IAC -11.A3.4

A SMART CLOUD APPROACH TO ASTEROID DEFLECTION

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ABSTRACT

This paper presents a novel idea for the successful deflection of asteroids. Adapted initially from the kinematic impactor approach, this new concept – Smart Cloud – combines the relative benefits of the ion beam shepard in providing a large cloud of small particles for the effective deflection and mitigation of asteroids. The cloud consists of a large number of incredibly low mass nano-size spacecraft that are released at a high relative velocity. Upon impact with the asteroid the smart cloud is shown to be highly effective in creating a large artificial drag, and therefore an associated thrust, onto the asteroid. The technique is also advantageous in avoiding the catastrophic fragmentation of the asteroid which might otherwise occur with the impact of a monolithic spacecraft and/or projectile. The impact energy of each colliding particle is significantly lower than the impact energy for disruption. . For analysis the smart cloud approach has been compared to other methods of potential deflection. This includes the low-thrust tug and the ion beam shepard. The paper will show that when the total deflection mass of the smart cloud is equivalent to the ion beam shepard approach, is has the advantage of significantly reducing the system mass and complexity of the spacecraft design. It is also superior in the deflection and mitigation of deep crossing asteroids.

I. ACRONYMS

GNC	Guidance, Navigation and Control
IBS	Ion Beam Shepard
Isp	Specific Impulse
LT	Low Thrust
NEA	Near Earth Asteroid
PPU	Power Processing Unit
TRL	Technology Readiness Level

II. INTRODUCTION

II. I Impact Risk

Asteroids, the rocky remains from planetary accretion, represent both an opportunity and a risk. Their pristine environment captures the early collision evolution of the solar system, while their inherent ground impact potential could result in the mass extinction of life. It is thought to have happened once before, 65 million years ago with the Cretaceous-Tertiary mass extinction of the dinosaurs [1]. The Earth has remained subjected to many other ground and air impacting events.

In 1908 the aerial explosion of the Tunguska fireball in Siberia, Russia, resulted in the wide spread deviation of over 2000 km^2 of isolated forests [2]. However had this event occurred just a few hours later, simulations suggest that it would have likely exploded over Northern Europe. An explosive power equivalent to 10-30 megatons of TNT would have produced a devastating effect and a substantial lost of life [3]. The last known impact event occurred in 1998 when a 40-60 m diameter stony asteroid impacted the shores of New Guinea. This created a 10 m tsunami that killed more than 2000 people [4]. Another possible impact scenario is of asteroid 99942 Apophsis. Based on current tracking data there is a non-negligible impact risk of an Earth collision event occurring in 2039. This is subject to a resonant return with Jupiter and would equate to the impact releasing 875 megatons of TNT [7]. Therefore the risk and possible occurrence of asteroid impact events must be considered. Each impact has the potential not only to cause local devastation, Earthquakes and/or Tsunamis but to significantly alter the long-term evolution and history of our planet [1].

II.II Deflection Methods

To address the asteroid-to-Earth impact risk, potential methods of asteroid deflection and mitigation have been addressed by many authors [2][5][6][7]. Possible deflection scenarios include kinematic impactors or nuclear interceptors [8], where an impulsive momentum change is used to actively deviate the asteroid. Mass drivers can also be used to provide a sequence of impulses for effective deflection [9]. Other possibilities include providing a low and continual thrust from low-thrust propulsion, gravity tractor(s) or surface ablation [10]. More exotic techniques include changing the thermo-optical properties of the asteroid. This includes the enhanced Yakovsky effect or enhancing the emissivity of the asteroid by coating it with white paint [11]. The rate of deflection therefore depends on several interrelated factors. This includes the overall performance of the mitigation strategy, the complexity of the approach, the available response time before impact and the Technology Readiness Level (TRL) of the technique [2].

III. IMPULSIVE DEFLECTION

III.I Kinematic Impactors

Amongst the many possibilities, kinematic impactors have been considered to be a promising mitigation technique. It is amid one of the highest TRL concepts. Deflection is achieved by the release and subsequent impact of high velocity projectile(s) against the given asteroid. The rate of deflection is caused by the impulsive transfer of momentum. This is initially created by the kinematic impulse of the projectile(s), but is greatly enhanced by the additional momentum that is carried away by the ejected particles. Therefore the success of kinematic impactors is heavily dependent on the overall efficiency of the projectile(s), the impact geometry and the composition of the asteroid. The latter is a function of both the surface and subsurface properties of the asteroid. This includes porosity, density and yield strength.

When two or more bodies collide, there is an immense spectrum of possible and often unpredictable outcomes. This includes the re-adjustment of shape, size, external surface and rotational state. The possibility of unanticipated and therefore uncontrolled fragmentation and re-aggregation of the asteroid also has to be considered [12]. Recently, Sanchez et al demonstrated that despite extended warning and performance times of over a decade, the occurrence of unwanted fragmentation always remains [10][12]. The energy required for kinematic impactors is too high to avoid any sufficient re-aggregation of the largest particles. The probability of causing significant secondary damage to the Earth always exists. All of these factors will therefore directly affect the efficiency of the kinematic impactor approach to asteroid deflection.

