Probabilistic Design of a Planetary Defense System

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The implementation of a successful Planetary Defense System (PDS) is crucial to ensure the future of Earth as a habitable planet in the face of threats posed by Near-Earth Object (NEO) impacts. However, due to the enormous costs and uncertainties involved in such an effort, no country or organization has committed to constructing a PDS as of yet. The design of a PDS is an inherently multi-disciplinary effort, necessitating the use of an integrated design framework from the earliest phases of its conception. Thus, a collection of probabilistic studies is applied to the design variables inherent to each of the studied NEO mitigation techniques. Such a probabilistic modeling framework enables designers to make physics-based design decisions that take into account the uncertainty inherent in several stages of this complex system-of-systems problem. Furthermore, such a modeling capability ultimately would allow designers to establish a quantitative top-level relationship between cost and safety.

Nomenclature

FFBD	=	Functional Flow Block Diagram
IPT	=	Integrated Product Team
MA	=	Matrix of Alternatives
M&S	=	Modeling & Simulation
NEO	=	Near-Earth Object
PDS	=	Planetary Defense System
PHO	=	Potentially-Hazardous Object
QFD	=	Quality Function Deployment
RSE	=	Response Surface Equation
TRL	=	Technology Readiness Level

I. Introduction

Over the last 15 years, geological and astronomical evidence has mounted that both asteroid and comet collisions occur regularly in the solar system.[7] The most recent event demonstrating Earth's danger was the July 1994 collision of the Shoemaker-Levy 9 comet with Jupiter, a dramatic event recorded on telescopes around the world. On Earth, natural disasters like the 2004 Tsunami and Hurricane Katrina have both claimed hundreds of thousands of lives and caused approximately $500B in rehabilitation[8], despite the warnings of scientific studies claiming that the now debilitated regions had been in danger for many years. Learning from the lessons of the past, and accounting for the inevitability of the future, it is imperative to establish a Planetary Defense System (PDS) to protect against devastating impacts from Near Earth Objects (NEOs).

Currently the asteroid Apophis is tracked closely to determine the possibility of its collision with Earth in the year 2029, or if not before its 2029 perihelion then afterwards in 2036. Apophis is an asteroid nearly 390m wide with a mass[10] of 2.1e10 kg and recent studies have indicated that Apophis presents a great threat to Earth's[9] biosphere. Furthermore, there remain thousands of undetected asteroids in our solar system even bigger than Apophis. Therefore a key ability of an effective PDS is to have ample detection abilities; otherwise, there may not be enough time to implement a response.

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Virtually all of the proposed countermeasures involve advanced technologies, which come with significant costs. Therefore, it is of great importance to identify and to select both technically feasible as well as economically viable solutions for such a complex problem. Using a systems engineering approach, both technical and economic requirements were used to determine the engineering characteristics of a PDS; they were derived with Quality Function Deployment (QFD). Furthermore, the QFD allowed an assessment of other proposals similar to the PDS proposed here. The PDS components that satisfy the engineering characteristics were determined and then organized into a Matrix of Alternatives (MA).

Using the MA, the PDS was decomposed into a functional architecture consisting of its three main subsystem functions: the detection, mitigation and reevaluation of the threat. Each subsystem was decomposed into its components to make it possible to simulate each of them with a modeling environment. Since it is seen as the most vital component for a known threat, this paper focuses on the mitigation system and its probabilistic analysis, rather than the detection or reevaluation systems. With the current knowledge of Apophis' danger to Earth, a mitigation system prototype has been modeled to determine its efficacy against mitigating such a threat. However, in no way is the design of this mitigation system limited to Apophis; rather, given several subsystem-level metrics, its design is applicable to a plethora of potentially-hazardous objects (PHOs) in our solar system.

II. Advanced Concept Description

The following sections are a summary of the PDS conceptual design, showing the relevant prior work done before the mitigation system analysis, which is the focus of this paper. Starting with the concepts briefly described in this section, it was possible to assemble initial concepts about what the key features of a PDS would be; these concepts were then quantified using a systems engineering approach.

A. Significance: Background Work

Three PDS mitigation concepts that have been proposed in the past were analyzed and compared as part of this study:

1. SpaceWorks, Inc.: MADMEN

Developed by SpaceWorks, Inc., a swarm of Modular Asteroid Deflection Mission Ejector Node (MADMEN)[2] spacecraft is a proposed concept for threat mitigation. To mitigate an inbound threat, thousands of these small, nuclear-powered spacecraft would be launched at and land on a potentially threatening object. Each would anchor itself onto the object, drill into it, and forcefully eject excavated mass, thereby delivering a sustained impulse to the object without carrying extra propellant. Since it is a *mitigation system only*, MADMEN can only be gauged partially against a complete PDS. Yet, the proposed abilities of the components of such a mitigation system are modeled in the forthcoming probabilistic analysis.

2. Human-Landing Mission

Due to the uncertainties in the physical characteristics of an NEO, the presence of human adaptability would strengthen the robustness of a mitigation technique. Therefore, a human landing mission is a possible solution to deflecting the course of an NEO. However, it was found during the systems engineering process that many alternatives exist with comparable robustness without the additional mass and complexity introduced by such a design. Thus the human-landing mission is not considered in the analysis of a mitigation system.

3. Boeing Airborne Laser

Developed at Boeing with support by the University of California – Irvine, the Boeing Airborne Laser is a potential threat mitigation system as well. The laser uses a direct energy system onboard one or several aircraft to eliminate inbound threats when they are within close range to the Earth. As with MADMEN, the Airborne Laser is also a *mitigation system only*, thus a complete PDS can only be partially gauged against this concept as well; this mitigation system is not modeled in the forthcoming probabilistic analysis because it was found to be unable to meet customer requirements during the systems engineering process since it can only deal with small targets close to Earth.

