

GENETIC ALGORITHMS FOR GNC SETTING AND DACS DESIGN APPLICATION TO AN ASTEROID KINETIC IMPACTOR

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ABSTRACT

This paper deals with an application of Genetic Algorithm tools in order to perform and optimize the settings phase of the GNC data set for the endgame phase of a Kinetic Impactor targeting a medium-size Near Earth Object. A coupled optimization of the GNC settings and of the GC-oriented design of the Divert and ACS propulsive system is also proposed. The illustration of the developed principles is made considering the NEOShield study frame.

Keywords: *Genetic Algorithms – Kinetic Impactor – Planetary Defence – Endgame phase*

1. INTRODUCTION

The collision probability with the up-to-now listed Near Earth Objects (or NEOs) is assessed to be small, but not null, and the impact with a small to medium-class asteroid (50 m to 100 m in diameter) could be catastrophic. Even if such event is not highly likely in a near future, preparing the technologies aiming at mitigating such event appears obvious when looking back, for example, at the damages generated by a 20 m diameter meteor that exploded over Chelyabinsk.

Within the frame of the NEOShield activities of the FP7 program funded by the European Council, a consortium of scientific and industrial partners has been set to assess different mitigation techniques: destruction by a surface or an underground nuclear blast or deflection using ion-beam propulsion systems, gravity or solar sail tractors but also kinetic impactor. Among these different techniques, and as more or less already experienced during the Deep Impact mission (head-on collision with the Tempel 1 comet), the most promising one seems to be the kinetic impactor. The main reasons for choosing this solution are first the lower complexity of the intercept / impact mission compared to the other solutions, and then the possible reuse of technologies developed within the frame of missile defence program. By comparison with a missile defense intercept mission, the mission requirements are relaxed with a final miss-range between 25 and 50 m. But the stress is put on the Navigation side: a long range (NEO acquisition may be done up to 24 hours before impact) and very narrow field-of-view visible camera (only ± 0.3 deg) is used to acquire and track the NEO until impact. Refurbishing existing GNC solutions that were extensively assessed during past exoatmospheric intercept analyses, 6 DOF Monte-Carlo simulations performed on a set of 4 endgame missions (from very optimistic to very pessimistic kinematic conditions at endgame handover: 30 km up to 600 km initial miss-distance) and for 2 classes of liquid-fuelled Divert and Attitude Control System, or DACS, (200 N or 3500 N divert) produced interesting results almost fully in line with the mission requirements for most of the cases ^[1]. The most tricky and time-consuming task to get such GNC performance level was to tune all the GNC data: Guidance and Control internal data and especially the 8-state Extended Kalman Filter parameters, the EKF objective being to estimate the miss-distance and the time-to-go

using only LOS angle measurements whereas miss-distance and time-to-go become well observable only very late.

In order to ease the GNC setting phase (up to 15 parameters have to be set) but also to optimize, if needed, the DACS definition (5 additional tuning parameters), a dedicated process relying on Genetic Algorithms (GA) has been implemented. Considering as reference baseline the Monte-Carlo results obtained during the NEOShield activities, this paper presents the impact on the GNC performance of a GA setting of the GNC chain for a fixed DACS design (medium or high thrust), and of a coupled GNC setting and DACS design optimization over the same set of endgame missions. The first part of this paper is dedicated to a quick survey of the NEOShield framework and of the GNC chain retained for the medium to high thrust DACS kinetic impactor and its performance. Next, the GNC performance as obtained at the end of the NEOShield is presented. Then, the GA-based process enabling an autonomous and robust setting of the GNC data and, if selected, a global optimization of the GNC data set and of the DACS main features is presented, and a comparison between “handmade” and GA settings is proposed relying on 6 DOF Monte-Carlo simulations results.

2. NEOSHIELD FRAMEWORK

One of the objectives of the NEOShield program was to investigate different NEO mitigation solutions. Among them, the kinetic impactor, or KI, appeared to be the most realistic one because of the potential heritage of exoatmospheric missile defence activities. Namely, the major differences between missile defence and planetary defence endgame tasks that are given to the interceptor / impactor are essentially a matter of scale factor:

- the acquisition by the on-board sensor of a NEO can be made up to 24 hours before impact but no more than a few hundreds of seconds for an incoming warhead;
- the expected final miss-range lays in the range of 25 m to 50 m for a medium-size NEO, but only a few tens of centimeters for a warhead (direct hit objective). For a missile defence kill vehicle, the objective of the endgame phase is to destroy its target, whereas for a kinetic impactor we only need to push it, the kinetic energy transfer acting directly on the orbital parameters of the NEO interplanetary path. Considering that the NEO impact occurs millions of kilometers away from Earth, even a very small ΔV induced by the KI impact can be enough to deviate the NEO's trajectory away from Earth;
- the initial miss-distance at endgame handover can be very large for a NEO, a few tens of kilometers; whereas it is much less for a missile defence interceptor. But because of the extended endgame duration, such extra initial miss-distance can easily be managed;
- the closing velocity on a NEO can be very high, up to several tens of km/s for a head-on collision. But if we limit the engagement scenarii to only pursuit the lateral configuration with prograde collision route, it is possible to keep the KI-NEO closing velocity (11.6 km/s for the retained scenario) to values similar to some ABM configurations. The next figure summarizes the main engagement conditions considered within the frame of the NEOShield activities.

The next figure illustrates a typical impact mission on a threatening asteroid.

