Deflection Of An Asteroid By Laser Ablation And Laser Pressure Technique

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ABSTRACT

The NEO deflection method employing laser ablation is an interesting and promising method to deviate the orbit of the asteroid. This technique employs trains of solar-pumped laser pulses, from a number of spacecrafts in specific formation, to ablate material from the asteroid surface. This process not only reduces the momentum of the asteroid by required amount but also creates a pressure in the opposite direction due to continuous bombardment of high pressure laser pulses. The main advantage of this technique is that it relieves the strict constraint on the proximity to the asteroid surface, thus mitigating the effects of inhomogeneous gravity field, temperature variations and damage of the spacecraft due to regolith. The solution requires no futuristic technology and would work on wide variety of asteroid types.

NOMENCLATURE

a Semi-major axis, m
[aI ; bI ; cI] Radial dimensions of an ellipse, m
A Area, m^2
A Matrix of Gauss planetary equation
c Speed of light (299792.458 km/s^2)
Cr Concentration ratio
C20;C22 Harmonic coefficients for a second order, second degree gravity field
Cineq Inequality constraint in optimisation
d Diameter, m
D Search space for a solution vector
D Directional cosine matrix
F; F Force, N
i Inclination, rad
H Enthalpy of sublimation, J
l Length, m
L Distance, or depth, from the surface of the asteroid, m
J Objective function
K Conductivity of a material, W/m_K
m Mass, kg
M Mean anomaly, rad
n Mean motion, m/s or index of refraction
v; v Velocity, m/s
$\bar{v}$ Average velocity of particles according to Maxwell's distribution of an ideal gas, m/s
θ True latitude, rad

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κ Angular in-plane component in gravity field, rad
λ Wavelength, m
μ Gravitational constant ($\mu_{\odot}$ =132724487690 km^3/s^2)
ν True anomaly, rad
ξ Variable used in calculation of δr($\delta\mathbf{k}$)
ρ Density, g/m2
ζ Variable used in calculation of δr($\delta\mathbf{k}$)
ϖ Variable used in calculation of δr($\delta\mathbf{k}$)
ϱ Variable used in calculation of δr($\delta\mathbf{k}$)

SOURCES

For the template and the rigorous mathematical works, I cite [1]. The plume technology has been inspirationally derived and I cite [2].

ASTEROIDS- A DISCUSSION

Asteroids are small rocky-icy and metallic bodies that orbit around the Sun. They are thought to be the shattered remnants of planetsimals, the bodies that never became massive enough to become planets. There are millions of these asteroids majority of them orbiting in the main asteroid belt between the orbits of Jupiter and Mars and co-orbital with Jupiter (Jupiter Trojans). Some other reservoirs where asteroids and comets are present are the Kuiper belt (Kuiper belt objects) and the trans-Neptunian orbit (Trans-Neptunians). However a significant population of asteroids with different orbital are present, some of which pass very close to the Earth's orbit. Such asteroids are known as Near-Earth Asteroids (NEAs) or generally Near-Earth Objects (NEOs). Some these NEOs actually cross the Earth's orbital path and calculations show that their probability of impacting the Earth is significantly higher than the other asteroid groups. These asteroids are termed Potentially Hazardous Asteroids (PHAs).
Asteroids are classified by their characteristic spectra and accordingly they fall into three main categories:

- **C-Type Asteroids:** They are carbonaceous and constitute the majority of the asteroids. They have an albedo ranging from 0.03 to 0.10.
- **S-Type Asteroids:** They are siliceous in nature and make up 17% of the asteroids.

They are a bit brighter than C-type with an albedo between 0.10 to 0.22.

- **M-Type Asteroids:** They are metallic in nature, most of them made up of iron. Albedo ranges from 0.1 to 0.2.

The orbits of asteroids are determined through different ways. Some orbitals are defined from observational records, while some are measured through the perturbations they cause in the nearby object as they pass close to it. Telescopes have also been used for identification and tracking of the asteroid orbit and now computational methods are used for such kind of calculations. Whatever techniques are used the orbital characteristics of an asteroid depends on some specific orbital elements. The numerical values of these elements for asteroid Apophis 99942 have been given in the table.

Element		Measured Values
Semi-major axis	a_A	0.9223 AU
Eccentricity	e_A	0.1911
Inclination	i_A	0.05814 rad
Argument of		2.2059 rad
periapsisω_A		323.50 days
Period	T_A	2.2479x10^{-7} rad/s
Mean motion	n_A	2.7 x 10^{10} kg
Mass	m_A	1.8015993 x10^{-9} km^3/s^2
Gravitational constantμ_A		191m,135m,95m
Dimensions		5.8177 x 10^{-5} rad/s
a_1, b_1, c_1		
Rotational velocity		
w_A		

Table 1.Some physical values of Apophis 99942.