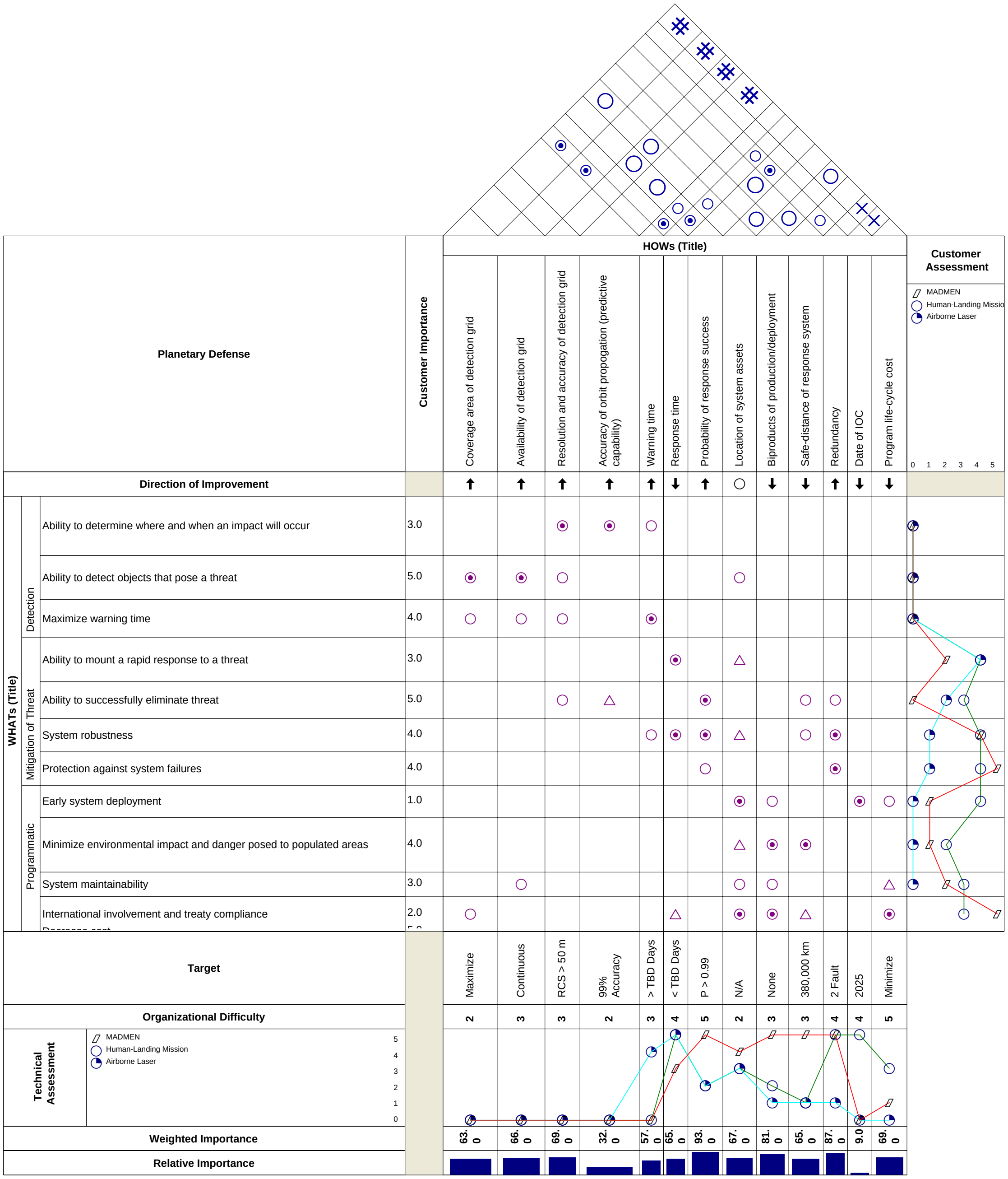

Figure 1: Quality Function Deployment. The Quality Function Deployment shows the way that the customer requirements are matched to the engineering characteristics of a Planetary Defense System. Also, the customer assessment of several mitigation systems can be seen on the rightmost column of the chart. MADMEN is the only mitigation system from this analysis that is examined further, due to its attractive characteristic of scalability.

B. Implementing the QFD

1. Customer Requirements and Importance

Following the QFD approach, it was necessary to gauge the *customer requirements*. It is important to note that the customer importance weightings are malleable to the requirements of the customer, but they have been approximated as a result of IPT discussions.

2. QFD Conclusions: Primary Objectives

The bottom rows show the results of the calculations done using the relationship matrix to determine the relative importance of each engineering characteristic. As expected, the most important characteristics are:

- High probability of response success
- Redundancy
- Cost of the PDS

The relative importance values of the QFD quantitatively justify the fact that a PDS must be not only robust in the completion of its task but also economically viable. Therefore with the QFD in mind, the PDS architecture could then be devised to satisfy the most important requirements.

C. Functional Decomposition: Functional Flow Block Diagrams

Having a semi-quantitative idea of what abilities it should have, three Function Flow Block Diagrams (FFBDs) were generated to establish the necessary flow of information between the functional components of a PDS. One FFBD was created for each of the subsystems: (1) detect threat, (2) eliminate threat, and (3) reevaluate threat, all of which are shown in Figure 2, Figure 3 and Figure 4, respectively.

D. Feasible Options: Matrix of Alternatives

Once the customer requirements had been translated to engineering characteristics and the functional requirements had been established, concept alternatives could then be generated to fulfill the components of the FFBDs.

The permutation of choices that form the design space was established through the use of a Matrix of Alternatives (Figure 5), which was assembled after a literature search. A Matrix of Alternatives maps physical solution alternatives to most of the functions and sub-functions established in the FFBD. Each concept is therefore an alternative solution for each of the functional requirements of a PDS.

III. Modeling & Simulation: Mitigation System Overview

The following section explains the detailed technical approach taken to perform a probabilistic analysis of the prototype design of a PDS mitigation system. A general overview will first lay the foundation for the details related to each of the mitigation techniques selected from the aforementioned MA.

A. General Overview

Even though the systems engineering tools described thus far illustrate some of its details, it is clear that the PDS occupies a huge design space (~10^9 designs) riddled with the uncertainties of world politics, schedule management and any other degree of freedom that could derail such a large scale design effort. Thus it is necessary to assess the technical feasibility and economic viability of each PDS concept probabilistically to insure a robust design. However, with such a large design space, there must be a rapid way to test the abilities of any PDS concept. Therefore, a computer-modeling environment has been created with which it is possible to determine both the technical feasibility and the economic viability of a PDS from a probabilistic vantage point.