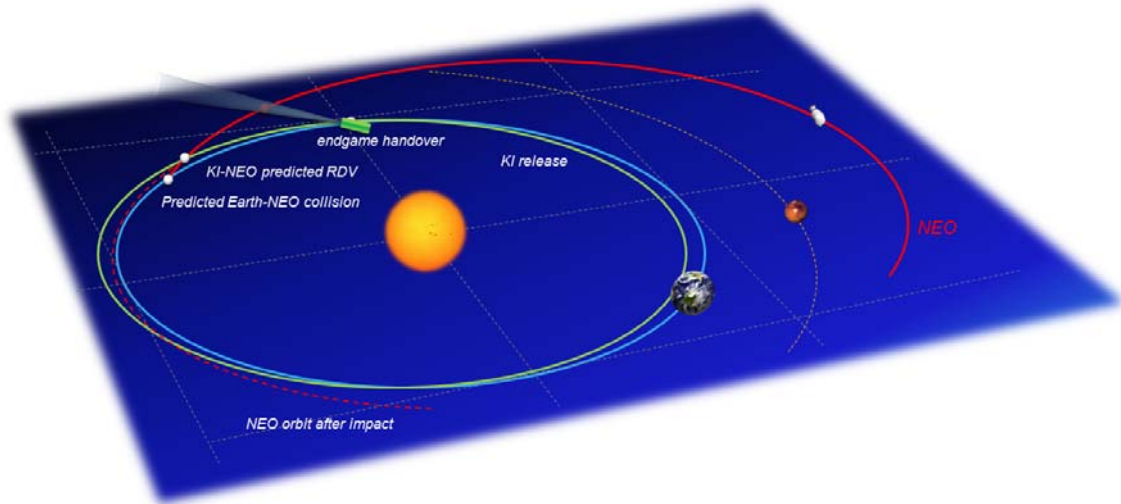


Fig. 1: NEO mitigation using a Kinetic Impactor

Doing so, reusing already investigated GNC algorithmic solutions as well as propulsive architecture (a liquid-fuelled DACS system is the baseline) can be considered to assess the feasibility of the NEO impact mission. Because of the very long range NEO acquisition by the on-board camera, there is no real need for a powerful divert system as it could be required for an exoatmospheric interceptor. Within the NEOShield framework, 3 DACS concepts have been considered relying on a 20 N (satellite-like AOCS engine), a 200 N (ACS engine from the ATV, right image of figure 2) and a 3500 N divert (MPS engine from the HOMER test platform ^[2], left image of figure 2).



Fig. 2: HOMER MPS and ATV ACS propulsion firings

This paper concerns only the medium (200 N) to high thrust (3500 N) level divert solutions that allow a reduced endgame phase. The nominal data of the DACS system are as presented in the next table.

	Divert	ACS (yax & pitch axes)	ACS (roll axis)
medium thrust KI	200 N	20 N	10 N
high thrust KI	3500 N	175 N	90 N
firing period	250 ms	50 ms	50 ms

With such propulsive characteristics, the endgame phase can be entered much later than with the 20 N satellite-like solution leaving more time for observing the asteroid and increasing the performance of the aimed point selection phase, see figure 3 for the corresponding GNC timeline.

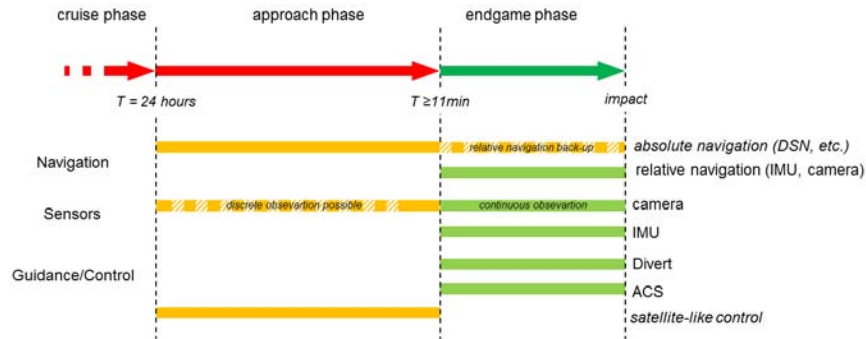


Fig. 3: GNC timeline, medium to high thrust diver KI

Within the frame of the NEOShield GNC activities, only the endgame phase is simulated (dedicated 6 DOF simulation tool). Thus, for simulation purpose, in order to ease the convergence of the Navigation filter for estimating the initial miss-distance, an observation phase (minimum 50 s) is added to the previous timeline at the beginning of the endgame phase. During this preliminary phase, only KI attitude corrections are performed.

The main point with respect to the design objective is to locate the nominal COG of the vehicle centered in the Divert positioning plane (4 thrusters aligned on yaw and pitch axes) in order to limit disturbing torques that would be generated by the divert firings with COG off-centering and/or thrusters misalignments. The ACS which is located at the back of the vehicle is designed with 4 thrusters for the pitch and yaw control, and a set of 4 others smaller thrusters for the roll control, see next figure displaying a very schematic view of the KI design.

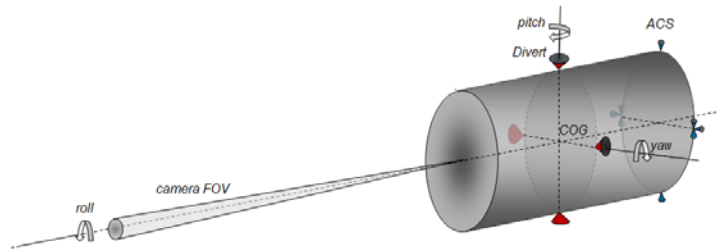


Fig. 4: Kinetic Impactor simplified model

The next tables summarize the main features of the KI (550 kg class vehicle).

Parameter	value
S/C mass	550 kg (at impact)
S/C size	cylinder 3.8 m height and 1.97 m diameter
S/C inertia	2140 kg.m ² (yaw and pitch axes) 770 kg.m ² (roll axis)
COG excursion	max ±10 cm longitudinal deviation max ±5 cm transverse deviation

The main on-board sensors are a LORRI-type narrow angle visible camera (± 0.38 deg field-of-view) and a SIRU inertial measurement unit from Northrop Grumman.