IV. LOW THRUST DEFLECTION

IV. I Introduction

A more controlled method of deflection can be achieved by applying a low, but continued thrust onto the asteroid. Over an extended period of time this can be used to gently deflect the asteroid away from its originally threatening trajectory. Possible methods include surface ablation, low thrust propulsion and gravity tractors. The transfer of momentum is therefore dependent on the way in which the spacecraft interacts with the asteroid.

IV.II Gravity Tractor

Gravity is one possible deflection medium. The gravity tractor exploits the mutual gravitational attraction between the asteroid and the spacecraft. This effectively pulls the asteroid away from its originally threatening trajectory [13]. It therefore provides a contact-less deflection method. An illustration of the gravity tractor is given in Figure 1.

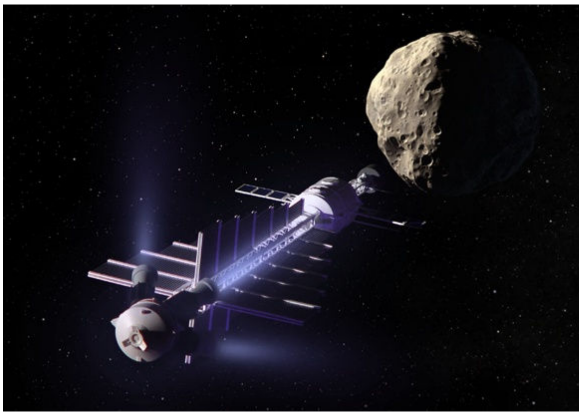

Figure 1: Gravity Tractor Approach [14]

However, to fully utilise the local gravitational attraction for deflection purposes the gravity tractor must maintain a constant and controlled hovering distance around the asteroid [13]. A substantial mass, in the order of tonnes, is also required to induce the required thrust. While the total mission mass is considered critical to this technique, the mission must be designed to ensure that the level of thrust does not exceed the gravitational attraction between the asteroid and the spacecraft. Otherwise the pull of the asteroid that causes the deflection to occur will become ineffective.

To maintain a constant hovering distance the simultaneous firing of two low-thrust engines is also required. It is critical that both engines fire with respect to the asteroid-to-spacecraft direction. This provides the projected thrust component. The effective thrust therefore depends on the mutual gravitational pull between the asteroid and the spacecraft. The closer the spacecraft is to the asteroid the higher the gravitational pull and the higher the associated thrust is. However at close proximity to the asteroid (a fraction of the asteroid's radius) the slant angles of the engines must be increased. Otherwise the thrusters' exhaust will impinge onto the asteroid and based on Newton's third law of motion no net thrust will be created. Therefore the technique becomes sensitive to uncertainties in the asteroid's shape, composition and rotational rate.

IV.III Ion Beam Shepard

Recently, an idea based primarily on the effective de-orbiting of space debris – the ion beam shepard - has been proposed to overcome the relative pitfalls of the gravity tractor approach. The idea is to push the asteroid away by continually hitting the surface of the asteroid with a high velocity beam of ions [15]-[19]. This is provided by a dedicated ion engine. Once the ions have intercepted the asteroid the momentum transfer is considered to act instantaneously [16]. The deflecting thrust – direction and magnitude – is therefore less dependent on the asteroid's local shape, composition and rotational uncertainty.

To achieve deflection the spacecraft needs to be equipped with two ion engines; one for deflection purposes and another for maintaining a controlled hovering distance. The latter will therefore always act in the opposing thrust direction. This prevents the spacecraft from drifting away from the asteroid [18]. The approach is further illustrated in Figure 2.

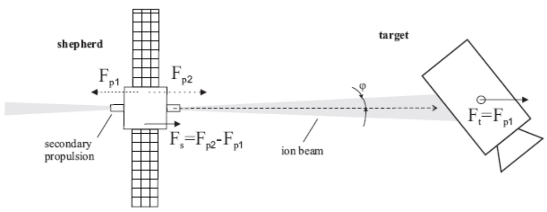

Figure 2: Ion Beam Shepard Concept [17]

The ion beam shepard technique is therefore highly reliant on the localised Guidance, Navigation and Control (GNC) of the spacecraft. Any beam pointing error will decrease the local transfer of momentum; ions could potentially miss the asteroid. The effectiveness of deflection is as such dependent in providing a dense beam of ions with little divergence. Current studies assume that the beam fully intercepts the asteroid, where the ion-to-asteroid collision is inelastic [15].

