Optimal Deflection of Hazardous Near-Earth Objects by Standoff Nuclear Detonation and NEO Mitigation Mission Design

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Introduction

The collision of a moderately large asteroid or comet, also referred to as a Near-Earth Object (NEO), with Earth would have catastrophic consequences. Such events have occurred in the past and will occur again in the future. However, for the first time in known history, humanity may have the technology required to counter this threat.

Many theories and conceptual designs for NEO mitigation systems that use a gradual application of force currently exist, and most require the development of substantial enabling technologies that will not be available in the near term. Since a collision could occur in the near future, it is necessary to devise and test mitigation systems that use only current or very near-term technology in order to provide for planetary defense.

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Technology Focus

The NEO mitigation technology that is examined in this paper is standoff nuclear detonation. A nuclear explosive device is brought to a rendezvous with the NEO, positioned at the optimal coordinates, and then detonated. The neutron radiation generated by the explosion penetrates a small depth into the NEO surface, superheating a thin shell of material that then blows off. An artistic conception of a standoff nuclear detonation is shown in Figure 1.

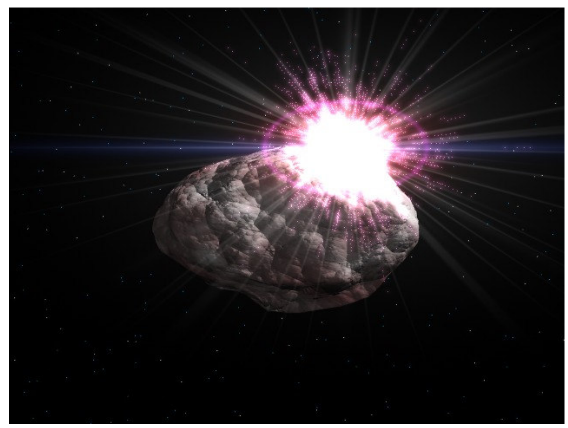

Figure 1: Artist's conception of a standoff nuclear detonation [1].

This virtually instantaneous blow-off of superheated mass imparts an impulsive thrust to the NEO in the opposite direction of the detonation coordinates, causing the NEO's subsequent trajectory to be altered slightly, which causes the NEO to miss Earth rather than collide. The imparted impulsive change, $\Delta\vec{v}$, to the NEO's inertial heliocentric velocity is much smaller than the NEO's velocity. Therefore, the impulse must be applied in the optimal direction to ensure effectiveness.

This NEO mitigation strategy is recommended because it is feasible with current technology. The process can be tested and refined as soon as we choose to do so. The other advantages, as well as the disadvantages, of standoff nuclear detonation are explained in detail later.

NEO Mitigation Mission Planning

While standoff nuclear detonation theory and technology, as well as the generalized concept of optimal impulsive NEO deflection, will be discussed in more detail later, a universally applicable system for designing a spacecraft mission to mitigate any arbitrary hazardous NEO with an arbitrary mitigation system will be presented first.

The timeline for a hazardous NEO scenario, from initial detection and threat assessment all the way through mitigation, is depicted in Figure 2.

Initial Phases

The first event is the detection of a NEO. At that point we don't know yet if it is a threat since time is required to process orbital observations and accurately propagate the NEO's orbit into the future. Once it is known that the NEO is indeed a threat, the mission planning phase begins.

Planning and Execution Phases

Once it has been determined that the NEO has a dangerously high probability of Earth impact, the mission planning phase is initiated.

Once the mitigation system, spacecraft, and launch vehicle are ready for launch and the mission launch time window arrives, the spacecraft departs to intercept or rendezvous with the NEO, depending on the type of mitigation system employed. Standoff nuclear detonation systems require rendezvous, while kinetic impactors, for example, require interception.