For the medium to high thrust divert KI, the main features of the endgame mission to perform are defined by the time-to-go T , or time remaining before impact, and the miss-distance M , or predicted final miss-range with no further KI trajectory correction, from very optimistic (scenario 1) to very pessimistic (scenario 4) conditions at endgame handover.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
$M_0 \text{ max } (3 \sigma)$	30 km	90 km	200 km	600 km
$T_0 \text{ nom}$	700 s	1500 s	3300 s	10300 s

The baselined targeted final miss-range is 50 m (99.7 % value) but for smaller NEO, a 25 m final miss-range might be required (secondary objective).

3. GNC CHAIN FOR THE ENDGAME PHASE OF A KINETIC IMPACTOR

For a kinetic impactor, the Guidance, Control and Navigation objectives are as listed hereafter:

- the Guidance is in charge of cancelling out the miss-distance, i.e. the predicted final miss-range, and to ensure that it will be null, or below the mission requirement, at the time of impact;
- the Control is in charge of pointing the strapdown camera onto the target and keeping the image of the target centered on the seeker focal plane. A secondary but essential objective is also to limit the dynamic disturbances (angular shifts and angular rates increases) induced by the divert firings. A third objective is eventually to limit the gyroscopic torques and to keep the roll rate as low as possible;
- last but not least because it will be the main driver for the GNC performance, the Navigation is in charge of feeding the Guidance and Control functions with accurate estimates of the miss-distance M and the time-to-go T (Guidance) and the LOS angles, LOS and YPR rates (Control). Within the frame of this study, we will rely on a simplified performance model of the sensor: point-mass model for the target, no sub-pixel processing and approximately a 1 s terminal blinding phase.

Without getting into the details of the GNC algorithms, the Guidance relies on differential games theory (even if the target is not maneuvering, the miss-distance estimation errors or the divert discrepancies can be regarded as pseudo-maneuvering capabilities of the target). Such guidance algorithm that defines in flight autonomously the divert firings is well suited to manage the final accuracy (to get $M = 0$ m at $T = 0$ s), the fuel budget and the performance of the Navigation function by building command barriers in the (M, T) space, splitting the (M, T) space in predefined command zones. The next figure illustrates the behavior of the DG guidance algorithm (scenario 1). The initial 50 s observation time period is needed for the convergence of the relative navigation filter, the approach being not simulated.

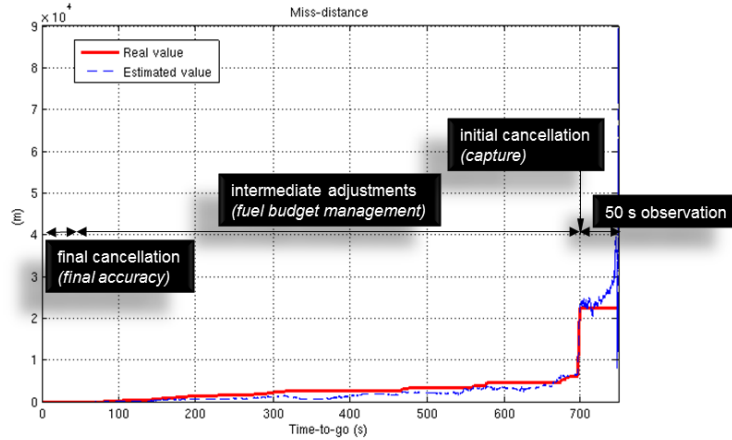


Fig. 5: DG guidance operating mode

The main setting parameters of the guidance are mainly linked to the consumption barrier that is added to the command barriers when an indetermination occurs in the choice of the command to apply (we are using a pulsed-mode divert). And a stop criterion of the guidance is added in order to limit potential degradation on the miss-distance due to a slow and late convergence of the time-to-go in parallel of a quick divergence of the LOS rate due to the KI-NEO closing at the very end of the endgame phase. The consumption barrier is modeled by a scaling factor k_G ranging from 0 to 1, that is linearly time-to-go dependent from T_0 till $T_0 - \Delta T_G$ and then constant. The stop criterion is defined by a time-to-go (T_{off}) and/or a miss-distance (M_{off}) condition.

The Control is decoupled into a minimum time command with limit cycle on the pitch and yaw axes for the LOS control, and a simple bang-bang regulation of the roll rate for limiting the gyroscopic torques. The next figure illustrates the behavior of the pitch and yaw control algorithm, with a tracking zone limited to ± 0.03 deg.

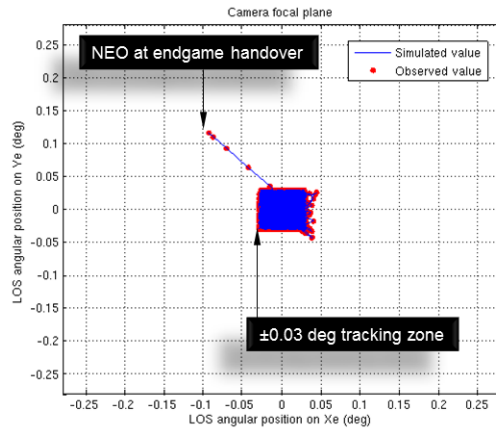


Fig. 6: Minimum time with limit cycle Control operating mode (w/ fixed tracking zone)

The Control settings parameters are directly linked to the angular size of the limit cycle that defines the tracking sub-matrix inside the seeker focal plane and the maximum roll rate triggering roll firings. As for the guidance, and mainly to limit the ACS budget, the size of the tracking zone is assumed linearly decreasing from endgame handover till $T_0 - \Delta T_C$, and then constant beyond.