The goal of the Modeling & Simulation (M&S) is to create a parametrized PDS design space, following the information flow described with the FFBDs. Using both Phoenix Integration's ModelCenter and Matlab, it was possible to create a parametrized PDS in which four mitigation techniques are evaluated. The four mitigation techniques that are modeled were chosen following a literature survey accounting for level of TRL, cost and required time of implementation. The four techniques are referred to by the following names:

- Thruster
- Impactor
- Mass Driver
- Nuclear Explosion

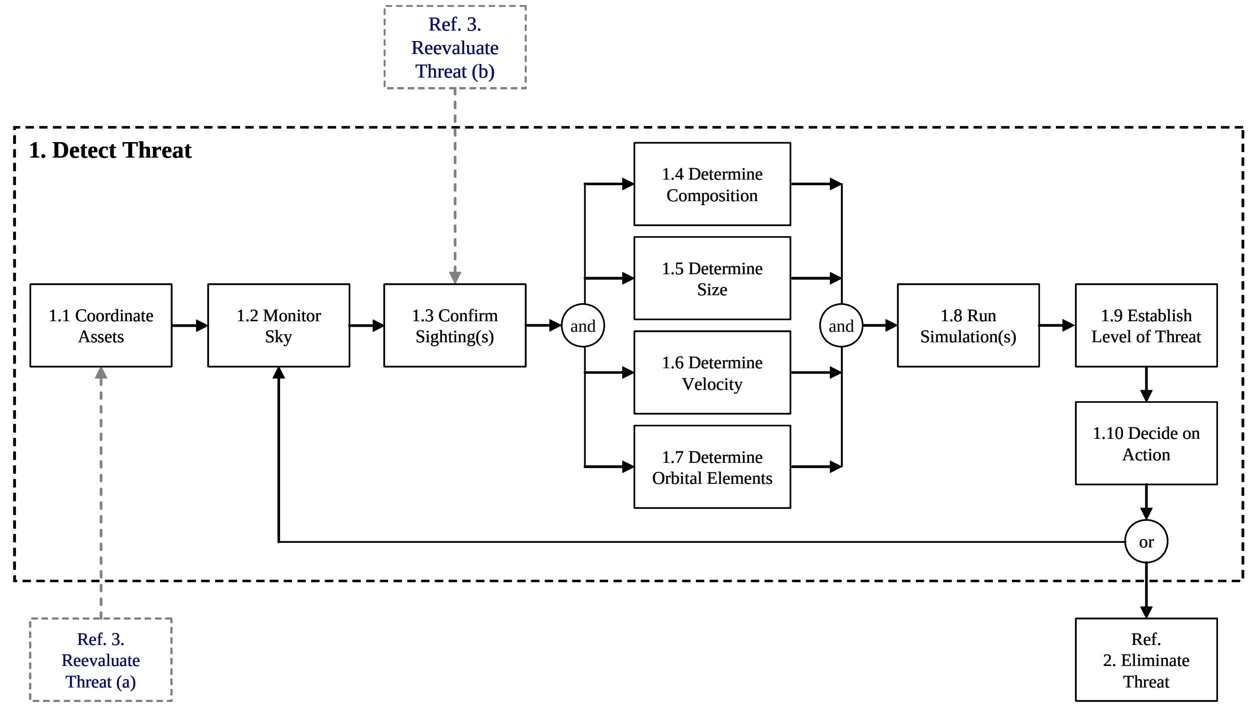

Figure 2: Functional Flow Block Diagram (1) - Detection System. The information flow for the detection system

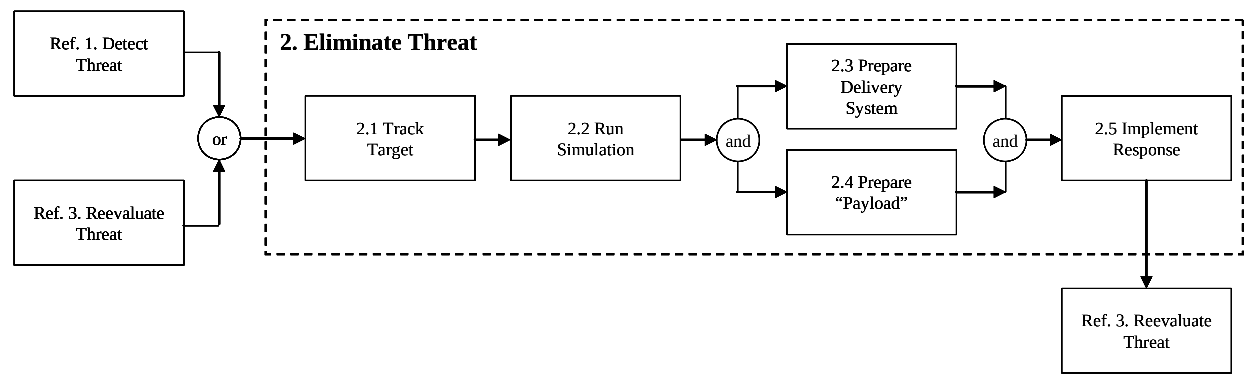

Figure 3: Functional Flow Block Diagram (2) - Mitigation System. The information flow for the mitigation system

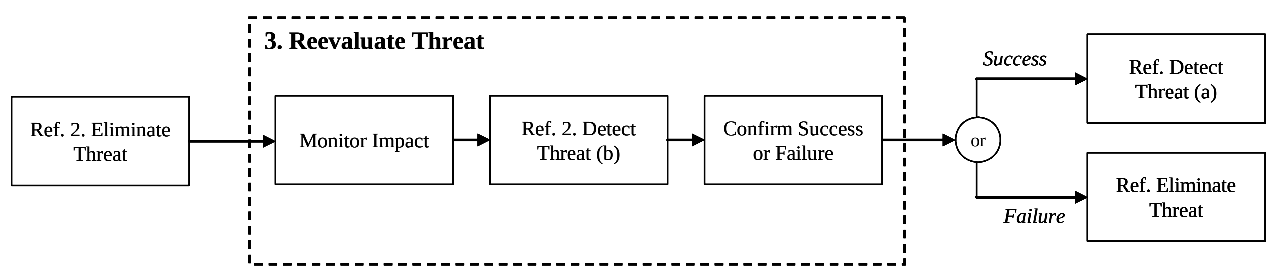

Figure 4: Functional Flow Block Diagram (3) - Reevaluation System. The information flow for the threat reevaluation system can be seen from this diagram.

Detection System	Type of detection assets	Optics (visible & IR)	Radio telescopes	Combination			
	Location of detection assets	Ground-based only	Moon-based only	Space-base only	Combination		
	Coverage area	<25%	25%-50%	50%-75%	>75%		
	Grid availablity	<25%	25%-50%	50%-75%	>75%		
	Establish composition	Spectroscopy	Sampling				
	Establish size	Reflected sunlight + heat	Silhouette measurement	Radio telescope	Probe(s)		
	Establish orbit and state vector	Range + Doppler	VLBI	Combination			
	Simulation & orbit propagation	Two-body problem	Variation of parameters	Cowell's Method	Encke's Method		
Mitigation System	Type of primary mitigation asset	Explosive	Kinetic Impactor	Mass Driver	Laser	Propulsive	
	Type of backup mitigation asset	Explosive	Kinetic Impactor	Mass Driver	Laser	Propulsive	None
	Location of mitigation assets	Ground-based only	Moon-based only	Space-base only	Combination		
	Levels of redundancy	Single-fault tolerant	Double-fault tolerant				
	Type of delivery system	Existing expendable LV	Dedicated LV	Reflector			
System Integration	Data transfer strategy	Real-time	Periodic	Event driven			
	Decision making strategy	Pre-set criteria	Executive power	Committee			
	International Partnerships	None	Limited	Extensive			
	Location of Ground Assets	U.S. Only	International				

Figure 5: Matrix of Alternatives. In the Matrix of Alternatives (MA), the results of a literature search are organized to serve as a point of reference when considering Planetary Defense System (PDS) subsystem components.

