. Ellery A "In-situ resourced solar power generation and storage for a sustainable Moon Village," *Proc. 70th Int. Astronautics Congress*, IAC 19-C3.4.4x49639, 2019.

92. D. Scheeres, B. Williams, W. Bollmnan, R. Davis, C. Helfrich, S. Synnott, D. Yeomans, "Navigation for low-cost missions to small solar-system bodies," *Acta Astronautica*, Vol 35 (Suppl), pp 211-220, 1995

93. J. Sanchez, C. McInnes, "Assessment on the feasibility of future shepherding of asteroid resources," *Acta Astronautica*, Vol 73, pp 49-66, 2012.

94. L. Wilson, K. Keil, S. Love, "Internal structure and densities of asteroids," *Meteoritics & Planetary Science*, Vol 34, pp 479-483, 1999.

95. A. Misra & Y. Panchenko, "Attitude dynamics of satellites orbiting an asteroid," *J Astronautical Sciences*, Vol 54 (3/4), pp 369-381, 2006.

96. M. Vetrisano, M. Vasile, "Autonomous navigation of a spacecraft formation in the proximity of an asteroid", *Advances in Space Research* Vol 57, pp 1783-1804, 2016.

97. A. Ellery, "Review and feasibility of micro-penetrators for planetary exploration", Canadian Space Agency Technical Report, MPC-CU1, 2011.

98. P. Michel, "Physical properties of near-Earth objects that inform mitigation," *Acta Astronautica,* Vol 90, pp 6-13, 2013.

99. S. Price, "Surface properties of asteroids" *Advances in Space Research*, Vol 33, pp 1548-1557, 2004.

100. M. Roch, "Experiments with the modular augmented staged electromagnetic launcher (MASEL) and comparison with simulations," *Journées Chercheurs en Genie Electrique*, 2014 – SEEDS, St Louis, France, 2014.

101. C. Sezenoglu, A. Balikci, "Design of axial flux permanent magnet generator for generator driven electromagnetic launcher," *Proc 9th Int Conf Electrical & Electronics Engineering, Bursa, Turkey*, pp 595-598, 2015.

102. J. Schroeder, J. Gully, M. Driga, "Electromagnetic launchers for space applications," *IEEE Trans Magnetics*, Vol 25 (1), pp 504-507, 1989.

103. R. Kaye, "Operational requirements and issues for coilgun electromagnetic launchers," *IEEE Trans Magnetics*, Vol 41 (1), pp 194-199, 2005.

104. Y. Zhang, W. Qin, J. Liao, J. Ruan, T. Huang, "Optimisation of three-stage electromagnetic coil launcher," *Sensors & Transducers*, Vol 171 (5), pp 121-127, 2014.

105. K. Leubner, R. Laga, I. Dolezel, "Advanced model of electromagnetic launcher," *Advances in Electrical Engineering*, Vol 13 (3), pp 223-229, 2015.

106. J. Ciceron, A. Badel, P. Tixador, "Superconducting magnetic energy storage and superconducting self-supplied electromagnetic launcher," *European Physical J Applied Physics* Vol 80, 20901, 2017.

107. G. Roesler, "Mass estimate for a lunar resource launcher based on existing terrestrial electromagnetic launchers," *Machines*, Vol 1, pp 50-62, 2013.

108. C. McInnes, "Near Earth asteroid resource utilisation for large in-orbit reflectors" *Space Policy*, Vol 37, pp 62-64, 2016.

109. M. Vasile, A. Maddock, "On the deflection of asteroids with mirrors", *Celestial Mechanics & Dynamical Astronomy* Vol 107, pp 265-284, 2010.

110. A. Ellery, "Solar power satellites for clean energy enabled through disruptive technologies," *Proc 23rd World Energy Congress (Award Winning Papers), Istanbul, Turkey*, pp 133-147, 2016.

111. P. Joshi, B. Upschulte, A. Gelb, B. Green, "Autophagus spacecraft composite materials for orbital propulsion," *Proc SPIE Smart Structures & Materials: Industrial & Commercial Applications of Smart Structures Technologies*, (ed A-M. McGowan), Vol 4698, pp 171-179, 2002.

112. J. Sanchez, C. McInnes, "Asteroid resource map for near-Earth space," *J Spacecraft & Rockets*. Vol 48 (11), pp 153-165, 2011.

113. N. Llado, Y. Ren, J. Masdemont, G. Gomez, "Capturing small asteroids into a Sun-Earth Lagrangian point," *Acta Astronautica*, Vol 95, pp 176-188, 2014.

114. J. Olds, A. Charania, M. Graham, J. Wallace, *League of extraordinary machines: a rapid and scalable approach to planetary defence against asteroid impactors*, NASA Institute for Advanced Concepts (NIAC) Phase 1 Report CP-NIAC-0202, 2004.

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