Eventually, the Navigation objective is mainly to estimate the miss-distance and the time-to-go using only LOS angle measurements via the visible camera. An absolute Navigation relying only on the

IMU data is always active, and a relative Navigation using both IMU and camera is enabled once the target has been locked on, ground stations telemetry data being used only to perform Trajectory Correction Maneuvers before being in sight of the asteroid (up to 24 hours before impact). Thus, once the endgame phase is entered, the KI is fully autonomous, and it uses only the relative navigation outputs, the absolute navigation which is still running being just a back-up solution. The relative Navigation relies on an 8-state extended Kalman filter (LOS and LOS rate components, YPR rates and time-to-go), LOS components and YPR rates being measured. The next figure illustrates the behavior of the EKF wrt the most important parameters that are given by the LOS rates components and the time-to-go which are directly used to evaluate the miss-distance under the simplifying assumption of a constant closing velocity. When the EKF is well tuned, the terminal divergence that can be observed on the LOS rates in the last 100 to 50 s of the endgame phase is normally compensated by the convergence of the time-to-go which occurs only late due to the difficulty to estimate a radial distance (the time-to-go) using only transverse distance measurements (the LOS angle components).

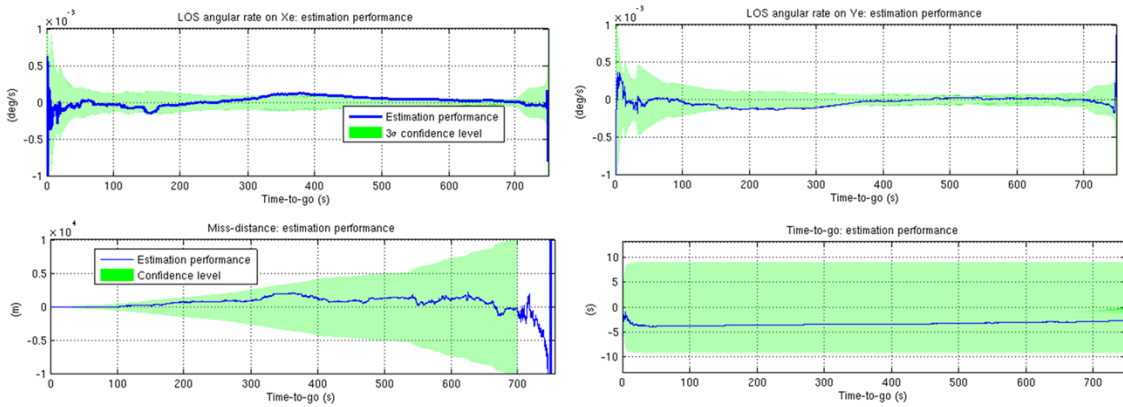


Fig. 7: EKF vision-based relative navigation operating mode

Because the performance of the relative Navigation will directly drive the GNC performance, its tuning is the trickiest part of the GNC activity, once the GNC algorithms have been designed, implemented and unitary validated. The set of settings parameters is also much larger than for the Guidance or the Control because it considers the initial value of the covariance matrix and the modelling noise standard deviations arising from the linearization and discretization steps of the state model (camera and IMU measurements are discrete whereas the KI-NEO state model is continuous).

4. GNC PERFORMANCE WITH CLASSIC HANDMADE GNC TUNING

First, the feasibility of the impact mission was demonstrated in the optimal but nonrealistic case of an ideal Navigation function (the KI-NEO state vector is estimated without any error) with a 100 % hit probability and for a final miss-range always below 3.5 m. Next, the GNC setting phase has been refurbished to handle the discrepancies introduced by the real performance of the relative navigation. After many trial-and-errors settings with a continuous increase of the performance, the settings process has been stopped to yield the GNC performance as summarized by the next figure.

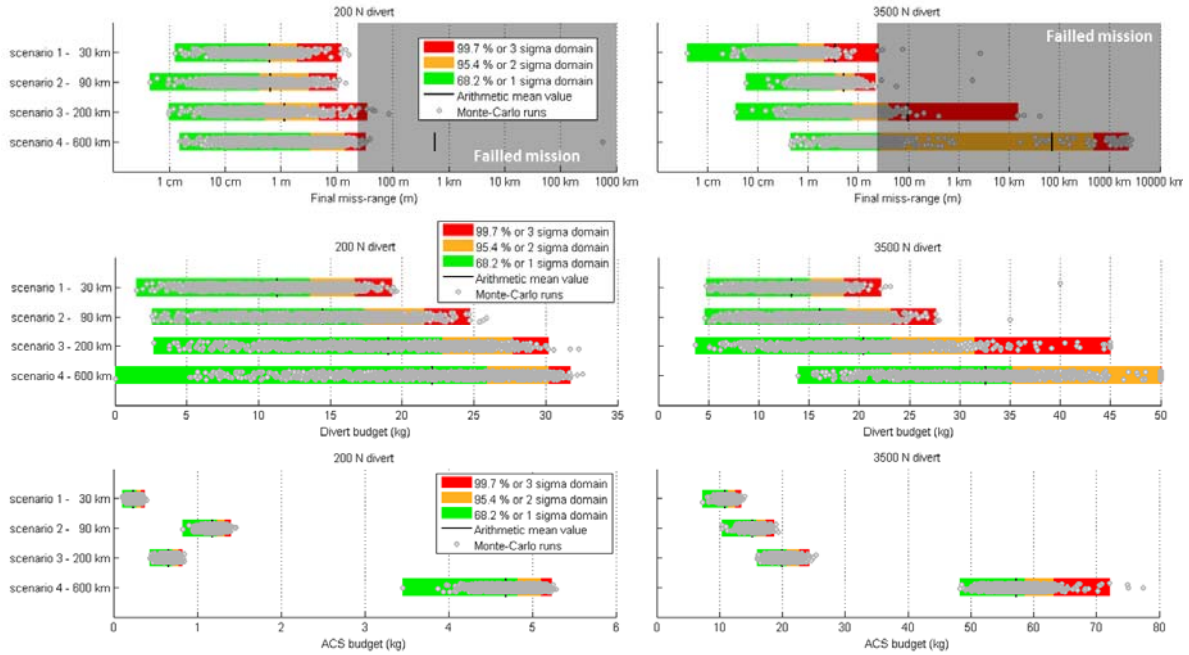


Fig. 8: GNC performance, handmade GNC settings

The next table summarizes the corresponding hit probabilities for a 50 m and a 25 m final miss-range objective.