Furthermore, since it has been identified as the most prominent threat to Earth within the next 30 years, the Apophis asteroid has been chosen as the baseline around which the M&S has been designed. Using Apophis, which has a slow rotation period (30.54 hrs)[6], each of the four identified techniques can be virtually tested on a real-life threat. Furthermore, even though it has been designed around Apophis, in no way is the PDS model's predictive ability restricted from handling other threats of different compositions, and rotational or orbital characteristics.

There were two main phases to the development of the mitigation system simulation, the details of which relates the architecture of the coding logic: the orbit propagation and the mitigation implementation.

B. Orbit Propagation Overview

Both to reduce the computation time and to improve the accuracy of the orbit propagation, the gravitational fields of all bodies in the solar system were neglected with the exception of the sun. Only gravitational interactions between the NEO and the sun were considered to determine the position of the NEO, while the positions of Earth[§] were imported from the JPL Horizons Ephemeris[4]. Also, all calculations take place within a Cartesian coordinate system, where the x-y plane is that of the J2000 Ecliptic. Since the least sustained acceleration imparted to the NEO by any mitigation system is several orders of magnitude more than the greatest acceleration exerted by Earth on Apophis (see Table 1), the physics of the situation completely sanctions the neglect of Earth's gravitational effects on an NEO. The distance shown in the table of course is different from that calculated by JPL Horizons (0.0328 AU in 2029) because possible variations in the position and velocity of Apophis have been taken into account in Table 1.

Table 1. Comparison of Maximum Probabilistic Gravitational Acceleration with Minimum Mitigation Acceleration

Max Grav. Accel. (m/s^2)	Distance (AU)	Thruster Accel. (m/s^2)
2.04385E-13	0.00204	4.76667E-05

One-hour time intervals are used from the date of last observation (12/14/2006) until the currently calculated year of closest approach (2029). While 2036 is also a possible year of collision, it is too early to tell, thus the effects on the 2029 close approach are gauged in this study. The only swath of time during which the interval is changed (to minutes from hours) is for the implementation of the thruster, impactor and nuclear explosion, since each of these techniques has its effect within a time span that is considerably less than one hour. Conversely, since the mass driver subsystem performance values are quoted in hourly rates, it is not necessary to change the time interval to study the effects of a mass driver on an NEO.

[§] The positions of Earth are in hourly and sometimes minutely intervals between 12/14/2006 and 12/14/2029.

C. Thruster Mitigation Overview

There are several main assumptions that are crucial to the implementation of the thruster: the ability of the thruster subsystem both to maintain a force on the NEO center of mass and to align its thrust vector so that its components have the following coefficients within the J2000-oriented Cartesian coordinate system:

$$\left(1/\sqrt{3}, 1/\sqrt{3}, 1/\sqrt{3} \right)$$

The rocket chosen to be the baseline for this design is assumed to be similar to the Saturn IV-B, which was the third stage rocket of the Apollo missions[3] and is certainly capable of in-space use.

With the time interval changed to minutes for the first week of 12/14/2012, which is near the closest point of Apophis' approach to Earth within the next 10 years (~ 0.11AU), the thruster system is ignited instantaneously at 00:01:00 on Dec 14, 2012. Using the known burn time of the Saturn IV-B (475s), an acceleration of 1001kN is imparted to the asteroid over the burn time interval, while the added mass of the rocket on the NEO and its subsequent loss of mass due to thrust production have been justifiably neglected.[#]

After the weeklong period of minute intervals following 12/14/2012, the interval returns to hourly updates as it had been in the original orbit propagation.

D. Impactor Mitigation Overview

Just as with the thruster, the first week of 12/14/2012 is divided into intervals of one minute, while all other time is divided into intervals of one hour. Like the thruster, a proven impact subsystem was used to assess its effect on Apophis: the Deep Space Tempel 1 Impactor[5]. From the Deep Space mission archive[5], the velocity vector in J2000 and the impactor mass (370kg) are used to determine the kinetic energy instantaneously imparted to the asteroid by an assumed completely inelastic and adiabatic collision at 00:01:00 on Dec 14, 2012.

It is important to emphasize the use of the conservation of kinetic energy of the NEO-impactor system, rather than conservation of momentum, which might also be thought to be valid for such an inelastic collision calculation. However, the conservation of energy is a more physically relevant relationship to use because of the possible loss of kinetic energy to the thermal energy generated from such a collision, as it had been observed on Tempel 1 with an impactor of 370kg. Since the question of heat losses is pertinent to this mitigation scenario, the flexibility of this modeling approach allows the question of energy transfer efficiency to be acknowledged when, and if, the appropriate data becomes available. Nevertheless, for the subsequent impactor calculations, the loss of imparted kinetic energy to thermal heating is assumed to be negligible.

E. Nuclear Explosion Mitigation Overview

Just as with the previous two mitigation codes, the time interval is parsed into one minute intervals during the first week of 12/14/2012. Due to the physics described in Gennery[1], there is a simple conservation of momentum equation that dictates the velocity imparted to the NEO when it is within a certain vicinity of a nuclear explosion, such as those typical of the U.S. stockpile.[**]

Assuming that the explosion occurs at a time such that the ejecta instantaneously departs the surface of the NEO within the blast radius at 00:01:00 on Dec 12, 2012, the calculation of the velocity imparted to an NEO involves an application of the conservation of momentum. As with the previous two calculations, the time intervals return to one hour through the end of 2029 after the week of minute intervals previously mentioned.

Also, there is a key assumption about the nuclear explosion subsystem as there had been with the thruster, namely that the explosion occurs at such a location and distance from the NEO such that the coefficients of the velocity vectors are $\left(1/\sqrt{3}, 1/\sqrt{3}, 1/\sqrt{3} \right)$. Finally, the baseline calculation is done with one 15Mton warhead at a particular height above the NEO's surface, assuming maximum change in momentum to the asteroid due to neutron radiation.

[#] The mass of the Saturn IV-B is 1.199e5kg[14], whereas the mass of Apophis is 2.1e10kg.

[**] This is an assessment in terms of their supply of neutrons, which is deemed crucial to the creation of ejecta from the NEO as detailed in Gennery.