However, in practice an ion beam typically diverges between 10-13 degrees [16]. It is therefore reasonable to assume that larger rates of deflection would occur at shorter distances (between the spacecraft and asteroid) [16]. For a beam to fully intercept a 300 m asteroid with an assumed beam divergence of 13 degrees, a maximum hovering distance of 667 m must be maintained [15]. This is considered to be an incredibly stringent GNC requirement. Also at such short distances from the asteroid the occurrence of secondary ion back-sputtering impinging onto the spacecraft becomes an issue. The complex nature of ion interactions, beam attenuation, thermal fluctuations and plasma instabilities - density and energy - needs to be taken into account [17][19]. This can have a degrading effect on the performance of any solar cells, multi-layering insulation and optical surfaces.

Also, although the transfer of momentum is more efficient than for the gravity tractor, the ions still need to be accelerated with respect to the asteroid. Ejection velocities within the region of 30-50 km/s must be maintained during the entire deflection process. Accelerating the ions to these velocities requires the spacecraft to have a substantial onboard power source. An efficient power conversion and heat dissipation system must also be used.

IV.IV Low Thrust Tug

If, for a low-thrust method, the momentum is transferred through contact with the asteroid, then the deflection technique is known as a low thrust tug. The low thrust tug requires the spacecraft to land and physical attach a controllable engine onto the surface of the asteroid. The deflection is created by the long-term operations of the deflection engine. This provides a slow push.

Besides the inherent problems related to attaching and controlling the propulsion system, the rotational motion of the asteroid prevents the engine from being continuously operated. Different solutions have been proposed to overcome this problem. This includes: initially de-spinning and re-spinning the asteroid to match its orbital period, the reorientation of the asteroid's rotational pole or the simultaneous pushing and precessing of the asteroid [5][20]. All of these techniques require significant modification of the asteroid's initial rotational state. This adds considerable mass and complexity to the mission design. Therefore another simpler solution could be to schedule the thrust so that the engine is only operational in favourable thrusting conditions. Consequently if a single engine is used its operational period would be limited to half the rotational period of the asteroid.

V. THE NEW APPROACH TO ASTEROID DEFLECTION

V.I Introduction

It can be observed that the transfer of momentum achieved by the ion beam shepard technique is effectively created by a constant, high velocity impact of small particles onto the surface of the asteroid. From a momentum transfer point-of-view, it can be argued that the concept is not dissimilar from the kinematic impactor approach. However, unlike the kinematic impactor (where the relative velocity is provided by gravity) the relative velocity between the ion particles and the asteroid is provided by the power system of the spacecraft. Therefore it can be concluded that if the kinematic impactor was not a monolithic spacecraft, but instead a cloud of minuscule particles distributed over an extended region of space, it could be expected that the individual impact of each particle will not cross the breaking limit – causing fragmentation and disruption - of the target asteroid. Sputtering might occur but the asteroid would not fragment.

Therefore a new approach to the deflection and mitigation of asteroids is proposed. This combines the relative benefits of kinematic impactors and the ion beam shepard techniques. Instead of having a heavily constrained beam of ions, this approach would release a large, dense cloud of smart particles onto a collision course with the target asteroid. A large swarm of low mass, high velocity impactors would then be used to induce an artificial drag, and therefore an associated thrust, onto the asteroid. The concept – smart cloud – is further defined in Figure 3 and Figure 4 .

V.II Smart Cloud

The smart cloud approach to asteroid deflection is based on the idea of releasing hundred and thousands of small size smart particles towards the asteroid. Each impact event is considered to be significantly smaller than the disruption limit of fragmentation. Illustrated in Figure 3, the centre of the reference frame is the barycentre of the smart cloud. The spacecraft approaches the asteroid on a collision course. Once the spacecraft is in close proximity to the asteroid it will be used to release the swarm of smart particles. It is therefore critical that the deployment system provides a low converging swarm of particles. Following deployment the spacecraft will then manoeuvre itself to avoid its own collision with the asteroid. This is shown in Figure 4. The maximum diameter of the cloud coincides with the largest diameter of the asteroid. The smart cloud is assumed to impact the asteroid shortly after being deployed. The deploying spacecraft would monitor and control the evolution of the cloud until impact occurs; therefore monitoring the overall effectiveness of the deflection event. If required, the deployment operations of the smart cloud and the subsequent deflection affects can be monitored by a secondary spacecraft. Denoted in Figure 4, V_e is the relative velocity of the asteroid with respect to the smart cloud. Within this reference frame the smart cloud is fixed with the asteroid moving forward.