	Phit 50 m		Phit 25 m	
	200 N	3500 N	200 N	3500 N
scenario 1	100.0 %	99.8 %	100.0 %	99.7 %
scenario 2	100.0 %	99.8 %	100.0 %	99.7 %
scenario 3	99.9 %	97.5 %	99.6 %	92.3 %
scenario 4	99.9 %	86.1 %	99.3 %	67.0 %

The mission requirement expressed towards the so-termed 3σ 50 m hit probability is almost met for the 200 N whatever are the initial endgame conditions (a longer investment in the tuning phase should yield such result: there is no reason for having a 99.8 % success rate with the scenario 4 but only 99.5 % with the scenario 2 which is less stressing). Such success rate is degraded for the 3500 N KI configuration, especially on scenario 4 for which the image of the target is lost shortly after the first divert firings due to a too weak ACS, the ACS firing period (50 ms) being constrained by the CPU time of the image processing (sizing hypothesis). In those cases, the Guidance lives only on the prediction of the target motion yielding in most of the simulated cases a final miss-distance well over the initial one.

The secondary mission objective (25 m hit probability at 3σ) is also almost fulfilled for the 200 N case what is far to be true for the 3500 N case whose mean 25 m hit probability is around 97 %, except for the scenario 4 for which it drops down to less than 70 %.

Nevertheless, because of the continuous improvement of the GNC performance and even if the main mission requirement is not fully met, the obtained results with a handmade but also time-limited GNC settings process opened the way to a potential improvement of the performance through an optimization of the GNC data set.

5. GNC SETTINGS WITH GENETIC ALGORITHMS

In order to shorten the settings phase process, but also to try to optimize it and to enhance the GNC performance, an automated process has to be implemented. According to some previous experience in that domain for roughly similar problems ^[3], the retained optimization process is based on genetic algorithms, or GA. Indeed, it may be a good candidate to solve such a complex problem as long as the optimization problem has been well set and the optimization criterion well defined. For our current application, the DACS propulsive design (i.e. thrust level, firing period) is frozen, even if the ACS appears slightly undersized for the 3500 N divert configuration as explained above. The optimization problem to solve is then to find the GNC data set (15 parameters to tune: 3 for the Guidance, 4 for the Control and 8 for the Navigation as presented in section 3) enabling the fulfilment of the mission requirement expressed towards the hit probability for the 4 scenarii and per KI configuration. Because of the various conditions at endgame handover, the optimization of the GNC data will be performed scenario per scenario at this stage of the project. If improving the performance goes naturally through the increase of the hit probability, one will try to minimize the fuel budget that was initially not constrained in the previous part of the study. This additional constraint helps in differentiating potential solutions for the Guidance and Control data set, the objective of the time-evolution of the scaling factor k_G as well as the size of the tracking sub-matrix aiming to limit the divert and ACS fuel budgets.

The performance of the Guidance is directly linked with the divert fuel budget and the final miss-range at impact. The performance of the Control, that will partially drive the performance of the Guidance, is defined by the limitation of the fuel budget and the ability to keep the image of the target well inside the tracking sub-matrix all along the endgame phase. Some transient excursions out of this tracking sub-matrix are enabled as long as the Control is able to put it back inside this reduced field-of-view. But defining a performance index for the Navigation is less obvious as it is the whole behavior of the navigation filter all along the endgame phase that will drive the performance of the GNC chain: terminal values may be well estimated with only a few errors, if the so-termed 3σ confidence interval has been violated too many times before impact, Guidance and Control will have fired too often the DACS thrusters yielding a too large fuel consumption and possibly a poor final miss-range. The performance of the Navigation function is thus modeled via the offset between the estimated error and the 3σ confidence interval barrier (upper or lower barrier according to the sign of the estimated error).

In order to make it as simple as possible, the objective function to be minimized by the GA process has been defined, after many trials, as an algebraic sum of elementary weighted performance indices c_i as:

$$F_{obj} = \sum_{i=1}^n w_i \cdot c_i$$

For illustration purpose, the objective function retained in the end for scenario 1 is the following one, all the red printed values highlighting the parameters/weights that are modified from one scenario to the other one.

$$F_{obj} = 1000c_{1_{mean}} + 20c_{1_{max}} + (100 - c_2)^3 + 20c_3 + 150c_4 + 100\text{abs}(c_5) + \frac{c_6}{3} + \left(\frac{c_7}{3}\right)^3 + 500c_8 + 500c_9$$

with the elementary cost functions c_i as depicted in the next table and ranked by order of importance:

Cost function	criterion
c_1	Final miss-range
c_2	Success rate (i.e. 50 m hit probability)
c_3	Divert fuel budget
c_4	ACS fuel budget
c_5	Estimated final time-to-go
c_6	Miss-distance estimation error at the end of the initial convergence phase
c_7	Number of NEO images lost by the sensor (over the endgame phase)
c_8	Time-to-go estimation error (from end of initial convergence phase till impact)
c_9	Miss-distance estimation error (from end of initial convergence phase till impact)

For the performance index linked to the miss-distance, we consider the mean value of the final miss-range ($c_{1,\text{mean}}$) as well as the maximum one ($c_{1,\text{max}}$).

In addition to tuning the GA process (number of individuals, epochs, selection, crossover, mutation and reinsertion processes, etc.), one of the difficulties of using genetic algorithms is to define the objective function and the associated weights. For instance, the settings of the objective function for scenario 1 or scenario 4 are very different.

All the results presented hereafter have been obtained considering the following GA tuning:

GA step	method
selection	Stochastic universal sampling
crossover	Intermediate recombination (80 % recombination rate)
mutation	Breeders-like real-valued mutation (5 % mutation rate)
reinsertion	Global reinsertion (70 % insertion rate)
migration	Not considered

The number of epochs has been fixed at 50 (no convergence criterion has been considered to stop the GA process), for 50 individuals with 4 chromosomes (G, N, C settings and GNC performance) for a total of 15 genes per individual. The objective function is evaluated for each individual over a limited Monte-Carlo process including 50 runs each, with every time a new drawing of the dispersions and uncertainties. It has to be noted that migration between sub-populations has been investigated but without any real conclusive results. In the end, it has been discarded from the GA baseline.