F. Mass Driver Mitigation Overview

The Mass Driver calculation is the only mitigation technique that does not analyze the mitigation implementation on a minute time interval because the expected performance values for MADMEN[2] were given in kg per hour of ejected material. Therefore, the coding logic specifically calculates the velocity imparted to the NEO if the amount of mass excavated in one hour is instantaneously ejected from the NEO every hour at 100m/s for a specified amount of time (1-10 hours). As the probabilistic analysis will show, the specified time has little impact on the overall efficacy of this mitigation technique.

Just as with the other subsystems, there are key assumptions used to carry out the calculation of the mass driver's effect on the course of Apophis. First of all, it is assumed that the mass drivers coordinate their activity on the subsystem level such that the overall velocity vectors have coordinate coefficients of $\left(1/\sqrt{3}, 1/\sqrt{3}, 1/\sqrt{3}\right)$. Also, it is assumed that the 100kg/hr is ejected in each of the three coordinate directions. Finally, it is assumed that both the added weight to the NEO from the mass drivers and the lost weight from the ejected material are negligible changes in mass to the NEO-mass-driver system.[††]

IV. Modeling & Simulation: Mitigation System Preliminary Validation

Necessarily, before any calculations could be carried out to assess the efficacy of a particular mitigation system, it is first necessary to validate the predictions of the dynamics of the simulation. By far the most extensively validated aspect of this PDS model is the orbit propagation calculations without any implemented mitigation. In fact, it is an aim of presenting this work at this conference to receive feedback about ways to demonstrate further the validity of the mitigation calculations.

A. Orbit Propagation Validation

Much analysis of the NEO's positions was performed to determine the accuracy of the orbit propagation. Since the Earth's positions are inputted from the data of JPL Horizons' ephemeris, it was not necessary to investigate their validity. But the most important and reliable calculation is that of the minimum distances between Earth and Apophis (see *Table 2*).

Table 2: Comparison of Calculated Minimum Distances With Those of JPL Horizons.

Year	Calculated Minimum Distance (m)	Calculated Minimum Distance (AU)	Actual Minimum Distance (AU)	%Error
2007	1.2981E+11	0.868	0.867	0.085
2008	2.0989E+11	1.403	1.402	0.073
2009	2.5568E+11	1.709	1.709	0.007
2010	2.0799E+11	1.390	1.393	0.191
2011	9.9762E+10	0.667	0.671	0.616
2012	1.6919E+10	0.113	0.111	1.886
2013	1.4975E+10	0.100	0.0989	1.218
2021	1.5797E+10	0.106	0.107	1.311
2028	3.8488E+10	0.257	0.261	1.427
2029	5.7117E+09	0.038	0.0328	16.403

The accuracy of the orbit propagation can be seen for the first seven years after the 12/14/2006 observation[‡‡] with several years skipped until 2021 and then several more skipped until 2028 and 2029, when the close approach is expected; while the comparisons of these years have been excluded for brevity, they can surely be verified to within a range of accuracy consistent with what is shown in the table. Notice that in 2029, the percent error makes a sharp jump to 16%; this can be explained by the fact that the margin for error decreased by one to two orders of magnitude for a predicted close approach in 2029 of ~ 5e9m. Finally, it is important to note that these calculations

[††] In three total directions this means that $3 \times 100 \frac{kg}{hr} \times 168 \frac{hr}{wk} \approx 5 \times 10^4 \frac{kg}{wk}$ is the weekly rate of mass ejected by the mass driver system. Thus in one week, only approximately 2e-5% of the NEO-mitigation system mass system has changed, which is a negligible amount.

[‡‡] Note that the year 2007 indicates the year from 12/14/2006 to 12/14/2007. Likewise, 2008 indicates the year from 12/14/2007 to 12/14/2008, etc.

are completely deterministic; in other words, no probabilistic variation is applied to either the positions or the velocities of the NEO, so as to show the correlation with the equally deterministic calculations of JPL Horizons.

Furthermore, though it has been omitted for brevity, the times of the closest approaches in each year fall within several days of the expected times of close approach calculated by JPL Horizons. These details are omitted though because the aim of this study is not as much accurate orbit propagation as it is an analysis of the probabilistic efficacy of a PDS using a reasonably correct prediction for solar system dynamics.

B. Mitigation System Validation: Discussion

It is quite difficult to validate something that has never been done. While the performance metrics of subsystems from past missions have been used to make calculations about the fate of Apophis' close approach with Earth in 2029, e.g. the mass and velocity of the Deep Impact impactor and both the burn time and thrust output of the Saturn IV-B, there is no experimental data with which to verify the claims of the subsequent results because such missions simply have never been done before today. While it adds excitement to the challenge of constructing a PDS, such a conundrum surely unsettles the engineering community, thus it is a primary aim of attending this conference to receive ideas about how to validate these calculations in other ways.

V. Modeling & Simulation: Results

With mitigation system calculation validations notwithstanding, results are presented in this section on the belief that the physics of each of the four mitigation scenarios has been hypothesized and implemented correctly. For each of the mitigation systems, both deterministic and probabilistic analyses are performed. While the deterministic analysis investigates each of the mitigation scenarios with baseline values in place for both the trajectory of Apophis and the subsystem level performance metrics, the probabilistic analysis accounts for uncertainties in the subsystem level performance metrics of each mitigation technique.

A. Thruster Deterministic Mitigation Results

With the calculations carried out in a deterministic manner, i.e. with no probabilistic variation to any of the inputs, *Figure 6* shows the change in minimum distance as a function of year by implementing the thruster scenario discussed above. It is important to note that each year shows the minimum distance between Earth and Apophis during that year, and that the difference begins in 2013 because the mitigation takes place in the first week of 12/14/2012. As the figure shows, there is moderate change in the minimum distances from year to year, but in 2029, the year of expected close approach, there is a nearly -3.5% change in the minimum distance from what it would have been without any mitigation. Note that this does not invalidate the Saturn IV-B as a feasible thruster to deflect an asteroid, yet it does show that it can have a substantial effect with only a burn time of 475 sec while imparting 1001 kN of force through the asteroid's center of mass. Nevertheless, a Saturn IV-B is not a technically viable way to deflect Apophis from a 2029 possible collision, with the following choice of thrust vector component coefficients:

$$\left({}^{1}\!/_{\sqrt{3}}, {}^{1}\!/_{\sqrt{3}}, {}^{1}\!/_{\sqrt{3}} \right)$$

However, such a result does not rule out the use of a Saturn IV-B because it is simply a constrained optimization problem to determine the optimum direction of the thrust vector, where the primary constraint is that the thrust coefficients add in quadrature to one. However, such analysis is beyond the scope of this study.