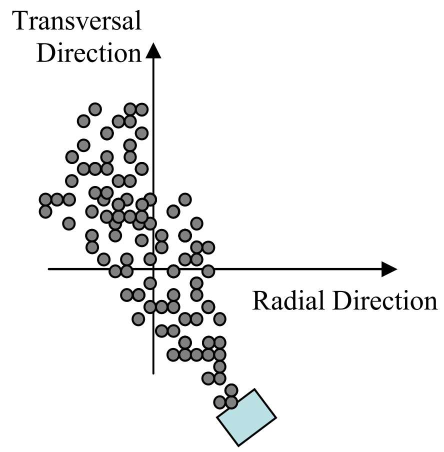

Figure 3: Initial Release of the Smart Cloud

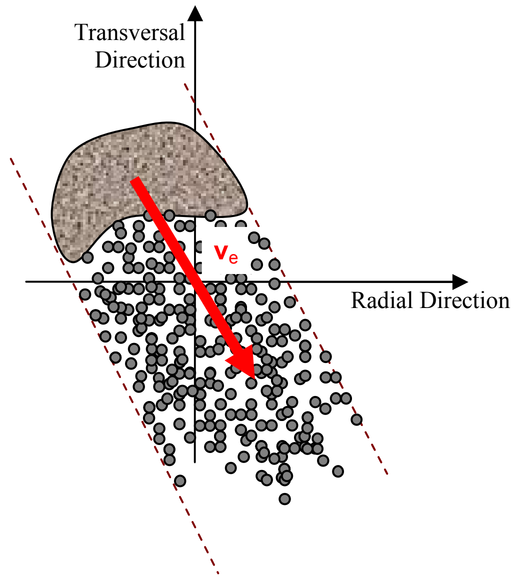

Figure 4: Smart Cloud Deflection Event

The cloud itself would be comprised of a large number of small silicon or gallium-arsenide microchips [21]. Passively operated, the spacecraft-on-a-chip approach would provide hundred to thousands of individual impact points onto the asteroid. Using state-of-the-art technology each individual device would have an area of 1 cm^2, and a thickness dependent on the then-current TRL of different nano-fabrication technologies [21][22]. To date, thicknesses as small as 2.5 µm have been successfully fabricated. Per chip, this corresponds to a total mass of 7.5 mg [21]. The total deflection mass of the smart cloud method, as given in this paper, is considered to be equivalent to the ion beam shepard approach to deflection.

The remainder of this paper will therefore compare the low thrust tug, the ion beam shepard and the smart cloud approach as an applicable technique for the deflection and mitigation of asteroids. Assessment has been made relative to deep (a = 2 AU, e = 0.7) and shallow (a = 1 AU, e = 0.1) crossing asteroids.

VI. DEFLECTION MODELS – MASS EFFICIENCY

In order to evaluate the efficiency of each deflection method a ratio is introduced. This is known as the mass efficiency, μ. Relative to the total mass of the spacecraft, it describes the fraction of the spacecraft mass that is dedicated only to the deflection mission. The total mass of the spacecraft is the combined mass of the deflection only system mass, m_{ds}, and the mass of the spacecraft bus, m_b. Therefore the mass efficiency, μ, can be defined as:

$$\mu = \frac{m_{ds}}{m_{ds} + m_b} \qquad (1)$$

For comparison purposes the mass of the spacecraft bus for all cases is assumed to be 500 kg. Furthermore it is assumed that all the orbits are planar and that the orbit of the Earth is circular. It is also assumed that the impact between the Earth and the asteroid occurs at one of the two intersections between the two orbits. At each intersection point the impact parameter, *b,* can be determined. This is measured relative from the b-plane, and is shown in Figure 5.

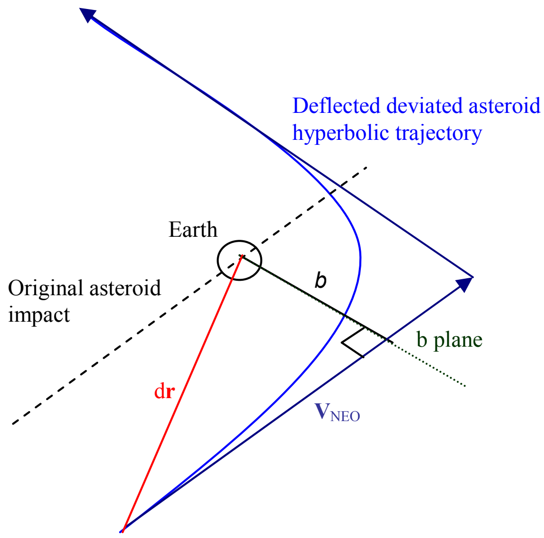

Figure 5: Definition of the Impact Parameter

Given in Figure 5, the dashed line indicates the impact trajectory of the asteroid. This corresponds to the un-deflected direction of the asteroid's velocity. It is assumed that any impact event will occur at the centre point of the Earth. Perpendicular to the impact velocity of the un-deflected asteroid, at the time of arrival, is the b-plane. It is from the b-plane that the impact parameter, *b*, is derived. This represents the distance from Earth to the intercept of the asymptote of the hyperbola of the deflected orbit of the asteroid [23]. Is it therefore considered to be a good approximation of the minimum distance from the Earth. The amount of deviation is always measured and represented from the b-plane. Perpendicular to this velocity vector, at the time of the expected impact, the impact plane on which the achieved deflection, δr, can be defined. This is projected at the time of the expected impact.