The next figure depicts the implementation of the GA process and the interaction with the 6 DOF SpaceShield simulation tool (red boxes when used).

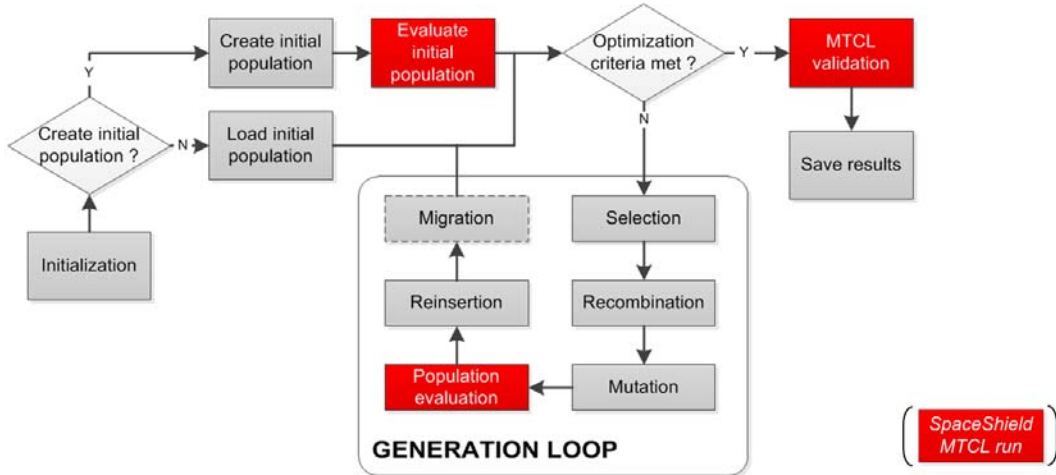


Fig. 9: SpaceShield simulation tool and GA implementation

Because the step before the GA process implementation was a handmade trial-and-error setting of the GNC data, we loaded as initial population the results obtained during that first step, but a pure random initial population could have been considered.

Unfortunately and mainly for a simple question of computation time (no less than 7 days computation for the GA process applied to scenario 4, for a single optimization of the GNC data), the optimization of the GNC data for the scenario 4 has been stopped because of a poor convergence process (see comparison of the time-history of the cost function for scenarios 1 and 4 on next figure) and no significant improvement of the GNC performance obtained with a trial-and-error handmade setting. For illustration purpose, the next figure presents the evolution of the fitness per individual and per epoch for the scenarios 1 and 4, with the same GA settings except the objective function.

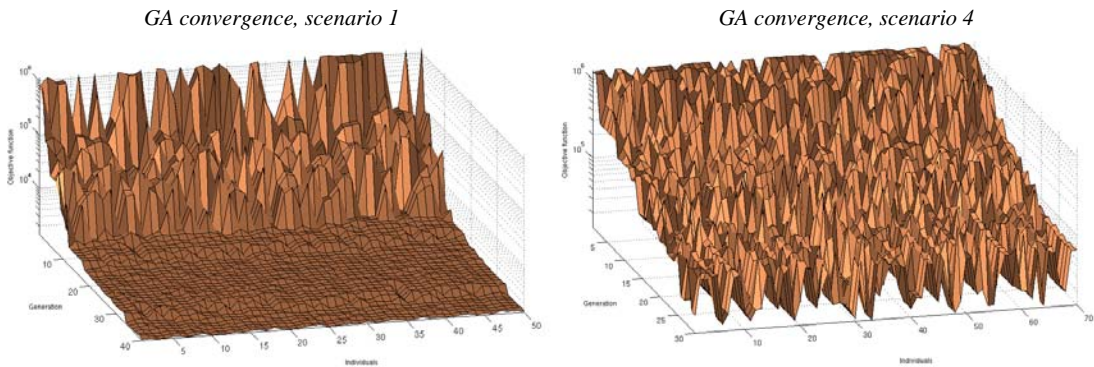


Fig. 10: GA convergence for extreme scenarii 1 and 4

We can observe a rather quick convergence, only 10 epochs being enough to get the convergence for scenario 1 whereas 50 epochs are clearly too few for scenario 4 with very different terminal values per individual.

The scenario 4 being the most pessimistic one and the less probable one, it was decided to focus only on the 3 first scenarios.

The next radar plots display a comparison between the initial handmade and the optimized GA setting of the GNC data for the 200 N and 3500 N divert cases (the smallest the surface, the better performance). The retained 5 comparison criteria are:

- the 99.7 % (or 3σ value) final miss-range;
- the divert fuel budget;
- the ACS fuel budget;
- the 99.7 % (or 3σ value) final time-to-go (one recalls that the objective of the guidance is to null the miss-distance at $T = 0$ s)
- and the failure rate expressed with respect to the number of simulated cases (1000 runs Monte-Carlo are considered) yielding a final miss-range over 50 m (the 25 m hit probability is only a secondary objective not retained at his level of comparison).