B. Impactor Deterministic Mitigation Results

Just as with the thruster, a deterministic analysis of the adiabatic inelastic collision of the impactor was performed. The deterministic change in minimum distance attributed to such a mitigation simulation can be seen in *Figure 7*. The figure shows a clearly beneficial effect of this mitigation technique. However, the muted fact is that in 2013 the minimum distance is decreased by over 6 million meters, bringing Apophis to a closest approach of approximately 8.5 million meters in this year; this is about only 50% more than the expected close approach distance in 2029. Thus even though the impactor technique shows remarkable benefits between 2014 and 2029, there is an extremely small risk that Apophis could be brought closer to Earth in 2013. A probabilistic assessment of the NEO trajectory in addition to the design variables would quantify the actual risk posed by this strategy; however, such a study is beyond the scope of this paper.

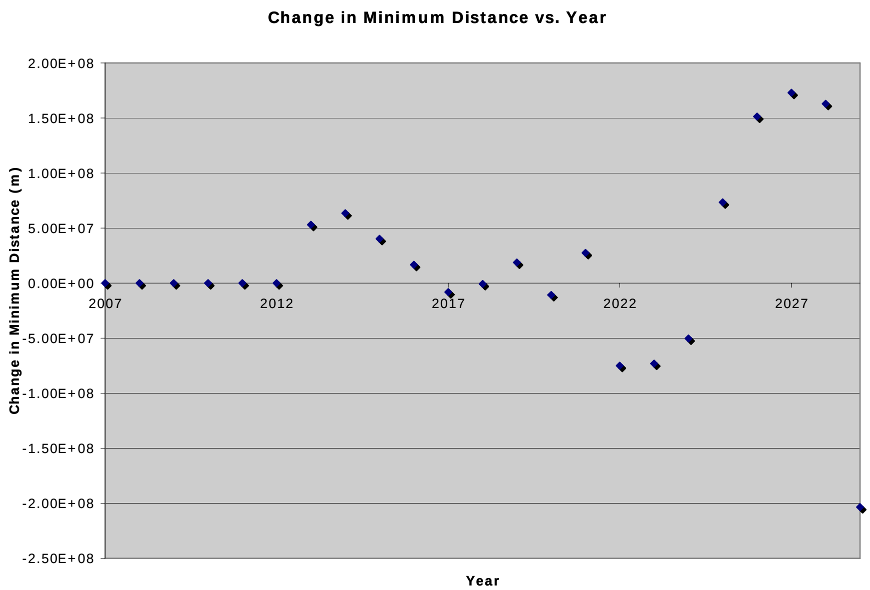

Figure 6: Deterministic Change in Minimum Distance vs. Year for a Saturn IV-B Thruster. The changes in minimum distance start in 2013 due to a mitigation implementation on Dec 14, 2012. However, in 2029 the NEO is brought almost 2.00e8 meters closer than it might have been without any mitigation; thus this option is not technically feasible as designed in this paper; though an optimization of the thrust vector coefficients could make it a valid option[§§].

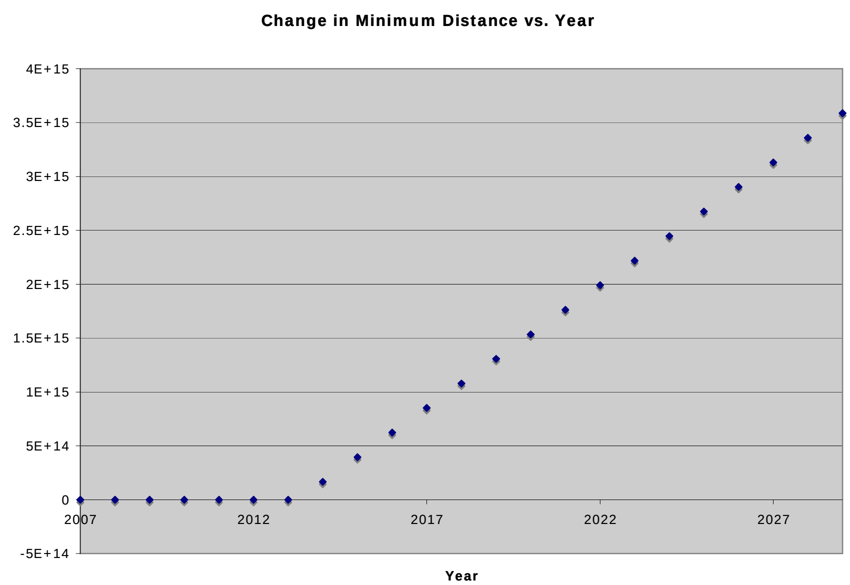

Figure 7: Deterministic Change in Minimum Distance for an Impactor Mission

[§§] It is important to realize that this calculation is for an implementation date of 12/14/2012, which was chosen for its proximity to Earth and therefore its minimum time of travel (and hence cost). However, it is very possible that implementing the same thruster in the same direction on another date may have a positive effect; this is another possible area of further study.

C. Explosion Deterministic Mitigation Results

Similarly, a deterministic change in the minimum distance for the standoff nuclear explosion of a 15 Mton warhead at a given height above the NEO is shown in *Figure 8*. Clearly, it is not beneficial to explode a nuclear weapon at some distance from Apophis imparting the momentum vector described in this paper because the minimum distance in 2029 is reduced by 200 million meters. Of course, an explosion imparting a momentum vector in another direction could have a markedly different result, yet either the same momentum or velocity vector component coefficients are used for the scenarios of explosion, mass driver and thruster so that they can be compared to one another.[****] However, just as with the thruster, there is a possibility that an optimization of the direction of momentum vectors imparted to the asteroid so as to give maximum change in minimum distance could save this type of mitigation technique from technical nonviability.[***]

D. Mass Driver Deterministic Mitigation Results

Finally, the mass driver is also analyzed deterministically and the results of such analysis are shown in *Figure 9*. In this case, the mass driver is operated for 5 hours at the rate of ejection (100kg/hr) and the speed of ejection (100m/s) quoted above. It is clear from this figure that the mass drivers designed to perform the excavation and ejection of material in the way specified are clearly sufficient to alter the course of Apophis with more than sufficient distance between it and Earth. Additionally, even though the profile of *Figure 9* is very similar to that of *Figure 7* there is no initial reduction of the distance between Earth and Apophis in 2013, as there had been with that of the impactor.[†††]