CONCEPT OF LASER ABLATION

Laser ablation may be defined as a sputtering process leading to the ejection of atoms, molecules and even clusters from a surface as a result from the conversion of an initial electronic or vibrational photoexcitation into kinetic energy of nuclear motion. In laser ablation, high power laser pulses are used to evaporate matter from a target surface. As a result, a supersonic jet of particles (plume) is ejected normal to the target surface. The plume, similar to rocket exhaust, expands away from the target with a strong forward directed velocity distribution of different particles. This ejected plume, thus, provides a reaction force that produces a significant amount of force on the target object in the direction opposite to that of its ejection. To apply this technique in the case of deflection of an asteroid, the spacecrafts responsible for this operation are equipped with lasing equipments that are discussed later.

The process of laser ablation has an operation time of many orders of magnitude, from the initial absorption of laser radiation to material ejection. In macroscopic level, modification occurs when the laser fluence is above the threshold fluence F_{th}(J/cm^2) or ablation threshold. This puts a lower limit to the fluence and the intensity of the laser pulse. The fluence would vary depending on the material and optical properties of the asteroid. In general, for a successful sublimation or ablation process, the laser pulse duration must be longer than the time between electron-electron collisions and the relaxation time of the electron-phonon coupling. If the pulse duration is shorter than the thermalisation time, the electric field of the laser pulse might exceed the threshold for optical breakdown and the target material is transformed on an ultra-fast time scale into plasma. When the target area, due to ablation is converted into plasma, the entire system may face extreme non-equilibrium situations resulting in orbital perturbations and instability in the asteroid. These effects are not at all welcome as they tend to destabilize the asteroid and might even disintegrate them which are held together by mutual gravitational attraction. Hence, an upper limit to laser pulse duration is established and the lasers onboard the spacecraft has to operate within this region of laser fluence and intensity.

The energy that is available for ablation is an important criterion. It depends on the laser wavelength, optical properties of the asteroid material and also on the diameter of the illuminated spot caused by the laser. This available energy is an interesting parameter that helps in designing the orbit of the spacecrafts around it. This issue has been dealt with later in the paper. The main importance of calculation of the amount of energy available for ablation purpose can be seen from the fact that the power needed to ablate required amount of material is in direct relationship with the distance of the spacecraft from the asteroid surface. The spacecrafts must be placed in such an orbit that would allow it to focus optimal power necessary for deflection. It can be calculated as follows,

The electric field of a monochromatic, linearly polarized plane wave pulse (laser pulse) in a homogeneous and nonabsorbent medium is given by

$$\boldsymbol{E} = \boldsymbol{E}_0 \exp[i\left(\frac{2\pi z}{\lambda}\right) - \omega t]$$

where, z is the direction of propagation of the pulse, ω is the angular frequency, λ is the wavelength of the laser radiation.

$$\lambda = \frac{2\pi}{\omega}\left(\frac{c}{n}\right)$$

n is the refractive index of the medium.

Analogous magnetic field is given by the similar expression. Both the field amplitudes are related by

$$\boldsymbol{H}_0 = \boldsymbol{E}_0 \varepsilon_0 n c$$

ε_0 is permittivity of free space.

Now irradiance I is given by,

$$I = |\boldsymbol{E}\ X\ \boldsymbol{H}| = n\varepsilon_0 c \boldsymbol{E}_0^2$$

Average power, P_{avg}, transmitted by a laser pulse is

$$P_{avg} = I \, . Area_{spot}$$
$$= n\varepsilon_0 c \boldsymbol{E}_0^2 \, . \frac{\pi d_{spot}^2}{4}$$

Energy of each laser pulse, $E = P_{avg}/T$, where T is the inverse of the laser frequency f.
Thus,

$$E = n\varepsilon_0 c \boldsymbol{E}_0^2 f \, . \frac{\pi d_{spot}^2}{4}$$

Net energy available for ablation per pulse,

$$E_A = E - E_{th}$$

where, E_{th} is the threshold energy which depends on the material type. Laser pulses may vary over a very wide range of duration (microseconds to picoseconds) and fluxes can be precisely controlled. This is an advantage of laser ablation technique.
As a consequence of the high pressure laser pulses applied during the ablation process, this technique can be used to transfer momentum to the target material. The effect is similar to hitting the material with hammer. This mechanical force, generated when a high pressure laser pulse strikes a target, may be termed as Laser Pressure. For materials with high linear thermal expansion (DL/L_d, where L_d is heated depth, DL the expansion), high Young's modulus(E_Y), high melting point and with high oxide concentration, significant stresses may occur due to laser irradiation. As materials get ejected, thermal shocks are generated repeatedly. Thermal shocks are indicated by the development of thermal stress,