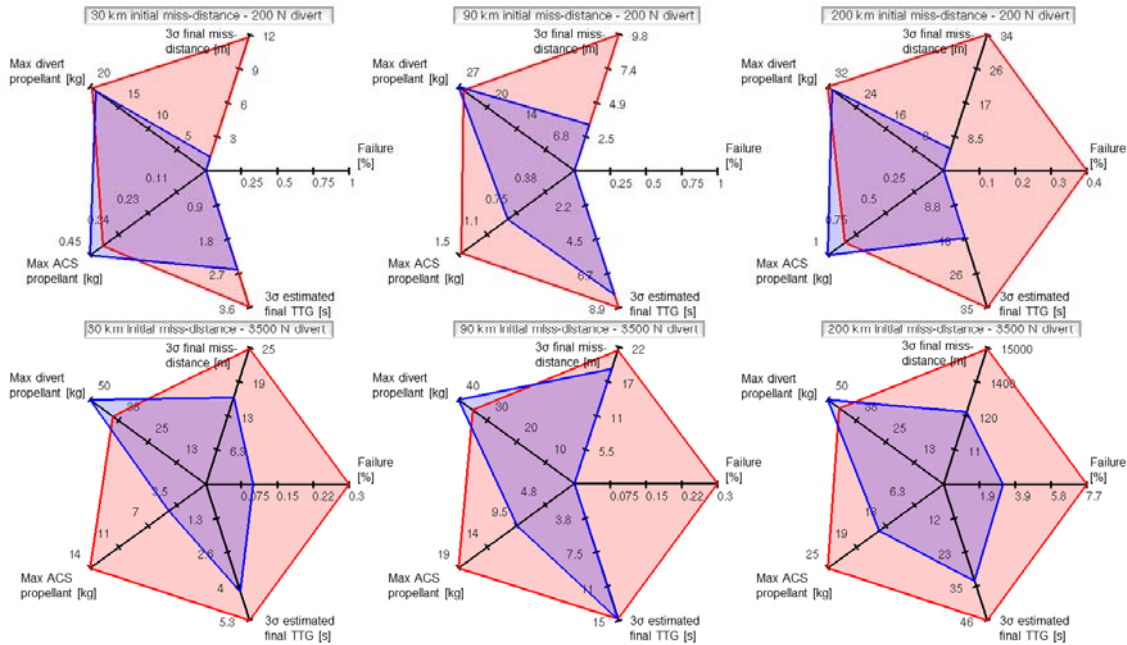


Fig. 11: Handmade vs GA GNC settings

It is clear here that the GA process is able to optimize the GNC performance acting on the GNC data set even if in some cases, the maximum divert consumption may be larger than with the handmade tuning. But if we analyze the 50 m or 25 m hit probabilities obtained on the final 1000 runs Monte-Carlo runs, we get the results summarized in next table.

Scenario	Setting method	200 N divert		3500 N divert	
		Phit _{50 m}	Phit _{25 m}	Phit _{50 m}	Phit _{25 m}
1 (30 km, 3 σ)	handmade	100 %	100 %	99.8 %	99.7 %
	GA	100 %	100 %	99.9 %	99.9 %
2 (90 km, 3 σ)	handmade	100 %	100 %	99.8 %	99.7 %
	GA	100 %	100 %	100 %	100 %
3 (200 km, 3 σ)	handmade	99.9 %	99.6 %	97.5 %	92.3 %
	GA	100 %	100 %	98.8 %	96.8 %
4 (600 km, 3 σ)	handmade	99.9 %	99.3 %	86.1 %	67.0 %
	GA	NA	NA	NA	NA

In all the cases, the GA-based settings process allows a better GNC performance. Nevertheless, the gains remain limited with respect to the 50 m or 25 m hit probabilities, but the extensive and time-consuming preliminary handmade GC settings yielded already interesting results.

At this level of the GNC optimization, a specific GNC data set has been defined for each scenario. Ideally, we would rely in the end on a single GNC data set enabling the fulfilment of the mission requirement for any kind of endgame conditions. However, because most of these GNC tuning parameters are scenario- or time-dependent, it is clearly not sure to perform such task with the same level of GNC performance for very different endgame scenarios unless entering the endgame phase with the same predefined timing (the one of the longest scenario) for any kind of initial conditions.

6. COUPLED GNC SETTINGS AND DACS DESIGN OPTIMISATION

One of the baselines of the NEOShield program was to consider at least existing propulsive solutions for the DACS, hence the choice for the 10 N, 200 N and 3500 N divert options. Nevertheless, such choice was maybe not the most adequate, the analysis of some failure cases highlighting a DACS definition issue, for instance under-estimation of the ACS needs for the 3500 N divert and a 20 Hz image-based relative navigation. Thus, the driving idea here is to add the main features of the DACS, i.e. thrust level and firing period (still considering a pulsed-mode operating DACS) to the set of GNC data to be optimized by the GA process. In the end, the number of genes of an individual is raised to 20, (2 for the divert and ACS firing periods, and 3 for the divert, yaw-pitch and roll ACS thrust levels). The variation range of the divert thrust has been set to [100 N; 5000 N], for a minimum command period of 50 ms for the Control function, compliant with the 20 Hz image-based navigation.

Without modifying the main settings of the GA processes (the optimization remains scenario-dependent) we get the following results concerning the final miss-range and the DACS fuel budgets.

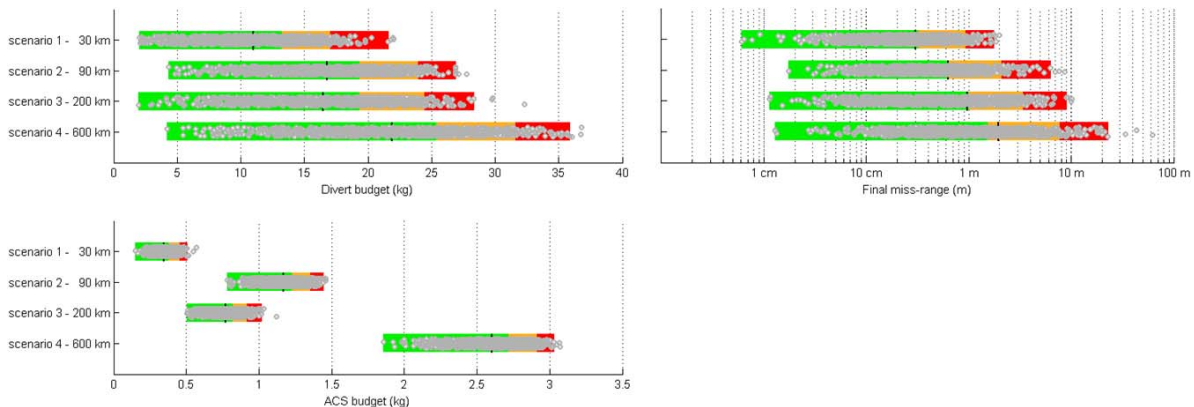


Fig. 12: GNC data and DACS optimization

Before detailing the optimization results, the first point to highlight is that the GA process has converged on the scenario 4, what was not the case when only the GNC data had to be optimized. That convergence is mainly due to the additional propulsive data whose GA setting enables a better adequation between the GNC functions, the DACS definition as previously considered being in the end too stressing for the endgame conditions of scenario 4.