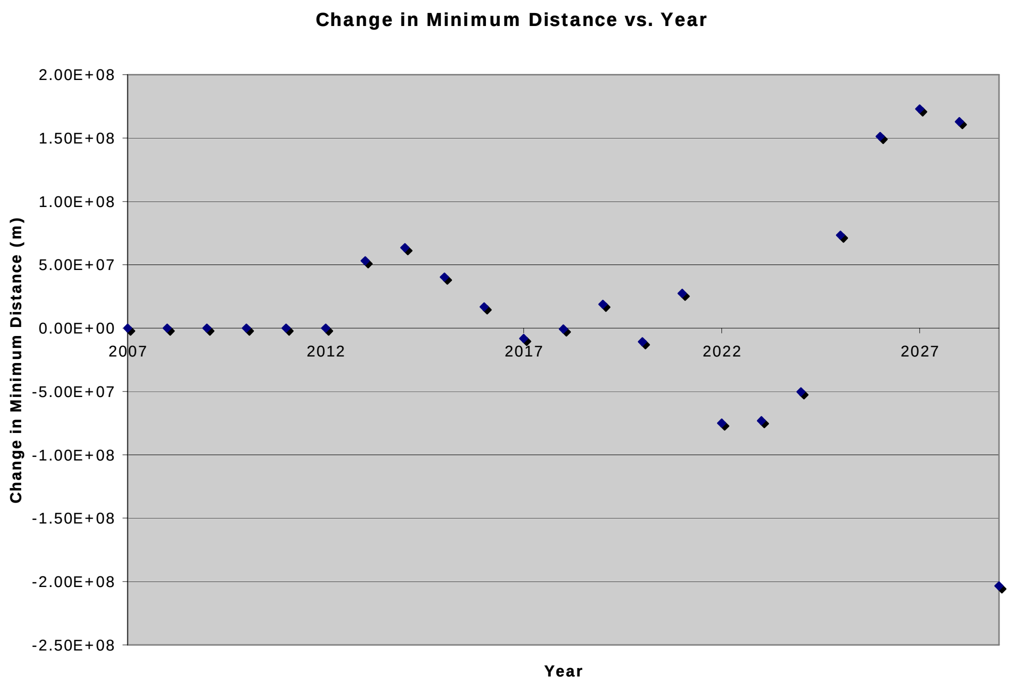

Figure 8: Change in Minimum Distance from a Nuclear Explosion

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[****] Impactor is the only scenario that does not have the same velocity vector coefficients because the magnitudes of each of the components were taken from the Deep Impact mission.

[***] Just as with the thruster, this calculation could have quite different results for a different implementation date. However, the 12/14/2012 implementation date was chosen for its proximity to Earth (and therefore its reduced travel time and cost), therefore such an issue remains as an area of possible further study.

[†††] This is for the case where the explosive energy is velocity-scaled to that of Deep Impact.

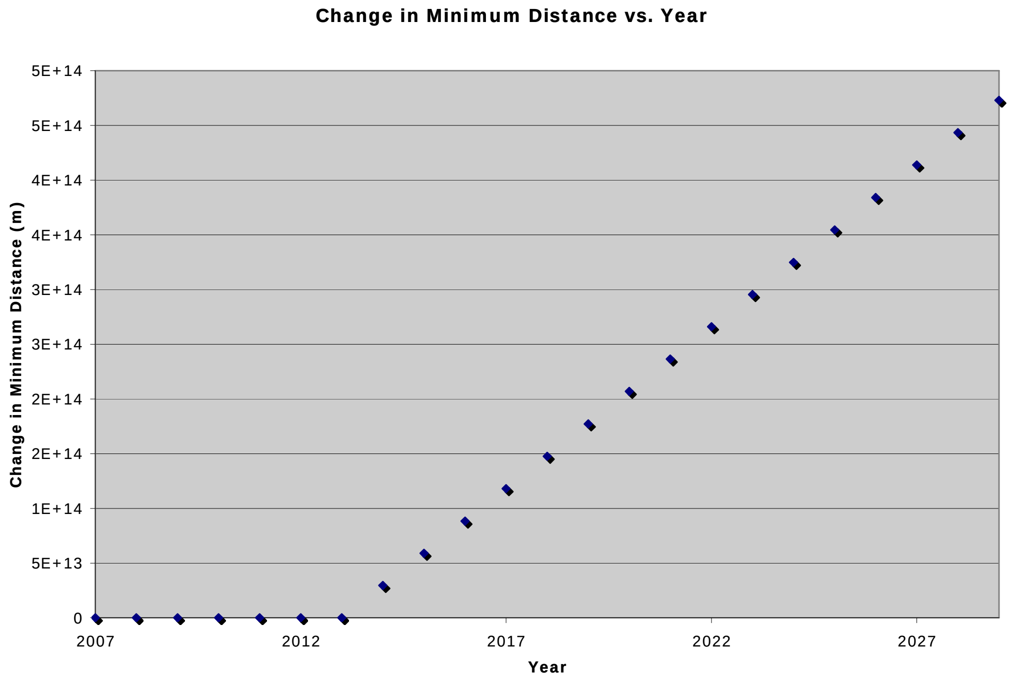

Figure 9: Deterministic Change in Minimum Distance for Mass Driver

E. Probabilistic Comparison of All Mitigation Techniques

Even though the deterministic calculations clearly show the benefits of some techniques over others, for the case of Apophis, there could be instabilities in these configurations that when perturbed lead to a drastic change in the significant FOM, the minimum distance between Earth and Apophis. Thus a probabilistic analysis is necessary to determine what, if any, factors exist that could effect a particular mitigation system.

The ranges of uncertainties for the considered mitigation techniques are shown in Table 3. It is important to note that these are subsystem level metrics that are to be the goals of any of these particular mitigation techniques. Yet since there may be some inabilities to meet the exact values of these design variables (as they were quoted in Section IV), the uncertainties inherently possible for each of the mitigation subsystems are considered via the ranges shown in *Table 3*.

Table 3: Design Variables and Their Ranges of Uncertainty

Design Variable	Units	Low	High
No. of Warheads	none	1	5
Explosive Energy	Mton	5	25
Mass of Impactor	kg	320	420
V_ImpactorX	m/s	1.40E+04	2.30E+04
V_ImpactorY	m/s	-1.70E+04	-8.00E+03
V_ImpactorZ	m/s	-2.00E+02	-1.20E+02
Running Time	hours	1	10
M_PropellantX	kg/hr	80	120
M_PropellantY	kg/hr	80	120
M_PropellantZ	kg/hr	80	120
V_Propellant	m/s	80	120

By generating a Response Surface Equation (RSE) of the overall minimum distance as a function of the listed design variables, a surrogate model of the PDS model can be used to perform rapid probabilistic analysis, since the runtime of each calculation takes about 15 minutes. The accuracy of the surrogate models is determined with the usual monitoring of R-squared values, actual vs. predicted plots, residual vs. predicted plots and finally assessing the error distribution of the surrogate model. Once a surrogate model has been created, the coefficients of the now existing functional relationship between design variables and the response (overall minimum distance) can be imported to Crystal Ball, in which 10000 cases of values of the design variables between the given ranges can be calculated. Thus the uncertainty in any of the design variables can be assessed from the point of view of its effect on the overall minimum distance in this way; this is how *Figure 10* was generated.