For a given mass efficiency, µ, the greater the *b*, the more effective the deflection technique becomes. Therefore the objective is to maximise *b* for the same value of µ or, vice versa, minimise μ or the same *b*.

For an impulsive deflection, such as the impact with the smart cloud, the deflection $\delta \mathbf{r}$ is computed using proximal motion equations and the deflection formulas developed in Vasile & Colombo [23]. The deflection is then projected onto the impact plane at the time of the expected impact with the Earth. For all the low-thrust deflection techniques, Gauss planetary equations are propagated numerically. This begins at the start of the deflection action until the time of the expected impact with the Earth is reached. For the ion beam shepard method, the low thrust deflection action is assumed to be always acting in the direction of the instantaneous velocity of the asteroid. For the low-thrust tug its velocity direction will change with the rotation of the asteroid. The rotation axis of the asteroid is therefore assumed to be perpendicular to its orbital plane. Furthermore if the plane perpendicular to the instantaneous velocity of the asteroid is taken to contain its centre of mass, then for the low-thrust tug approach, the engine will only be operational when the thrust vector is in the semi-space that does not contain the velocity vector of the asteroid. This is illustrated in Figure 6.

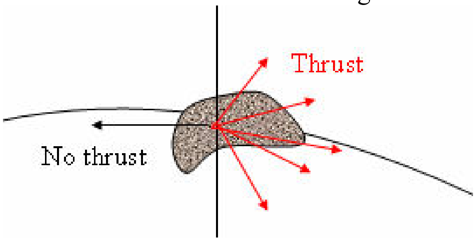

Figure 6: Scheduled Thrust Generation

VII. MASS EFFICIENCY OF THE DELECTION METHODS

VII.I Low Thrust Tug

The mass of a low-thrust tug is defined by the combined mass of the spacecraft bus, m_b, and by the required attachment hardware and engine mass. The latter is needed to provide the deflection push to repel the asteroid. A dedicated power system is also required to operate the engine. Therefore the low-thrust tug needs to carry enough propellant to initially rendezvous with the asteroid, and then to operate the engine for deflection. If the mass of the spacecraft bus and the propellant for the rendezvous transfer are included within the total mass of the spacecraft bus m_b, then the mass efficiency for the low-thrust tug can be defined as:

$$\mu_{LT} = \frac{m_{dh} + m_{dp}}{m_{dh} + m_{dp} + m_b} \quad (2)$$

m_{dp} is the mass of the propellant required only for the deflection of the asteroid. m_{dh} is therefore the mass of the dedicated hardware required only for the deflection technique to occur. This, critically, includes the mass required to land and anchor the low-thrust tug onto the surface of the asteroid. Therefore the combined mass of m_{dh} can be defined as:

$$m_{dh} = m_S + m_H + m_P + m_e + m_R \quad (3)$$

Where m_S is the mass of the solar arrays, m_H the mass of the harness, m_P the mass of the power processing unit (PPU), m_e the mass of the engines and m_R the mass of the radiators required to reject the excess of power. The mass per unit area of the radiators are assumed to be 1.4 kg/m^2. The effective area is computed assuming that the radiators operate at 100 ^{o}C and that the radiators are also used to dissipate the power not used by the engine, i.e. $(1-\eta_e\eta_P)$. η_e is the efficiency of the engine and η_P is the efficiency of the power system. The mass of the harness is assumed to be 15 % of the mass of the power system mass, and that the mass of the engine is 0.02 kg/W multiplied by the input power from the solar arrays. The mass of the PPU is given by the regression curve:

$$m_P = n_e 0.024 P_S + 0.002 P_S \quad (4)$$

P_S is the input power from the solar arrays. The solar arrays are assumed to have a specific mass, μ_S, equal to 1.5 kg/m^2, therefore the mass of the solar arrays is:

$$m_S = \mu_S A_S \quad (5)$$

The mass of the solar arrays is proportional to their area, A_S. The area is proportional to the power required to operate the engines. This can be defined as:

$$A_S = \frac{P_r}{\eta_S P_S} = \frac{\frac{1}{2}\eta_E \frac{\dot{m}_d v_e^2}{\eta_P \eta_e}}{\eta_S \frac{P_{1AU}}{r_{AU}^2}} \quad (6)$$

Where m_d is the mass flow of the engines, v_e is the exhaust velocity of the gas, P_r is the required power input to the engines and r_{AU} is the distance from the Sun. It is also assumed that the engines have an efficiency, η_e, of 60 %, the solar arrays have an efficiency, η_S, of 35 %, and that the power system has a combined efficiency, η_P, of 85 %.

VII.II Ion Beam Shepard

The mass efficiency for the ion beam shepard technique is computed in the same manner as for the low-thrust tug, expect that the number of engines, m_E, is two, instead of one. One engine is needed for deflection purposes and another for maintaining a controlled hovering distance from the asteroid. For simplicity the mass required to maintain the ion beam shepard spacecraft in close proximity to the asteroid is neglected.