$$s_{th} = E_Y \mathrm{DL}/L_d$$

These thermal shocks pressurize the layer beneath the ablated layer and when integrated over a cylindrical volume with height is the diameter of the asteroid and radius is the radius of the thermal shock front, it accounts for a significant amount of force. This force is termed as laser pressure. It must be noted that laser pressure is a consequence of the ablation process by lasers.
This technique has been discussed in this paper as a possible and effective method for the deflection of an earth-bound NEO. The plume produced by the ablation process would produce a thrust on the NEO, which would decrease its momentum creating a force opposite its direction of flow. Also another force have been introduced here called the Laser Pressure, which is a single stake force that has the capability to push the asteroid off its present course given enough time is available. At the end of the paper possible improvements have been discussed which could help in improving the overall effectiveness and make it more feasible economically.

FOCUSSING AND BEAMING SYSTEMS

The laser ablation of the asteroid in space is a sophisticated issue. The laser has to produce enough power which would sublimate the asteroid surface using the readily available resource i.e. the solar energy. The design of the spacecraft using solar pumped laser is a critical aspect. The spacecraft must be able to concentrate a minimum power density at all times which means controlling the Concentration ratio, C_r. Concentration ratio of the system is the ratio of the power density at the input to the system and the output. The attitude of the spacecraft has to be controlled to maintain a constant C_r.
In general, each spacecraft must have the following three fundamental components,

1. A power collecting unit
2. A power conversion unit
3. A power beaming unit

The power collecting unit would consist of the solar array capable of collecting power from the sun. These arrays will be attached to the main body of the spacecraft just like a conventional satellite. The utility of a power conversion unit is to convert the solar energy into electrical energy. This is, as we shall see later, because of the limits imposed by the present day technological glitches, the direct-solar pumped lasers are very lossy and would not be able to produce enough power for successful ablation.

Beaming Unit: Solar Pumped Laser

Lasers work by exciting electrons by simulating them with the addition of photons which temporarily boost them up to a higher energy state. This continues until a population inversion exists. Where there are more electrons at a higher energy state the electrons drop back to their original ground state releasing photons that produce emissions having the same spectral properties of the stimulating radiation which makes it highly coherent. The energy that is not released as output emission manifests as heat. This implies that the heat must be dissipated by large radiators attached to the spacecraft as shown in figure 1.
There are two methods of powering the laser in space using solar energy:

1. Indirect Pumping: Indirect-pumped solar lasers convert the solar energy first into electrical energy which is then used to power the laser. Photovoltaic cells are the best options for space applications. The drawback of this process is the addition of an electrical power generator which will add to the mass, size and power requirements of our spacecraft. This problem can solved by using high efficiency solar arrays in conjunction with solid-state lasers. Solid state lasers pumped with electric power can currently have 60% efficiency. If the solar

arrays give us 30% efficiency, we can have an overall 18% efficiency.

2. Direct Pumping: In direct solar-pumped lasers, the laser is directly energized using solar radiation. Due to mismatch between the wide-band emissions of the sun with the narrow absorption band of the lasers, the efficiency is very less. Hence this method of laser pumping is still not feasible. Further research into this method can make this method very suitable for this sort of missions.

Lasing Materials

The lasing materials that can be used for a solar pumped solid state laser include

- **Nd:YAG** with chromium doping which contains neodymium ions (Nd^{3+}) in yttrium aluminum garnet ($Y_2Al_5O_{12}$). It is relatively cheap to produce and readily available, and more importantly, has good thermal resistance, durability and lifetime.
- **Nd:Cr:GSCG** which has a host of Gadolinium Scandium Gallium Garnet. It is highly efficient.
- **Nd:YLF** where the host material is Yttrium Lithium Fluoride (YLiF_4).