NEO Mitigation System Deployment

Once the mitigation system has been either positioned in close proximity to the NEO or anchored to it, the mitigation system is activated. In the case of impulsive methods, such as standoff nuclear detonation or high-thrust attached thrusters, this is a single point event, taking place at some specific time within the time block in Figure 2, labeled

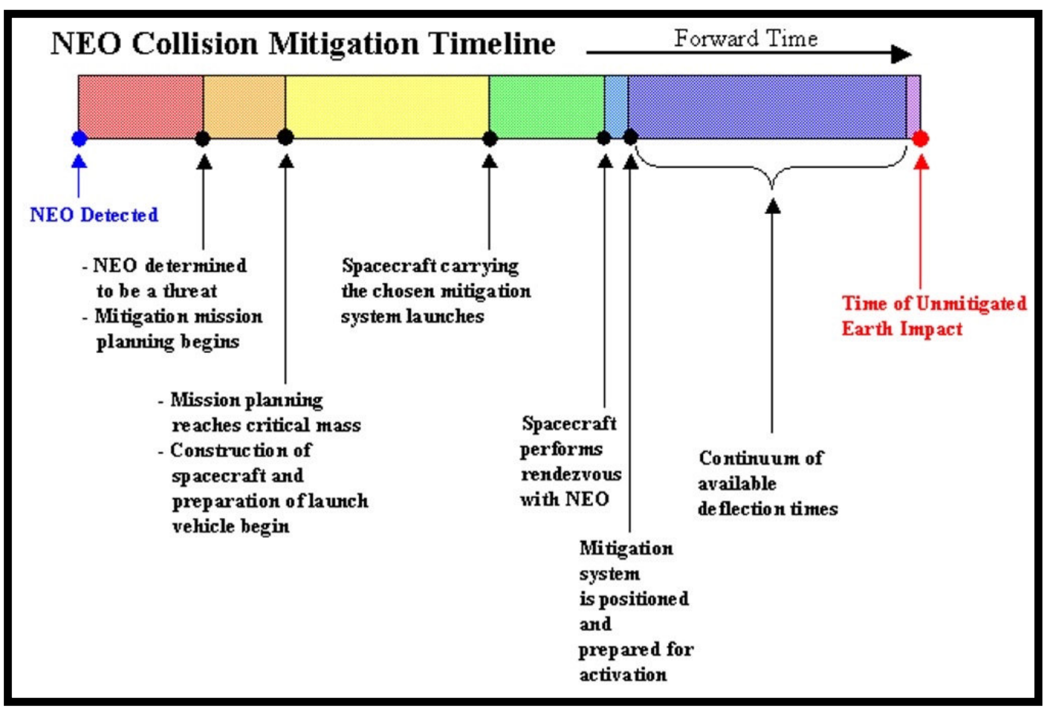

Figure 2: NEO mitigation timeline used in spacecraft mission design.

"Continuum of available deflection times."

While intuition may indicate the optimal time to perform an impulsive deflection or begin an extended one is the earliest available time, analysis has shown that this is not always true. The more generally accurate statement is that the optimal time to perform a deflection is during the NEO's first available perihelion passage. This influences the trajectory design for the mission.

NEO Mitigation Mission Design

Figure 3 depicts a universal system for designing NEO mitigation missions. The NEO mitigation mission design process is divided into three phases: Detection and Reconnaissance, Design Cycle, and Implementation.

Detection and Reconnaissance

During this initial phase the NEO is detected and determined to be a threat worth mitigating. At this point, it is desirable to send one of two types of missions to the NEO immediately:

1. Transponder-only mission, or
2. Science and transponder mission.

The transponder-only mission takes an X-band transponder beacon to the NEO so that the NEO's orbit can be precisely determined. The expected accuracies for a characteristic beacon system with 5 watts of radio frequency power and a low-gain antenna on the beacon system coupled with a 35 m receiving dish on Earth are on the order of 0.1 mm/s in velocity and 100 m in position within a geocentric range of 2 AU [2]. This type of mission is simple and low-mass. However, it is preferable to send the full science mission if possible.

In either case, the Detection and Reconnaissance phase ends with humanity in possession of the most accurate physical and orbital knowledge of the NEO possible, either from spacecraft missions or ground observations or both.

Design Cycle

The Design Cycle phase is an iterative process. The NEO mitigation mission is designed to optimize each phase of the mission. If the design is deemed unfeasible because of thrust, fuel, or launch vehicle requirements, the Design Cycle is repeated until an effective mission design is found. However, there are some cases in which current technology is inadequate or the warning time too short, or a combination of both, to permit effective mitigation.

Implementation

The Implementation phase occurs immediately after the Design Cycle yields a complete mitigation mission plan and spacecraft design. Once the mission is designed and the hardware is prepared, the spacecraft is launched and mission operations are conducted.