During the comparative analysis two separate cases of the ion beam shepard technique was examined. This includes: (1) when the ion engine has a constant specific impulse (Isp) and (2) when the ion engine has a constant mass flow but the velocity of the ions can be increased when the power is available. For this latter case a variable Isp is used. For all the deflection methods the dry mass of the spacecraft bus was assumed to be 500 kg. This accommodates all the subsystem mass required to operate the spacecraft and the mass of the propellant that is needed to successfully transfer and rendezvous with the orbit of the given asteroid.

VII.III Smart Cloud

The smart cloud approach to deflection has two main advantages. It avoids the risk of inherent fragmentation of the asteroid and it reduces the overall system complexity and mass of the mission design. Fragmentation is avoided by decreasing the impact energy of each particle to be significantly lower than the asteroid's disruption limit. Shown in Figure 7 the critical specific energy for asteroids ranging from 40 m to 1000 m in diameter is given. The potential for disruption depends on the composition and structure of the asteroid and the velocity and spread (i.e. impact area) of the deflection approach. Given in Figure 7 for the range of diameters studied, the catastrophic fragmentation limit is considered to occur at either 1000 J/kg (for rocky asteroids) or 100 J/kg (for rubble pile asteroids).

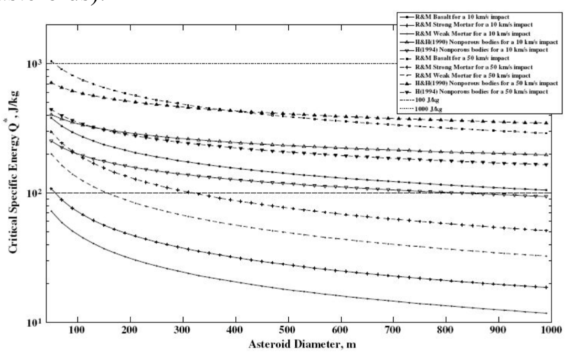

Figure 7: Critical Specific Energy for Barely Catastrophically Disruption as a Function of Asteroid's Diameter [12]

To assess the impact energy of the smart cloud approach the relative velocity between the asteroid and each particle of the cloud is examined. This is shown in Figure 9 and Figure 8 and is given as a function of the semimajor axis and the eccentricity of the asteroid's orbit. It is assumed that the smart cloud is in an orbit which is equal in eccentricity and semimajor axis, but is rotated in the orbital plane so that the relative velocity at the orbit intersection point is maximised.

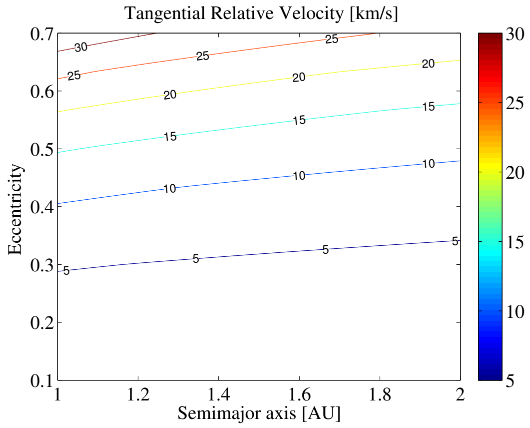

Figure 8: Achievable Relative Velocity in the Direction of the Velocity of the Asteroid

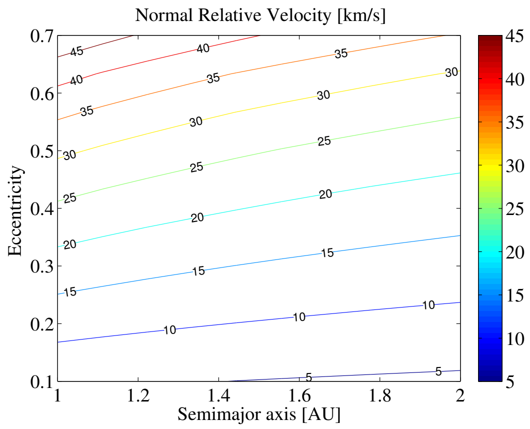

Figure 9: Achievable Relative Velocity in the Direction Normal to the Velocity of the Asteroid

Given in Figure 8, for deep crossing asteroids (a = 2 AU and e= 0.7) the velocity in the direction of the asteroid can exceed 20 km/s. This value, illustrated in Figure 9, can exceed 30 km/s when the smart cloud is directed normal to the velocity of the asteroid. Therefore the total combined relative velocity can exceed 50 km/s. This is equivalent to the ion beam shepard approach of accelerating the ions to the same velocity (i.e. the exhaust velocity v_e in Eq (6) should be 50 km/s). However, unlike the ion beam shepard technique such a high relative velocity is not provided by any dedicated acceleration system. This is simply caused by the relative motion of the smart cloud and the asteroid on their orbits.