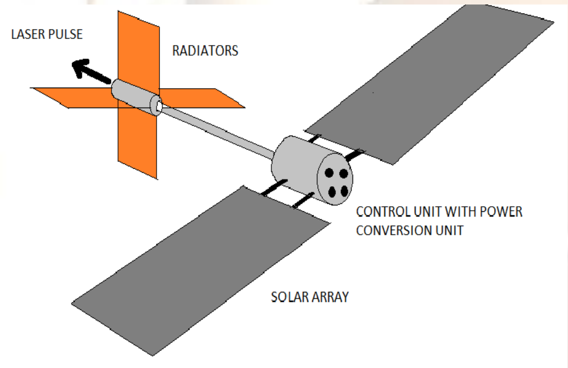

Figure 1. A model spacecraft with solar laser system

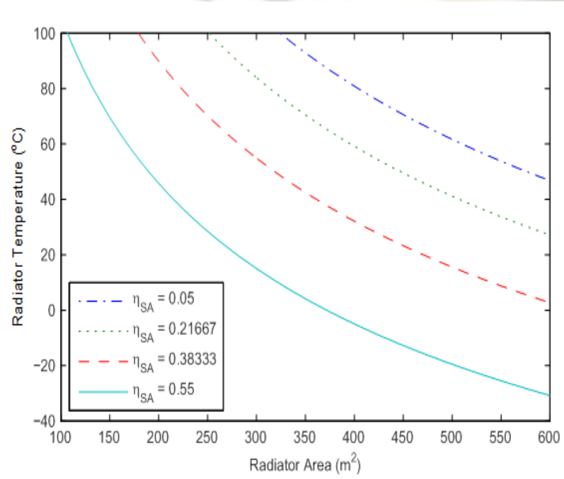

Figure 2.Radiator area vs Radiator temperature

CONCEPTUAL OPERATION DESIGN

The navigation strategy of the entire operation is designed on the basis of the attitude measurements of the spacecrafts and the 2D image from the onboard camera. Since a single spacecraft would mean a single point failure of the whole mission and lesser power to attack the asteroid, a mission with an optimal number of spacecrafts in a specific formation is conceived. Each spacecraft in the formation should be able to measure its attitude with a star tracker and stay in position with respect to the entire formation. Once the formation is deployed from a mother ship, a leader spacecraft searches for the programmed location of the asteroid until it is in the field view of the camera. The centroid of the image is determined by simple geometry and aligned with the camera's boresight. The pointing vector is relayed to the entire formation. When the entire formation is fed with the position of the centre of the NEO, the range of spacecraft and asteroid is triangulated as the spacecrafts align themselves in the plane containing the centroid of the image of the asteroid. The feed of the relative positioning of the spacecrafts is used to direct the laser beams on a single point on the asteroid. The employed formation is deliberately not aligned in line with the sun and the asteroid to overcome the factors that come into play when the solar arrays are shadowed by the asteroid. This is shown in figure 3.

For the spacecrafts to hover at a fixed distance from the asteroid, the solar arrays are so designed that the solar radiation pressure and the force due to the asteroid gravity field are in equilibrium. These static points are called Artificial Equilibrium Points (AEP). These points are not fixed in space and the spacecrafts hovering around these points cannot remain indefinitely in any AEP. This is due to the dynamic forces that work continuously here. The position of these equilibrium points over the full orbit of the Apophis is shown in figure 4.

For a spherical and homogenous gravity field of the asteroid, the dynamics of the arrays is governed by the following set of equations,

$$\ddot{x} = 2\dot{v}\left(\dot{y} - y\frac{\dot{r}_A}{r_A}\right) + x\dot{v}^2 + \frac{\mu_\odot}{r_A^2} - \frac{\mu_\odot}{\delta r^3}(r_A + x) - \frac{\mu_A}{\delta r^3}x + \frac{F_{s_x}(x,y,z)}{m_{sc}} + \frac{F_{u_x}}{m_{sc}}$$

$$\ddot{y} = -2\dot{v}\left(\dot{x} - x\frac{\dot{r}_A}{r_A}\right) + y\dot{v}^2 - \frac{\mu_\odot}{r_{sc}^3}y - \frac{\mu_A}{\delta r^3}y + \frac{F_{s_y}(x,y,z)}{m_{sc}} + \frac{F_{u_y}}{m_{sc}}$$

$$\ddot{z} = -\frac{\mu_{\odot z}}{r_{sc}^3} - \frac{\mu_A}{\delta r^3}z + \frac{F_{s_z}(x,y,z)}{m_{sc}} + \frac{F_{u_z}}{m_{sc}}$$

where, m_{sc} is the estimated mass of the spacecraft, $\boldsymbol{F}_{SRP} = [F_{s_x}, F_{s_y}, F_{s_z}]$ is the solar force, $\boldsymbol{F}_u = [F_{u_x}, F_{u_y}, F_{u_z}]$ is control force.

To fulfill the objective of the mission, an optimal number of spacecrafts must be deployed around the asteroid as justified earlier. For spacecrafts flying in formation with the asteroid orbiting in tandem around the sun, their orbits must be designed as such so that they can maintain a constant power density of laser on the asteroid surface and also avoid the irregular gravity field of the asteroid and the plume of debris ejecting from the surface.