NEO Mitigation Mission Design Conclusions

The overall goal of the optimization process is to maximize the extent of available deflection times shown in Figure 2 since applying the deflection at the earliest available NEO perihelion passage maximizes the NEO deflection. This is accomplished by minimizing the time required for

1. Threat determination,
2. Mission planning,
3. Spacecraft and mitigation system construction, and
4. Launch vehicle preparation.

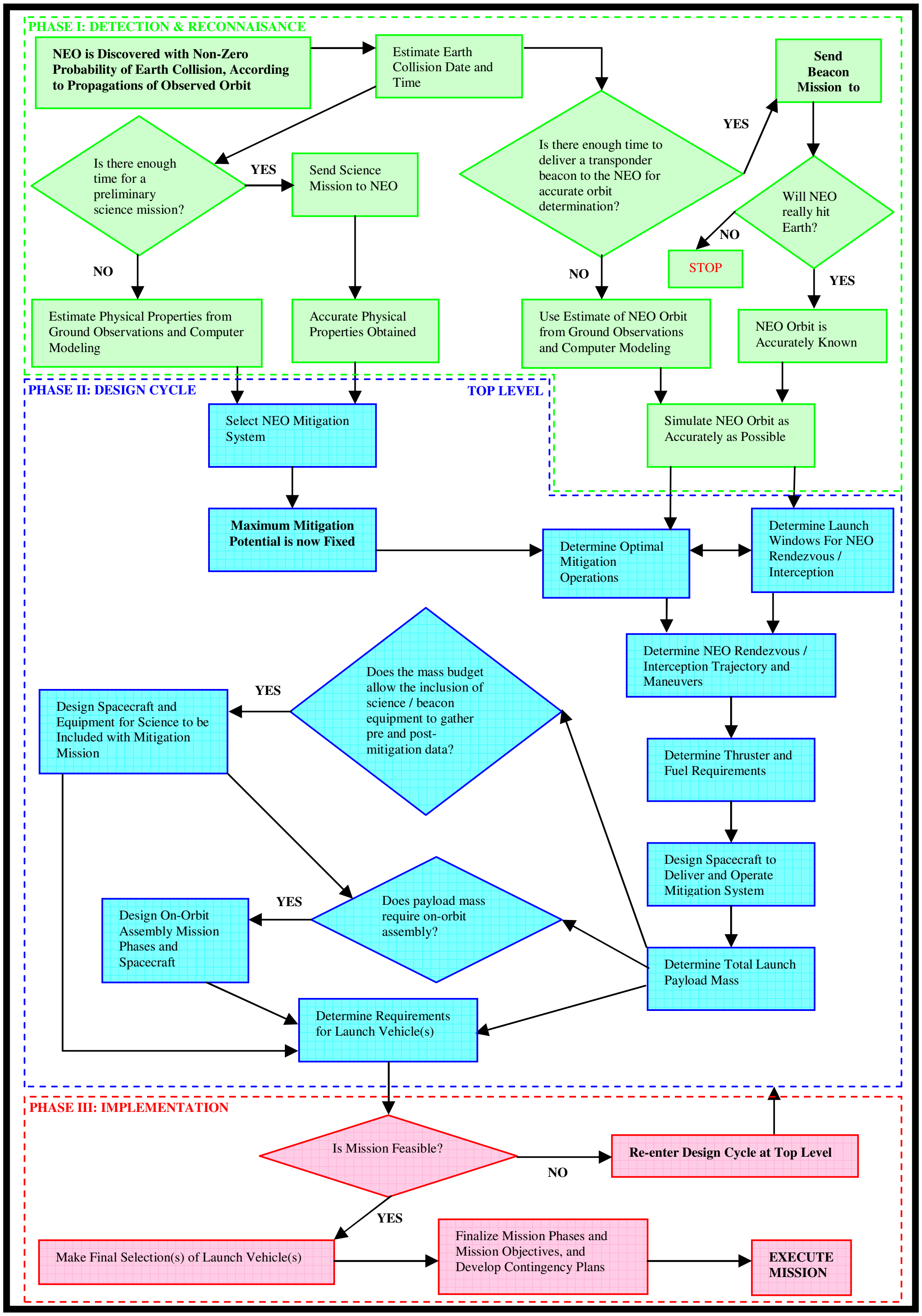

Figure 3: NEO mitigation mission planning flowchart

Time to Perform Threat Assessment

Improved techniques and equipment for accurate processing of orbital observation data and orbit propagation are constantly under development, and this development should be continued. In addition, systems for detecting and tracking NEOs should be continually upgraded and expanded to minimize the time required to both detect a NEO and determine whether it is a threat. Early warning is the most important ingredient in successful mitigation of a hazardous NEO.