The results of the augmented GA process are summarized in the next table.

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Divert thrust	230 N	483 N	440 N	289 N
ACS P-Y thrust	9 N	23 N	20 N	15 N
ACS R thrust	11 N	42 N	24 N	46 N
Guidance loop	500 ms	500 ms	150 ms	150 ms
Control loop	100 ms	100 ms	50 ms	100 ms
Divert budget (max)	22 kg	28 kg	32 kg	37 kg
ACS budget (max)	0.6 kg	1.5 kg	1.2 kg	3.1 kg
25 m hit probability	100 %	100 %	100 %	99.7 %
50 m hit probability	100 %	100 %	100 %	99.9 %

According to these results, there is no real need for a high thrust level divert, the obtained thrust levels ranging from roughly 200 to 500 N. For an extended endgame duration and an enlarged variation range of the divert thrust level, a lower divert thrust level would probably have been selected by the GA process. But there is also no unique DACS solution and it is not possible to define a clear trend in the sizing of the DACS or to derive sizing rules from the obtained results. In addition, the GA sizing of the DACS provides results that are different from the ones that would have been obtained using in-house explicit sizing methods. These differences may be explained by the fact that those sizing principles rely on some simplification that may be over-sizing in some cases and using a stochastic method as used by a GA process enables a relaxation of the DACS sizing. In addition, divert and ACS fuel budgets are reduced. If it is quite direct to derive a relation between the endgame conditions (maximum miss-distance and time-to-go at endgame handover), the divert fuel budget and the divert thrust, the ACS consumption which is mainly linked to the duration of the endgame phase does not evolve as expected: scenario 2 and 3 have similar ACS values, but the maximum fuel consumption for the scenario 2 which is twice shorter than scenario 3 is 30 % higher. This over consumption that was already observed when only the GNC data were optimized is essentially the result of a different GA sizing of the camera tracking zone, but the fuel budget remains limited.

Last but not least because this is the most important result with respect to the mission objective, the better adaptation of the DACS to the GNC data enables an important improvement of the GNC performance with 25 or 50 m hit probability equal or very close to 100 %. This higher performance of the GNC demonstrates the interest of relying on a joint optimization of the GNC data set and the main DACS features.

7. CONCLUSION

Among the different mitigations techniques investigated within the frame of the NEOShield program funded by the European Commission (FP7 framework), the kinetic impactor appeared the most promising to deviate a threatening asteroid far away from the Earth. The analysis performed during the NEOShield activities demonstrated that a kinetic impactor with a medium (200 N) to high (3500 N) thrust liquid-fuelled divert or even a very low thrust level (10 N) for a satellite-like KI was able to impact an asteroid with a final miss-range below 50 m, or even 25 m, in most of the cases, even for very degraded conditions at endgame handover. Nevertheless, such performance level that

was established for a given definition of the divert and Attitude Control System (driving idea being to consider existing propulsive system) left some room for improvement of the GNC performance, only time-consuming handmade settings of the GNC data set having been done.

Limiting the analysis to the medium to high thrust divert kinetic impactor and to each endgame scenario (from very optimistic to very pessimistic conditions at endgame handover), it was then decided to replace the classic handmade setting of the GNC data set (15 parameters to tune) by an optimization process relying on genetic algorithms. As usual with such optimization method, the most challenging aspect is the definition of the objective function and the genetic algorithms parameters (number of chromosomes, individuals, epochs, mutation, reinsertion, selection, etc.). But once this preliminary step is completed after some iterations, the optimization allows an improvement of the GNC performance in addition of shortening the setting phase. Discarding the possible re-use of existing DACS solution that may be undersized for some degraded endgame conditions, and considering 5 additional genes, it is possible to perform a coupled GNC-DACS optimization which yields a much larger improvement of the performance.

According to these results, next step would be to re-run the GA optimization process restricted to the GNC data set and considering an intermediate and unique DACS definition (for instance, the one obtained with the GNC-DACS optimization on the worst endgame scenario), and to redefine the set of the GNC data to remove the time-dependency of some parameters in order to enable a unique GNC setting compliant with all the retained endgame scenarii.

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ACRONYMS AND NOTATIONS

ABM	Anti-Ballistic Missile
ACS	Attitude Control System
ATV	Automated Transfer Vehicle
COG	Centre of Gravity
DACS	Divert and Attitude Control System
DG	Differential Games

DOF	Degree Of Freedom
ΔT_{ACS}	ACS call/firing period
ΔT_{Divert}	Divert call/firing period
EKF	Extended Kalman Filter
F_{ACS}	ACS Thrust level
F_{Divert}	Divert Thrust level
FOV	Field Of View
GA	Genetic Algorithms
GNC	Guidance, Navigation and Control
HF	High Frequency
HOMER	HOver ManeuVER
IMU	Inertial Measurement Unit
KI	Kinetic Impactor
LORRI	Long Range Reconnaissance Imager
LOS	Line of Sight
M	Miss-distance
MIB	Minimum Impulse Bit
MPS	Main Propulsion System
NEO	Near Earth Orbit
SIRU	Space Inertial Reference Unit
T	Time-to-go
V	Closing velocity
YPR	Yaw, Pitch and Roll