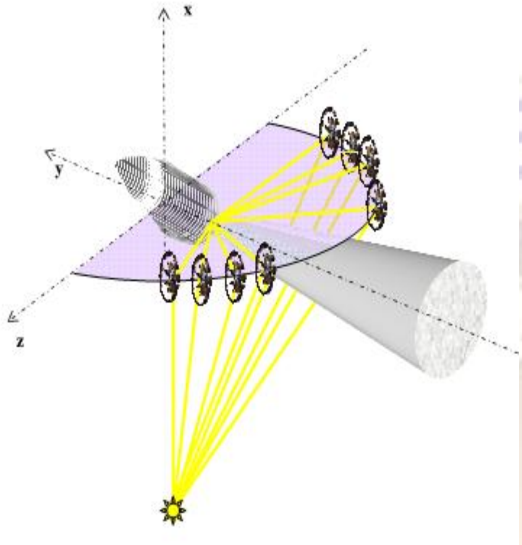

Figure 3. Operation design using formation of spacecrafts.

To design the formation orbits, we use the orbital element difference between a chief orbit (which can be virtual, and is located at the origin of the Hill reference frame)and a spacecraft in the formation.

$$\ddot{x}(t) = 2\dot{v}\left(\dot{y} - y\frac{\dot{r}_A}{r_A}\right) + x\dot{v}^2 + \frac{\mu_\odot}{r_A^2} - \frac{\mu_\odot}{r_{sc}^3}(r_A + x)$$

$$\ddot{y}(t) = -2\dot{v}\left(\dot{x} - x\frac{\dot{r}_A}{r_A}\right) + y\dot{v}^2 - \frac{\mu_\odot}{r_{sc}^3}y$$

$$\ddot{z}(t) = \frac{\mu_\odot}{r_{sc}^3}z$$

with, $\boldsymbol{r}_{sc} = \boldsymbol{r}_A + \delta\boldsymbol{r}$, $r_{sc} = \sqrt{(x + r_A)^2 + y^2 + z^2}$

where, $\boldsymbol{r}_{sc}$ *and* $\boldsymbol{r}_A$ are vectors from the sun to the formation spacecraft and the asteroid respectively, $\dot{v}$ is the angular rate of change of the solar orbit.

This is a first approximation of the spacecraft motion neglecting the gravity field of the asteroid and the solar pressure but suffices our requirements.

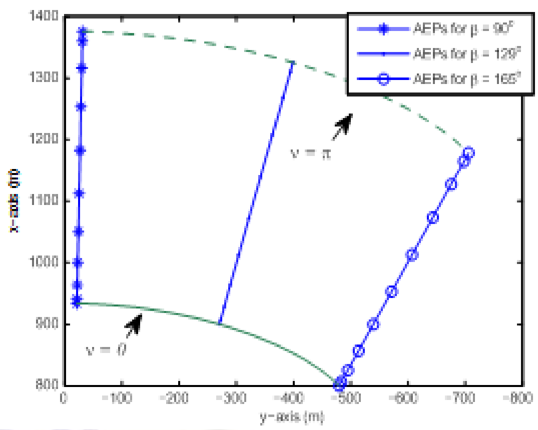

Figure 4.Position of the equilibrium points over a full orbit of the asteroid Apophis.

The formation orbit can be thought of as an orbit around the Sun with a small offset in the initial position δr_0 and velocity δv_0. This offset can also be expressed as the difference between the orbital parameters of the chief (e.g. the asteroid) and the formation. As long as there is no difference in semi-major axes, the two orbits will remain periodic.

$\delta\mathbf{k} = \boldsymbol{k}_{sc} - \boldsymbol{k}_A = [\delta a \;\; \delta e \;\; \delta i \;\; \delta\Omega \;\; \delta\omega \;\; \delta M]$

As the mean anomaly is a function of the semi-major axis, the difference in mean anomaly will remain constant throughout the orbit so long as $\delta a = 0$.

If the optimal thrust direction that maximizes the deviation is along the unperturbed velocity vector of the asteroid, then the exhaust gases will flow along the y-axis of the local Hill reference frame. Therefore, the size of the formation orbits projected in the x-z plane should be maximal. All the requirements on the on the formation orbits can be formulated in mathematical terms as a multi-objective optimization problem,

$$\min_{\delta\boldsymbol{k}\,\epsilon\, D} \; \min_{v} J_1 = \delta r$$

$$\min_{\delta\boldsymbol{k}\,\epsilon\, D} \; \min_{v} J_2 = -\sqrt{x^2 + y^2}$$

subject to constraints:

$$C_{in_{eq}} = \min_{v}(\delta r(v) - r_{LIM}) > 0$$

where, r_{LIM} is the minimum radius sphere imposed to avoid the non-linearity in the asteroid gravity field and D is the search space for the solution vector $\delta\boldsymbol{k}$; J_1 ,J_2 being objective functions.