Mission Planning

A complete mission planning system for designing NEO mitigation missions has been developed and presented above. Using this system will facilitate efficient and timely NEO mitigation mission planning. However, the process must be practiced in order to demonstrate feasibility and to improve the process. We can dramatically improve our response time and effectiveness during a true emergency by performing mitigation test missions on harmless NEOs.

Spacecraft and Mitigation System Construction

Performing mitigation system tests on harmless NEOs is the best way to reduce the time required for spacecraft and mitigation system construction. By learning what combinations of equipment work well together and what the design pitfalls are, an effective mitigation system can be developed in minimum time with minimum risk.

Launch Vehicle Preparation

Improvements in both the reliability and deployment speed of launch vehicles resulting from recent responsive space efforts will enable more effective NEO mitigation missions.

NEO Mitigation Mission Trajectory Considerations

In general, the rendezvous or interception trajectories will be designed to minimize flight time with the constraint that the required launch vehicle, thrusters, and fuel must be realistically realizable. In the event that the scenario is such that even an absolutely optimized trajectory still requires non-existent launch and/or propulsion systems, humanity may choose to attempt to develop these new systems rapidly if possible since the very existence of the human race is threatened, though success is not guaranteed.

Standoff Nuclear Detonation Technology

Standoff nuclear detonation is the simplest and most straightforward method for dealing with a threatening NEO. Therefore it should be tested before other methods. It will require the least initial investment because most of the required technology currently exists. If it proves successful then we will have demonstrated one viable method and can proceed with testing other systems. If it proves unsuccessful then we won't waste precious time and effort during a real emergency finding out that it doesn't work and that we need to attempt something else.

Advantages and Disadvantages

The advantages and disadvantages of standoff nuclear detonation as a NEO mitigation strategy are enumerated and explained below.

Advantages

1. Most of the required technology is currently available at TRL 9 except for

space-based implementation of nuclear device payload handling and precision proximity operations near a NEO.
2. It provides a beneficial use for nuclear explosives.
3. This mitigation technique is capable of deflecting NEOs with relatively little warning time (5-10 years).
4. No anchoring of equipment to the NEO's surface is required.
5. The NEO's spin state is not a factor.
6. No extended on-orbit operation of equipment is required.
7. Nuclear explosives provide the highest energy density of any currently available technology.

It is critical to note here that the vast majority of other NEO mitigation concepts do not possess any of these advantages. Most other NEO mitigation strategies require some or all of the following:

1. Substantial advance warning, on the order of two or more decades.
2. Anchoring of extensive equipment to the NEO's surface.
3. Very long periods of operation on orbit, often on the order of years or decades.
4. De-spinning the NEO, which requires tremendous amounts of energy.
5. Considerable general enabling technologies. One example is a very large and robust ion engine that produces several orders of magnitude more thrust than current and foreseeable ion engines do.

<u>Disadvantages</u>

1. Standoff nuclear detonation may not be effective against all types of NEOs. NEOs of very low porosity or complete "rubble pile" NEOs may be unaffected by a standoff nuclear detonation.
2. The interaction between a nuclear explosion in space and a NEO body is purely theoretical and unproven.
3. Proper selection of the correct nuclear device to deploy against a specific NEO requires knowledge of the NEO's physical parameters. Only estimates of these parameters may be available in a true emergency with short warning time.
4. If the launch vehicle explodes while still in Earth's atmosphere it is possible that some radioactive material could be scattered on Earth.
5. There is an international treaty currently in place that forbids the detonation of nuclear weapons in space [3].

These disadvantages can be addressed as follows.