As shown earlier, the explosion technique is still an infeasible solution according to the choice of the coefficients of imparted momentum used in this simulation. Also, the impactor has withstood the uncertainties in its mass[‡‡‡] and the various changes in velocity in each of the three coordinate directions. The inconsequential variation in its overall minimum distance is indicative of the fact that any variations of the impactor's design variables within the ranges prescribed in *Table 3* will not bring Apophis closer to Earth than the 2029 unmitigated close approach distance.

The mass driver and the unmitigated cases are solid lines because for the latter case there are no design variables to change, while for the mass driver, its performance is quite literally 'off the charts' so that the overall minimum distance occurs in the year of mitigation implementation. In other words, from 2013 forward, there is nothing but benefit from the mass driver technique, therefore any changes in the design variables[§§§] yielded insignificant effects on the potency of such a technique.

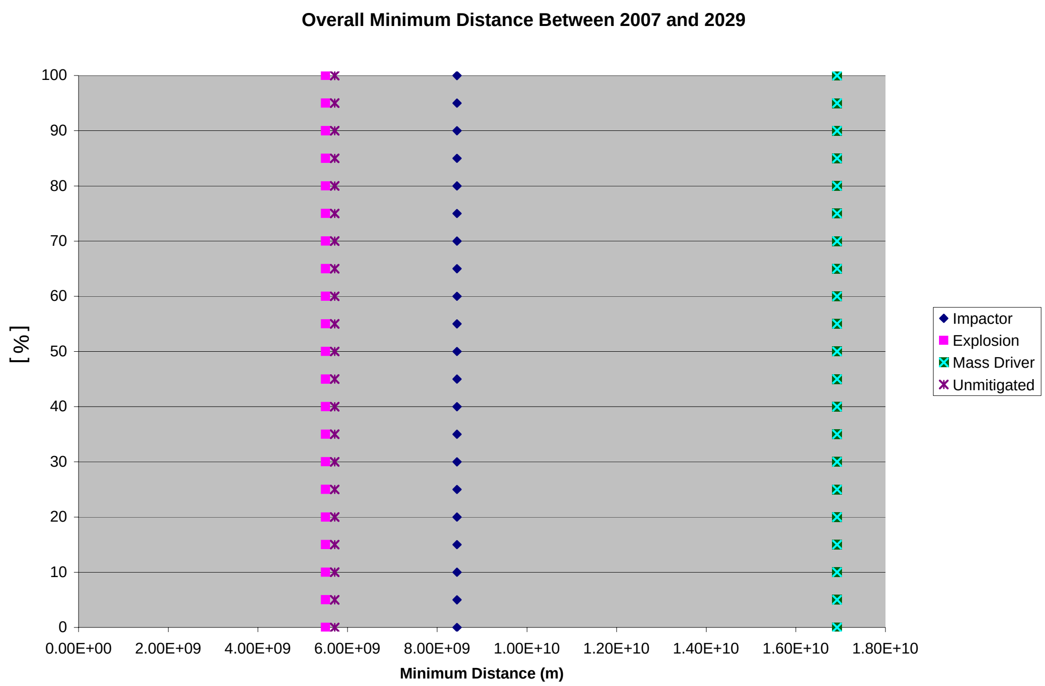

Figure 10: Probabilistic Analysis of Overall Minimum Distance Due to Uncertainties in Design Variables

While uncertainties in the design variables[###] are quite likely, there are uncertainties in the NEO trajectory that can be acknowledged as well. This is in fact the aim of future calculations, but the key to determining these uncertainties amounts to determining the observational error, which involves a study beyond the scope of this paper.

‡‡‡ Such uncertainties could arise because of unexpected weight increases on its launch vehicle.
§§§ Except for making the running time equal to zero hours.

Or better yet, the abilities of the subsystems to meet these performance goals.

VI. Conclusion

There is clearly a threat posed by the 2029 close approach of Apophis, not only because of the non-zero chance of impact in that year but also, because of the possibility of it setting the stage for a 2036 impact. A Planetary Defense System (PDS) model prototype has been designed to analyze mitigation options for this scenario; however, it is also applicable to most other PHOs observed in the solar system. The probabilistic and deterministic analyses show a strong chance for both an impactor and a mass driver mission to be beneficial to reducing the likelihood of an Earth-Apophis collision. Furthermore, in the case of the impactor option, the Deep Impact mission has already proved its technical feasibility in terms of implementation. Thus there is an added certainty in the validity of the calculations done for the impactor technique that does not exist for the overwhelmingly effective mass driver option.

Further research will focus on the incorporation of the detection system into the already existing PDS model prototype, as well as improvements to the currently existing model. Finally, with a quantitative account of current detection abilities, it will then be possible to develop a sound relationship between the cost and safety regarding the probabilistic design of a Planetary Defense System.

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References

[1] Gennery, D., “Deflecting Asteroids by Means of Standoff Nuclear Explosions,” 2004 Planetary Defense Conference, AIAA 2004-1439, Orange Country, CA, 2004, pp.

[2] Olds, J., Charania, A., Graham, M., Wallace, J., “The League of Extraordinary Machines: A Rapid and Scalable Approach to Planetary Defense Against Asteroid Impactors,” NASA CP-NIAC 02-02, 30 April, 2004.

[3] “Apollo Systems Descriptions” Vol. II, URL: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710065502_1971065502.pdf [cited 15 January 2007].

[4] Yeomans, D., HORIZONS Web-Interface [online database], URL: http://ssd.jpl.nasa.gov/horizons.cgi#top [cited 15 January 2007].

[5] Deep Impact Technology [online database], URL: http://deepimpact.jpl.nasa.gov/tech/impactor.html [cited 15 January 2007].

[6] European Asteroid Research Node [online database], URL: http://earn.dlr.de/nea/099942.htm [cited 15 January 2007].

[7] National Geographic: Asteroids: Deadly Impact, 1997.

[8] “Cost of Katrina is Expected to Break Records.” URL: http://www.washingtonpost.com/wp-dyn/content/article/2005/08/31/AR2005083102395.html [cited 28, January 2006].

[9] “Asteroid Watch: Odds of 2029 Collision Stuck at 1-in-40.” URL: http://www.space.com/scienceastronomy/asteroid_update_041227.html [cited 8 February 2006].

[10] Near Earth Object Program [online database], URL: http://neo.jpl.nasa.gov/risk/a99942.html [cited 8 February 2006].