Solving the problem by a hybrid-stochastic-deterministic approach based on multiagent search tool combined with a decomposition of the search space, results in several groupings of formation orbits. The existence of families can be seen, for example, through $\delta\omega$ and $\delta\Omega$, where for a given input value there are multiple values for the objective functions J_1 and J_2.

ASTEROID DEFLECTION MODEL

A very general set of formulas with no approximation is discussed here. The deviation distance is defined here as the difference in r_A between the original undeviated orbit and deviated orbit at t_{MOID} where MOID is minimum orbital intersection distance. Non-linear equations were derived for determining the difference in r_A are expressed as a function of the ephemeris in the Hill reference frame $\mathcal{A}$ centered on the asteroid with $\Delta\boldsymbol{k}$ giving the difference in Keplerian parameters between the undeviated and deviated orbit.

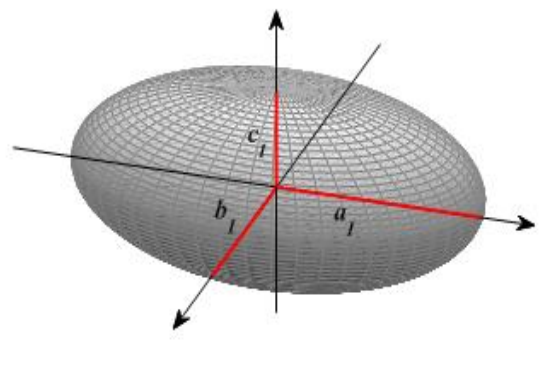

Figure 5.Ellipsoid model of an asteroid with radial dimensions.

We define,

$$\Delta\boldsymbol{r} = \begin{bmatrix} \varrho \cos\theta + \zeta \sin\theta \\ -\zeta \cos\theta + \varrho \sin\theta \\ -\cos(\Delta\theta - \theta)\sin\Delta\Omega \sin i + \varpi \sin(\Delta\theta - \theta) \end{bmatrix}$$

where,

$$\varpi = \cos i \sin(\Delta i - i) + \cos\Delta\Omega \cos(\Delta i - i) \sin i$$
$$\varrho = -\cos\Delta\Omega \cos(\Delta\theta - \theta) + \cos(\Delta i - i)\sin\Delta\Omega \sin(\Delta\theta - \theta)$$
$$\zeta = \cos i \cos(\Delta\theta - \theta)\sin\Delta\Omega + \xi \sin(\Delta\theta - \theta)$$
$$\xi = \cos\Delta\Omega \cos(\Delta i - i)\cos i - \sin(\Delta i - i)\sin i$$

In the remaining paper $\Delta\boldsymbol{r}$ is used to compute both relative position of the spacecraft with respect to the asteroid and the deflection at the Earth.
By definition of the coordinate system,
$\boldsymbol{r_A} = [r_A, 0,0]^T$
The change in the orbital parameters are calculated by numerically integrating the Gauss planetary equations using tangential thrust vector $\boldsymbol{u}_{dev}$ induced by the sublimation method.

$$\Delta k = \int_{t_0}^{t_1} \frac{dk\,(\boldsymbol{u}_{dev})}{dt} dt$$

The change in angular location calculated at the MOID is:

$$\Delta M = \int_{t_0}^{t_1} \frac{dM}{dt} dt + n_{A_0}(t_0 - t_{MOID}) + n_{A_i}(t_{MOID} - t_i)$$

where, mean motion, n= $\sqrt{\frac{\mu}{a^3}}$

The thrust produced by the deflection method is a direct function of the expelled surface matter $\dot{m}_{exp}$
Therefore,

$$\frac{dm_{exp}}{dt} = 2v_{rot}\int_{y_0}^{y_{max}}\int_{t_{in}}^{t_{out}} \frac{1}{H}\left(P_{in} - Q_{rad} - Q_{cond}\sqrt{\frac{1}{t}}\right) dt\, dy$$

where, $[t_{in}, t_{out}]$ is the duration of lasing on the point, $[y_0, y_{max}]$ are the limits of the vertical illuminated surface, H is the enthalpy of sublimation, P_{in} is input power due to solar arrays, Q_{rad} is the heat loss due to black-body radiation and Q_{cond} is conduction loss.