1. Field testing. Tests will determine which types of NEOs are resistant to standoff nuclear detonation, how to avoid inadvertent adverse fragmentation of a given target NEO, and how well theory can predict the interaction of nuclear explosives and NEOs.
2. Once plans are in place, the appropriate international parties can amend the international treaty prohibiting nuclear testing in space to allow for planetary defense against NEOs and testing of mitigation systems.
3. Nuclear devices have already been designed to not accidentally detonate even if subjected to a launch vehicle explosion. The only other necessary step is to design methods for packaging them within the launch vehicle to eliminate or

minimize the possibility of radioactive material being scattered by a launch vehicle explosion.

Overall, we rate standoff nuclear detonation technology at TRL 3. Furthermore, we estimate the Research and Development Degree of Difficulty level at R&D^3 – II.

Baseline Mission Heritage

The standoff nuclear detonation mission concept has strong heritage from actual spacecraft missions, most notably the Near-Earth Asteroid Rendezvous (NEAR) mission in 2001 and the Deep Impact mission in 2005. The NEAR mission demonstrated the ability to successfully rendezvous with an asteroid (Eros), conduct proximity operations, and gather scientific data over an extended time period. The Deep Impact mission demonstrated the ability to intercept a comet and successfully guide a small impactor to collide with the comet.

This means that most of the required spacecraft systems for the standoff nuclear detonation mission have been tested and proven in the field. The following spacecraft subsystems have already been largely developed:

1. Spacecraft bus (TRL 9).
2. Scientific instruments (TRL 9).
3. Navigation and attitude determination sensors (TRL 9).
4. Main thrusters (TRL 9).
5. Power generators (TRL 9).
6. Attitude control (TRL 9).
7. Communications and data handling (TRL 9).
8. Thermal control (TRL 9).
9. Integrated Guidance, Navigation, and Control (GNC) system (TRL 9).
10. Launch vehicle system (TRL 9).

Standoff Nuclear Detonation Implementation

The goal of a standoff nuclear detonation is to impart an impulsive velocity change to a NEO. First, the spacecraft carrying the nuclear device follows a conventional rendezvous trajectory and matches orbit with the NEO.

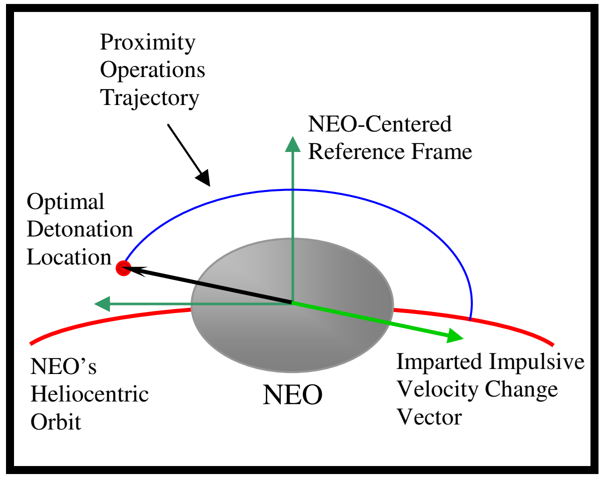

Figure 4: Nuclear device positioning prior to detonation.

If the nuclear device is fitted with basic thrusters and a GNC system, the spacecraft will then deploy it so that it may position itself at the optimal detonation coordinates. If not, the main spacecraft carries the nuclear device to the optimal location relative to the NEO. Once this positioning is complete, as shown in Figure 4, the nuclear device is detonated. Techniques for safely performing precision proximity operations near NEOs need to be developed to enable the required positioning of the nuclear device.

If logistics permit, a science instrumentation package can also be sent with the spacecraft so that scientific data on the NEO can be gathered before and after the detonation in order to better understand the NEO and the interaction between the nuclear explosion and the NEO, as shown in Figure 5.

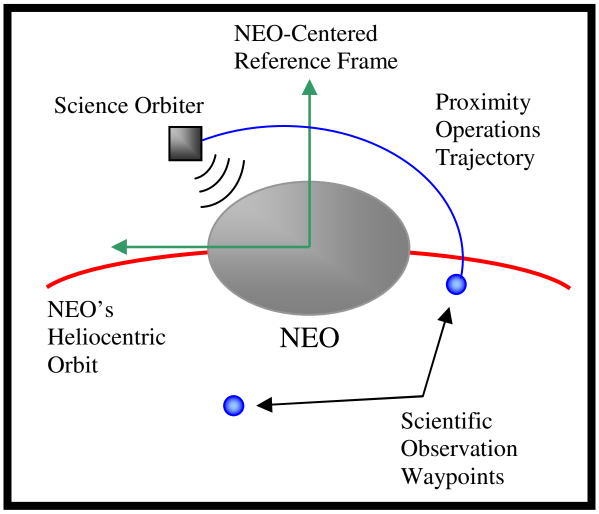

Figure 5: NEO science operations.