Since the highest component of velocity of the smart cloud is in the normal direction, the transfer of momentum will not be as efficient when compared to any low-thrust techniques. For the latter case the action is always aligned with the velocity of the asteroid [23][24]. Therefore, it can be considered that the majority of the velocity contributions are given by the tangential components. For deep crossing asteroids, as given in Figure 8, the tangential component of velocity can reach as high as 24 km/s. Assuming an asteroid mass, based on Apophiss, of $2.7 \cdot 10^{10}$ kg, then the corresponding impact energy, Q, for a single particle (7.5 mg) within the smart cloud impacting the asteroid would be $8 \cdot 10^{-11}$ J/kg.

For shallow crossing asteroids (a = 1 AU, e = 0.1) the velocity in the normal direction reduces to below 10 km/s. This reduces to below 5 km/s in the tangential direction. This corresponds to an impact energy of below $1.39 \cdot 10^{-11}$ J/kg and $3.47 \cdot 10^{-12}$ J/kg respectively. For both cases – shallow and deep crossing – the impact energy is considerably lower than the catastrophic fragmentation limits given in Figure 7. Sputtering will occur but this will only serve to contribute to the increased transfer of momentum.

Furthermore, since the smart cloud particles do not need to be accelerated to the required relative velocity, the mass efficiency is simply given as:

$$\mu_{SC} = \frac{m_C}{m_C + m_b} \qquad (6)$$

Where m_b is the mass of the spacecraft bus and m_c is the mass of the smart cloud.

VIII. COMPARATIVE RESULTS

For both shallow and deep crossing asteroids, Figure 10 and Figure 11 respectively show the comparison between the smart cloud (drag cloud in the figure), the low-thrust tug (LT tug) and the ion beam shepard technique (IBS). The latter has been separated into two configurations; either a fixed or variable Isp. Throughout the analysis a constant operational thrusting period of 8.6 years has been assumed. This is assumed to act on an asteroid with a diameter of 250 m and was included to portray a realistic mission to intercept and deflect a Near Earth Asteroid (NEA). Furthermore, for all three deflection methods the transfer and rendezvous of the spacecraft to the asteroid's equivalent orbit was considered to be identical. Therefore the delta-V cost of the transfers are the same.

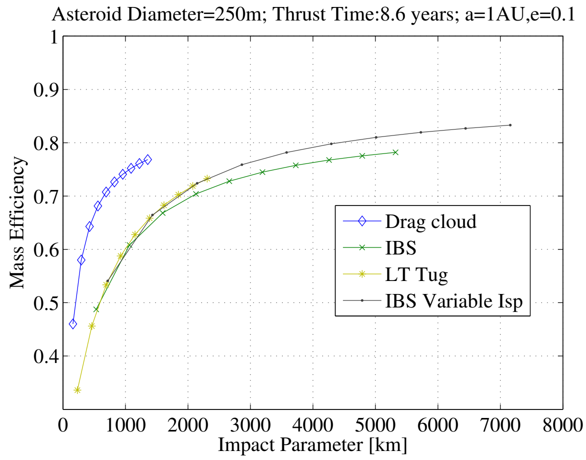

Figure 10: Comparison for Shallow Crossing Asteroid

Shown in Figure 10, during the deflection of shallow crossing asteroids (a = 1AU, e = 0.1) the low relative velocity between the smart cloud and the asteroid results in a comparatively low overall effectiveness. This is in comparison to the other two low-thrust methods. With a relatively high efficiency of 0.75 a deflection distance, measured from the b-plane of only 1500 m can be achieved. This therefore does not provide enough thrust to deflect the asteroid by at least one Earth radius (~6378 km). One Earth's radius is considered to be the accepted standard to which all deflection methods are assessed [25]. However for shallow crossing asteroids both the low thrust tug and the ion beam shepard techniques can provide greater levels of deflection. The amount of deflection increases with efficiency. With efficiencies ranging from 0.5-0.8, deflection distances of 2500 km to over 7000 km can be accomplished. To provide the required deflection of one Earth radius then the mass efficiency needs to be at least 0.8. This is however still considered to be a demanding requirement. Furthermore, as illustrated in Figure 10 both the low-thrust tug and the ion beam shepard techniques performs similarly. They have a comparable level of efficiency. Only minor differences – in the impact parameter - occur at high efficiencies. However the analysis did not consider the additional mass of the attachment system needed for the low-thrust tug. This may have affected the results, making the low-thrust tug far more effective than should be accurately portrayed. There was also no affect in the ion beam shepard technique being configured to operate in either the variable or fixed Isp.

Figure 11 shows the same comparison but in the case of a deep crossing asteroid (a = 2 AU, e = 0.7). Here the relative velocity between the cloud and asteroid is much higher and therefore the smart cloud significantly outperforms against the other low-thrust methods of deflection.