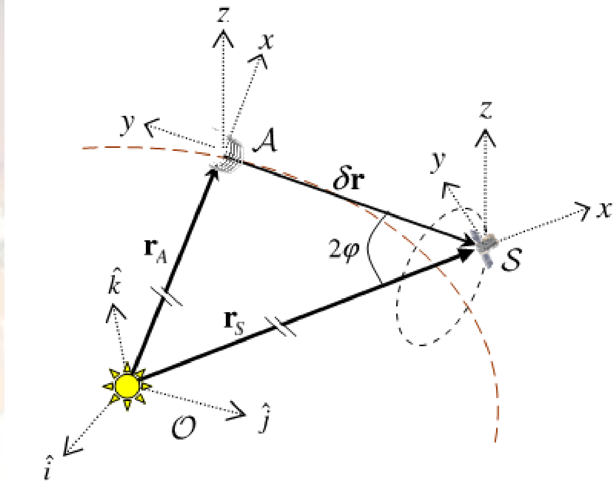

Figure 6. Definition of relative reference frames
$\mathcal{A}$ is centered on the asteroid
$\mathcal{S}$ *is* centered on the spacecraft.

The magnitude of induced acceleration is then given by

$$\boldsymbol{u}_{dev} = \frac{\boldsymbol{\Lambda}\bar{v}\dot{m}_{exp}}{m_{A_i}}.\boldsymbol{v}_A$$

where, $\boldsymbol{v}_A$ is the direction of velocity vector.
$\boldsymbol{\Lambda} \cong \left(\frac{2}{\pi}\right)$ is scattering factor assuming debris plume is uniformly distributed over half a sphere.
$\bar{v}$ is the average velocity of the debris particle according to Maxwell distribution of an ideal gas.
m_{A_i} is the remaining mass of the asteroid.
Apart from the thrust produced by the ejection of debris plume, the high pressure pulsed laser would produce a pressure on the asteroid. The transfer of momentum by the laser pulses accumulated over a significant interval of time is capable of changing the momentum of the asteroid by a desired amount. This change of momentum plays a very significant role in the design of asteroid deflection procedures.
Using general vector notation,

Momentum of the asteroid, $\boldsymbol{M}_a$.
Momentum transferred by a single laser pulse be $\boldsymbol{M}_l$.
Resultant momentum due to a single pulse,

$$\boldsymbol{M}_R = \boldsymbol{M}_a - \boldsymbol{M}_l$$

Net momentum shift required,

$$\boldsymbol{M}_a - \boldsymbol{M}_R = m_a(\boldsymbol{v}_a - \boldsymbol{v}_R)$$

where, m_a is the asteroid mass, v_a is the asteroid velocity and v_R is the resultant velocity of the asteroid.
From literature, an earth-bound NEO would require 1 cm/sec of velocity change to increase its MOID.
Thus,

$$|\boldsymbol{v}_a - \boldsymbol{v}_R| = 1$$

Therefore,

$$|\boldsymbol{M}_a - \boldsymbol{M}_R| = m_a$$

Taking only magnitude of the vectors,

$$M_a - M_R = m_a$$
$$\Rightarrow M_R = M_a - m_a$$

If the mass of the asteroid is roughly 10 million tones and its velocity 56 km/sec,
Then,
$M_R \simeq$ **5.59999 x 10^{16} kg-cm/sec**

So a slight change in momentum is required to deviate the asteroid. Since this method is an additive process where both the forces act in the same direction, the deflection would be more than any other method in the same time interval thus constituting a force that is stronger than any other method available. This is shown in the figure 7.

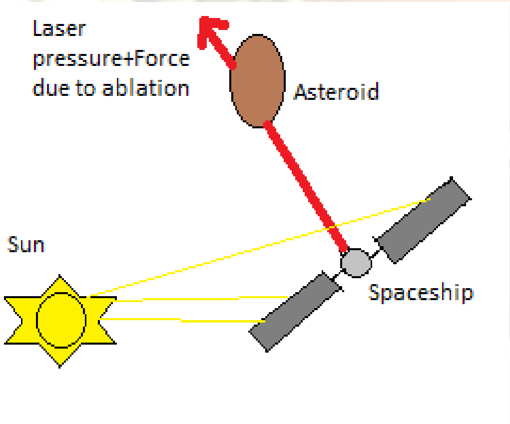

Figure 7. A Diagram showing Laser ablation and Laser pressure forces acting in the same direction

POSSIBLE IMPROVEMENTS

The technique discussed in this paper is an overall concept of deflection of an asteroid. It is worth mentioning that for a very successful NEO mitigation to occur, all the process mentioned here would require an optimization re-evaluation to increase the effect produced by this technique.
One of the major areas of improvement is the plume dynamics modeling. This plume dynamics is very important as it forms the soul of our asteroid deflection mechanism. Based on the model of Kahle, the sublimation process is comparable to the generation of jets in comet tail and the plume expansion is similar to a rocket exhaust through a nozzle. The density of the gas can be computed analytically as,

$$\rho(r, \Theta) = \rho^* j_c \frac{d_{spot}^2}{\left(2r + d_{spot}\right)^2} (\cos(\frac{\pi\Theta}{2\Theta_{max}}))^{2/k-1}$$

where, r is the distance from the spot on the surface of the asteroid, d_{spot} is the illuminated spot diameter, Θ is the elevation angle of the spacecraft with respect to the asteroid Hill reference frame $\mathcal{A}$, j_c is jet constant, Θ_{max} maximum expansion angle, ρ^* is the density at the sublimation point.