Conducting precision proximity operations relative to a NEO either autonomously or via ground commands (or both) is a challenging task and has never been done as required for this mission. In particular, the NEOs of interest range in size from about 100 m to 1000 m in mean diameter and so their gravity is too weak to be used to assist in proximity operations as it was in the NEAR mission. Thus precision proximity operations techniques and hardware will have to be developed that are capable of rejecting the small but persistent perturbation of the NEO's weak gravity, among other things. We rate such technology at TRL 7 since the systems flown with NEAR and Deep Impact can be considered as prototypes for the proposed precision system. Furthermore, we rate the research and development difficulty of this technology at R&D^3 – II.

Nuclear Device Selection and Positioning Considerations

The best nuclear device for the target NEO must be chosen and then be positioned at the optimal coordinates for a standoff nuclear detonation to be successful. The optimality of the detonation coordinates depends on two important aspects of standoff nuclear detonation theory:

1. The distance between the center of the nuclear explosion and the surface of the NEO determines the magnitude of the impulsive velocity change vector imparted to the NEO, for a given nuclear device yield.
2. The coordinates of the center of the nuclear explosion determine the orientation of the impulsive velocity change vector imparted to the NEO.

It is always optimal to maximize the magnitude of the velocity change imparted to the NEO, and this is accomplished by selecting the yield of the nuclear device based on the physical structure and composition of the NEO to ensure that, at the optimal detonation distance, the maximum impulse is imparted to the NEO, with the constraint that the impulse will not shatter the NEO and hence waste energy as well as turn the NEO into a collection of fragments that will likely still strike and damage Earth's surface.

The work of scientists such as Holsapple has yielded computer models that can determine the above factors with reasonable accuracy [4]. More recently, researchers at the Sandia National Laboratories used the Red Storm supercomputer to perform a series of high-accuracy asteroid deflection simulations using nuclear devices and determined that standoff nuclear detonation is likely to be a viable means of hazardous NEO mitigation [5].

Optimal Impulse Orientation and Time of Deflection

In addition to determining the optimal orientation for the impulsive velocity change vector to be imparted to the NEO, it is necessary to determine the optimal time at which to apply the deflection. Figure 6 depicts the relevant geometries.

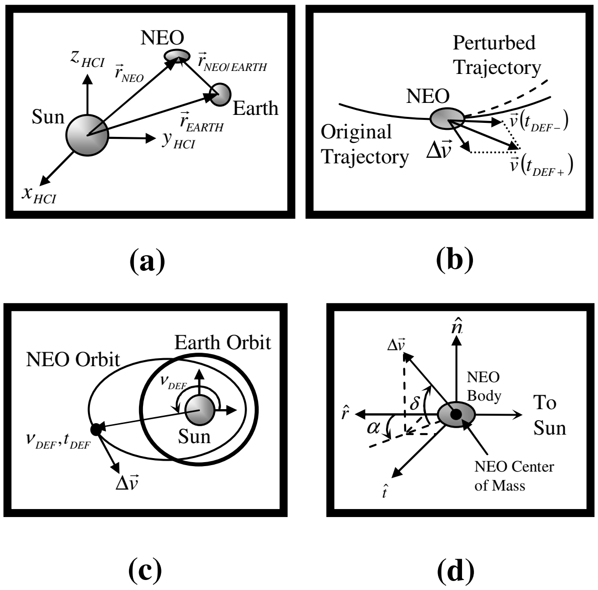

Figure 6: (a) The relative geometry between the NEO and Earth in the heliocentric inertial (HCI) frame. (b) The geometry of a velocity perturbation being applied to the NEO's inertial velocity vector. (c) An illustration of a time of deflection and corresponding true anomaly of the deflection point on the NEO's orbit. (d) The geometry of the deflection velocity change vector in the NEO's Radial-Transverse-Normal (RTN) reference frame in terms of spherical coordinate angles α and δ, termed the azimuth and elevation, respectively.