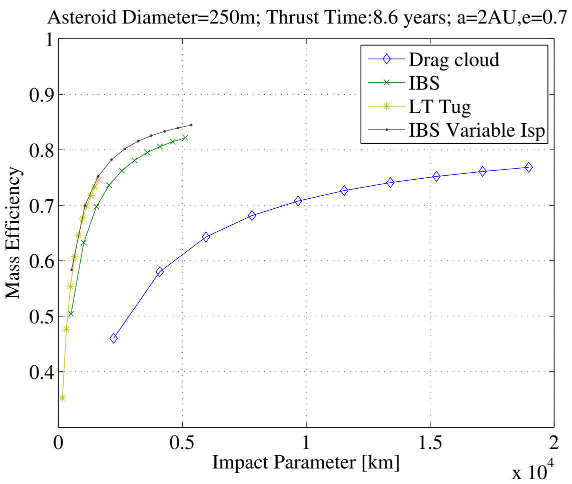

Figure 11: Comparison for Deep Crossing Asteroids

The main reason is that the ejection of the smart cloud does not require any additional mass to accelerate the particles. The relative velocity is provided for free, by gravity. The ion beam shepard technique is burdened by the heavy mass penalties of accelerating the ions to provide hypervelocity impact events. Therefore the smart cloud approach can offer significantly larger amounts of deflection. Measured from the b-plane this ranges from 2500 km to 20000 km. To provide the deflection equal or greater to one Earth radius, the mass efficiency of the smart cloud has to be at least 0.65. This is less efficient than the other two remain techniques – low-thrust tug and ion beam shepard – when attempting to deflect shallow crossing asteroids. Also shown in Figure 11, both the low-thrust tug and the ion beam shepard techniques provide limited amounts of deflection. As the efficiency increases from 0.5 to 0.8 the deflection distance only increases from 100 to 500 km. The maximum distance of 500 km is not enough to provide the required amount of deflection of one Earth radius. Similarly to the shallow crossing scenario there is no difference between the ion beam shepard technique using a constant or variable Isp.

IX. DISCUSSION

The comparative analysis demonstrated that for deep crossing asteroids a cloud of small smart particles can be highly effective. This is in comparison to the ion beam shepard and the low-thrust tug approaches. However the smart cloud is comparatively less effective when it attempts to deflect shallow crossing asteroids. Nevertheless the relative population of deep crossing asteroids far exceeds the population of shallow crossing asteroids. 61 % of all NEAs are considered to be deep crossing asteroids. This compares to only 9 % of shallow crossing asteroids [25]. Of the 61 % of deep crossing asteroids over 50 % of the resident population are likely to become impactors (i.e. to impact the Earth) in the future [25]. All of these bodies are in orbits that will, at some point, intersect the orbit of the Earth. It is therefore far more likely that a deep crossing asteroid will become a considerable threat than compared to a shallow crossing asteroid. This, most significantly, would favour the use of the smart cloud technique for the successful mitigation and deflection of the approaching asteroid.

However, in order for the smart cloud to be effective it needs to be properly deployed, and to maintain its shape until it impacts with the asteroid. It is proposed that each smart particle could be a small nano spacecraft-on-a-chip spacecraft [21] [22] [26]. Each nano spacecraft would have a degree of control in their orbit and will therefore be able to maintain the overall geometry of the cloud. Instead of traditional thrusters and attitude control, each nano spacecraft would exploit the dynamics of small bodies – solar radiation pressure – to provide localised manoeuvring. The spacecraft releasing the cloud of nano particles would therefore be used to monitor and control the evolution of the cloud until impact. The size of each nano-spacecraft will depend on the fragmentation limit and physical response of the asteroid. This is considered to be a function of surface material, geometry and local morphology. Experimental work is therefore required to verify the response of different materials – dense, (in)-homogenous and highly porous – to the subsequent impact response of a relatively large cloud of small particles impacting at hyper-velocities. This is relative to the conventional monolithic impact projectile. Throughout the presented analysis the efficiency of three different types of deflection methods have been presented. Assumptions have been made on the relative system efficiencies of both the solar arrays and the deflection engines. This is based on the state-of-the-art technology. Higher efficiencies require further development and are at a lower TRL. An increase of the efficiency of the solar arrays above 40 % and of the engine above 70 % can make the low-thrust methods competitive, even on shallow crossing asteroids.

X. FINAL REMARKS

In summary the smart cloud approach to asteroid deflection has been shown to be most effective in the mitigation of deep crossing asteroids. Deflection rates in excess of three times the radius of the Earth can be achieved. The high relative velocity between the asteroid and the spacecraft makes the smart cloud a promising technique. Furthermore it is not penalised with any heavy attachment device, nor is there the requirement to physically provide an onboard particle acceleration system. Catastrophic fragmentation of the asteroid can also be avoided. Further work is required to develop the deployment system of the spacecraft, and to understand the long-term evolution of the smart cloud of nano size spacecraft. Experimental work is also required to assess the physical response of this deflection scenario.

XI. REFERENCES

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