$$\rho^* = \frac{\dot{m}_{exp}}{(A_{spot}\, v_{gas})}$$

where, A_{spot} is the area of the spot and v_{gas} is the velocity of the exhaust gas.
Putting this in the previous equation,

$$\rho(r, \Theta) = \frac{4\dot{m}_{exp}}{\pi v_{gas}} j_c \frac{1}{\left(2r + d_{spot}\right)^2} (\cos(\frac{\pi\Theta}{2\Theta_{max}}))^{2/k-1}$$

This model predicts that the density at a distance r weakly depends on the size and spot geometry. In a nutshell, the maximum expansion angle is not a function of the spot geometry which is a bit under justified. For a massive extended object, much bigger than the spot, the expansion cone may be a little different. Hence there is an utter need for a better plume dynamics modeling.
The direct solar-pumped laser is another genre in which significant improvement is required. Due to mismatch between emission band of the sunlight and absorption band of the laser, a highly efficient system is yet to be developed. Although recent studies with ceramic laser currently reported a 40% efficiency with pseudo solar light, its effect for space-based application is yet to be tested.
Another region of possible improvement is the solar array technology. Solar arrays currently do not yield as much power as would be desired for this method. A very effective prospect could be to use a conglomeration of solar arrays where each array is connected parallel to each other so that maximum amount of input solar power is available every time for pumping the laser and each array can produce its maximum output. Also it must be made sure that in case of indirect solar-pumped lasers, the electric power generator consumes as much less power as possible.

DISCUSSION

In near future there is an ample probability of asteroids either impacting the Earth or passing very close to it. In both cases, a massive destruction will be the outcome and the face of the Earth would not remain as beautiful as it is today. So to mitigate this problem, a number of techniques have been proposed. Some of them include –

1) Impulsive change in the linear momentum of the asteroid by nuclear interceptors.
2) Producing continuous gravitational tugs on the asteroid by thrusters attached to the spacecrafts.
3) Producing a passive low thrust on the asteroid by an induced change in its thermo-optical properties.
4) Driving the asteroid by an electric solar sail attached to it.
5) Producing controlled thrust on the asteroid by ablation of its surface (through laser pulses or solar mirrors)

These are some of the legitimate methods available to us for deflecting the asteroids. Hence, a thorough investigation is required to select an optimal technique or even a number of techniques clubbed together and their actions divided into various stages. A study conducted by the Space Advanced Research Team, University of Glasgow, made a thorough comparison of the deflection methods based on certain criteria – miss distance at the Earth, warning time available and mass into orbit. The result from the study reported the sublimation method to be the most effective and safe.

But this sublimation can be done by laser or by mirrors. A technique using laser ablation, applied by a number of spacecrafts in formation have been discussed here and have advantages over the sublimation technique using mirrors. These advantages are as follows:

- It requires lesser payload as no large mirrors are required to place in orbits.
- It requires lesser control elements as no control element is required to control the position of the mirrors.
- Laser ablation is effective even at large distance from the sun, provided enough power is available for laser pumping, but power for sublimation will be significantly reduced in case of solar mirrors.
- This technique has an advantage of the availability of an extra force (laser pressure) acting along the line of action of the thrust due to ablation.
- In case of solar mirror method continuous beaming of concentrated solar energy will heat up the asteroid which may cause thermal instability and even defragmentation. This consequence is not present in laser ablation process as very less heat is dissipated on the asteroid by the laser pulses.
- No extra effort is required to place the spacecrafts strategically or further from the asteroid to avoid damaging of the mirror or its reflectivity due to debris plume.
- Push time of this technique is independent of mirror lifetime and the method works until technical glitches arise.

Also this method has advantages over all the other methods of asteroid deflection. It is insensitive to the asteroid morphology unlike gravity tractors. It is applicable for asteroids that are made up of chunks of rocks held together by mutual gravitational attraction. It also does not involve landing or going very near to the asteroid thus cancelling the effects of non-linear gravity fields.

This technique mentioned in this paper has been discussed as deeply as possible within the limited scope. The concept of laser ablation and the available energy for ablation has been discussed with the introduction of the laser pressure concept. The dynamics and navigational strategy of the operation has also been presented. Although it would require a high initial investment for the space-based application of this process, subsequent running cost is low. The research and development of better technologies might solve the problem of initial investment in near future.

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