Figure 6a illustrates the NEO's inertial position relative to Earth, which is of primary importance in optimizing a deflection. Figure 6b depicts the vector geometry associated with the application of an impulsive velocity change to the NEO, and Figure 6c illustrates the fact that this deflection takes place at a particular time, which also corresponds to a particular location along the NEO's heliocentric orbit. Figure 6d illustrates the conventions used to parameterize the orientation of the deflecting impulse in terms of spherical coordinate angles measured relative to a NEO-centered frame, which allows the problem of optimally orienting the impulse to be treated.

The key results of our current optimal impulsive deflection research are:

1. The optimal time of deflection is generally the first logistically available perihelion passage of the NEO (see Figure 7).
2. The optimal impulse vector lies in the NEO's orbit plane, meaning that the optimal elevation angle is always zero (see Figure 8).
3. There are generally several key features found in the deflection solution space (see Figure 9):
    a. One globally optimal orientation.
    b. Two solutions that have zero effect on the NEO.
    c. In the case where the NEO is already going to miss Earth and we want to increase the miss distance, there is a solution that has the undesirable effect of pushing it closer to Earth.
4. There are moderately sized ranges (± 15 - 30° in some case studies) about both the optimal azimuth angle and elevation angle (zero) for which 90% of the maximal deflection is still achieved (see Figures 10 and 11).

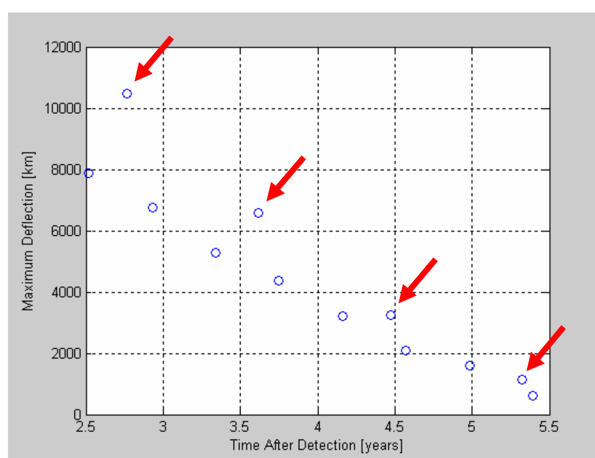

Figure 7: Deflection as a function of time for optimally oriented impulsive velocity change vectors. Times for which the NEO is at perihelion are marked with red arrows.

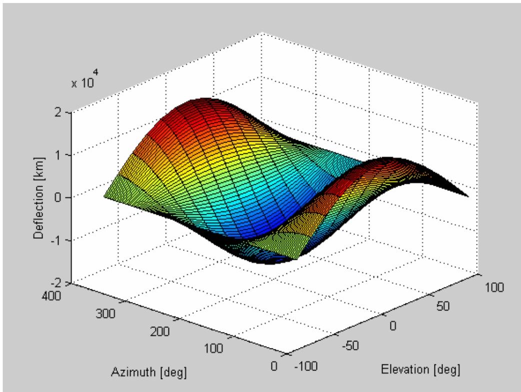

Figure 8: Deflection solution space surface in azimuth and elevation. The maximum deflection is achieved at an elevation angle of zero.

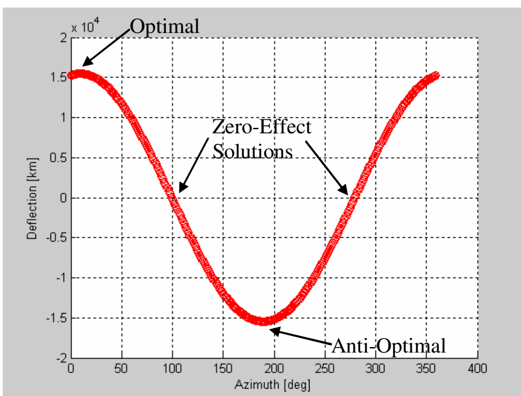

Figure 9: Deflection as a function of azimuth for a constant elevation angle of zero.

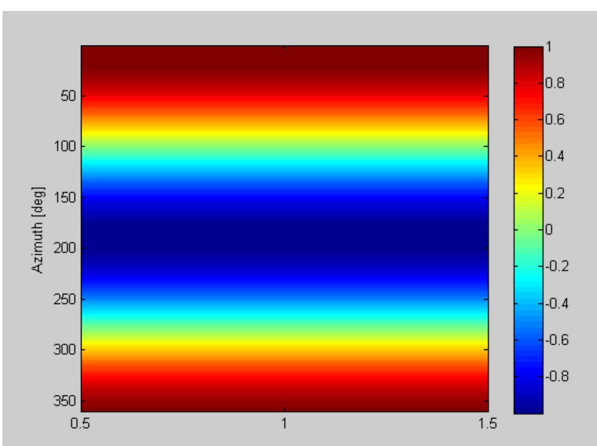

Figure 10: Spectral plot of normalized deflection as a function of azimuth angle, where a value of 1 indicates maximum deflection.

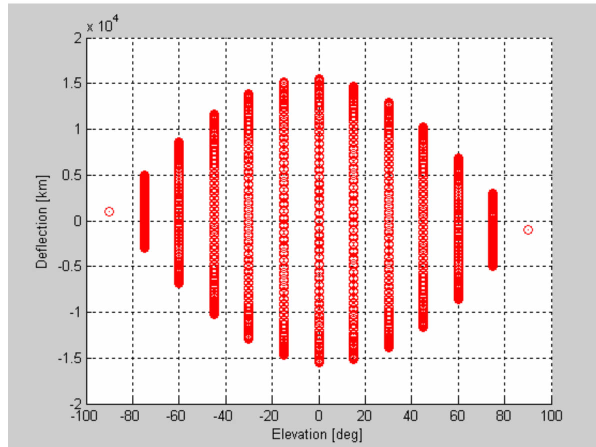

Figure 11: Deflection as a function of elevation showing lines of constant azimuth.

Figures 7 though 11 were generated for sample NEOs using optimal impulsive NEO deflection software.

The performance index used for optimization is: *the minimum distance between the NEO and Earth with the NEO following the deflected trajectory minus the minimum distance between the NEO and Earth with the NEO following its original trajectory*. The algorithm seeks to maximize this performance index.

Conclusions

Our current research efforts have produced the following results:

1. NEO mitigation mission design methodologies.
2. Standoff nuclear detonation implementation principles.
3. Optimal impulsive deflection principles.
4. An analysis of steps that need to be taken to ensure planetary defense:
    a. Identification of safe and scientifically interesting target NEOs for mitigation system testing.
    b. Testing of NEO mitigation systems by sending combined

science and mitigation test missions to viable target NEOs.
   c. Testing and refinement of standoff nuclear detonation as a NEO mitigation technology due to its simplicity and potential for rapid, relatively low-cost development.
   d. Use of previous NEO science missions as a baseline to rapidly and effectively prepare and deploy NEO mitigation test missions with minimum cost and risk.
5. Identification of technologies that need further research and development in order to be considered viable for planetary defense.
   a. Operation of nuclear devices remotely in space, particularly in the context of applying the yield of a nuclear device to a NEO body (TRL 3 and R&D^3 – II).
   b. Precision proximity operations near NEOs, especially NEOs ranging from several hundred meters to a couple of kilometers in mean diameter. The gravity of these NEOs must be treated as a perturbation to be managed by the spacecraft's GNC system rather than utilized for orbiting the NEO as it was during the NEAR mission to the relatively large and massive asteroid Eros, which is several tens of kilometers in mean diameter (TRL 7 and R&D^3 – II).

Hazardous NEO mitigation represents a multi-disciplinary engineering design problem and is best treated with a systems engineering approach.

Finding solutions to this problem will enhance our scientific knowledge of asteroids, comets, and our solar system. It will also enhance our spacecraft technology.

Since Congress has passed legislation requiring NASA to assume responsibility for NEO mitigation, we recommend that mitigation system testing begin as soon as possible, starting with standoff nuclear detonation. It is both an honor and challenge for NASA to be tasked with developing such systems. We hope that they will never be needed, but proving our ability to mitigate the threat posed by hazardous NEOs is necessary to ensure the survival of humankind.

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