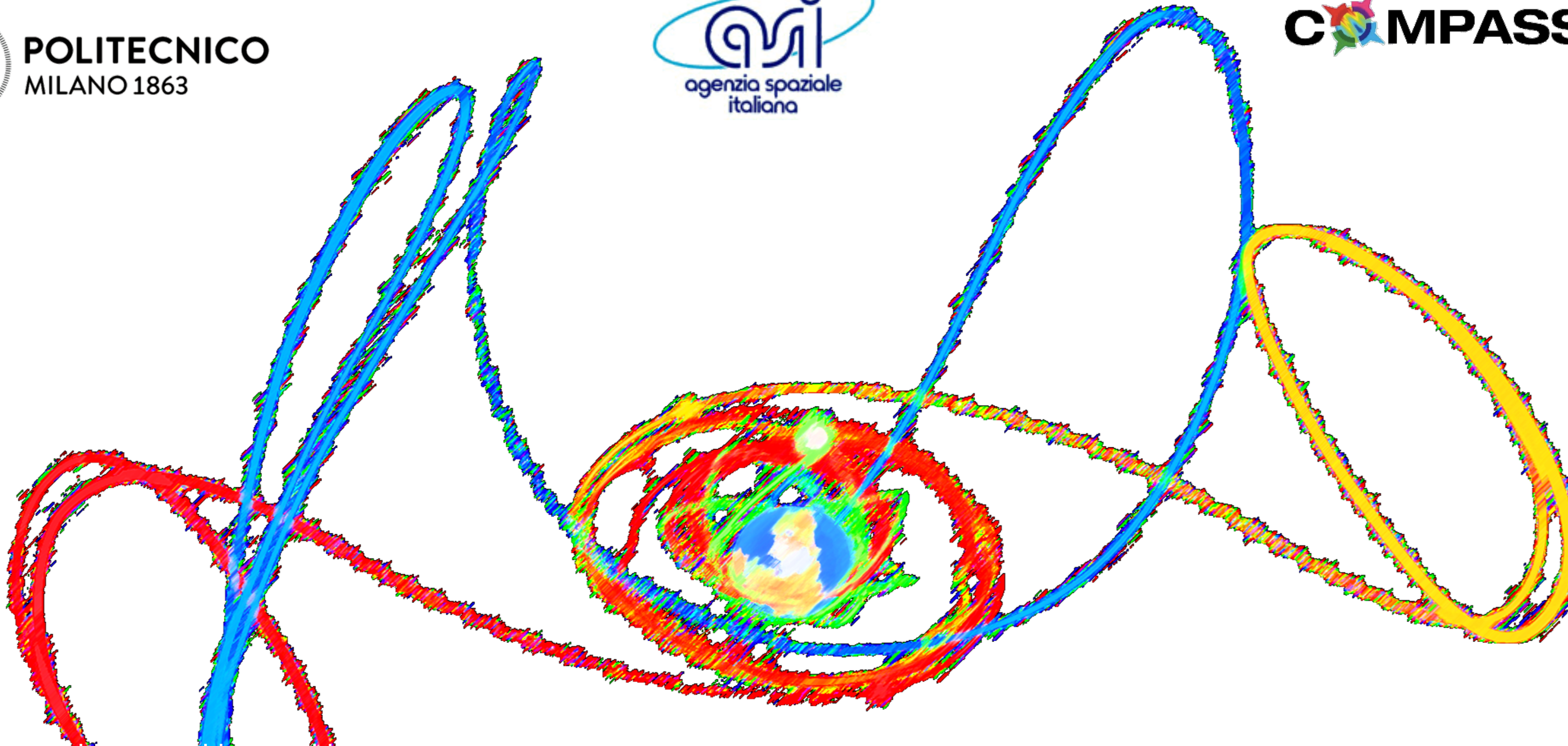

Mission analysis for potential threat scenarios: optimal impact strategy and technology evaluation

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INTRODUCTION

Introduction

Space Mission Planning Advisory Group (SMPAG)

Prepare a coordinated response protocol to an impact threat scenario

- Criteria and thresholds for impact response actions
- Mitigation mission types/technologies to be considered
- Mapping of threat scenarios to mission types
- Reference missions for different NEO threat scenarios
- A plan for action in case of a credible threat
- Communication guidelines in case of a credible threat
- Roadmap for future work on planetary defence
- Criteria for deflection targeting
- Toolbox for a characterisation payload


Chelyabinsk, Russia (2013), 17-30 m diameter asteroid


Tunguska, Siberia (1908), flattening 2000 km^2 of forest, 50-70 m asteroid

Introduction

Reference missions for different threat scenarios

- Define a number of typical Near Earth Objects (NEOs) threat cases (based on time to closest approach, material characteristics, dynamical properties)
- Set of reference mission identified (e.g. mass; orbit; time-to-closest-approach) and evaluated in accordance with criteria defined (e.g. time between the impact alert and the launch window opening, etc).
- Sensitivity analysis on accuracy of orbit determination
- Robust control on the magnitude and direction of the imparted delta-velocity, centre of impact point
- For each reference mission investigate political and financial implications and constraints in the risk mitigation analysis
- Considering several deflection strategies

TARGET ASTEROID SELECTION

Definition of threat scenarios

Criteria

- Different NEO threat cases analysed to identify a restricted number of scenarios, to be adopted as reference use-cases for the mission definition.
  - Dimensions of NEO
  - Type of orbit (direct-impact, resonant, …)
  - Time to closest approach
  - Amount of available information
  - Representativeness of known NEOs population

- To guarantee the representativeness of the scenarios a "reverse approach" has been adopted through "adjustments" of representative real NEO cases to fulfil all desired characteristics

Definition of threat scenarios

Synthetic case

- Adopted NEOs classification:
  - Small-size NEOs: ~10 m equivalent diameter
  - Medium-size NEOs: ~100÷200 m equivalent diameter
  - Large-size NEOs: ~1000÷2000 m equivalent diameter

Scenario A: Direct hit scenario

Reference diameter	100 m
Magnitude	21÷20
Mean density	2600 kg/m^3
Estimated Total Mass	1.3614 x 10^9 kg
Detection Time	2085
Expected Impact Time	2095
Type of impact	Direct hit
Orbital parameters	as 2010RF12

Scenario B: Resonant hit scenario

Reference diameter	1000 m
Magnitude	17÷18
Mean density	2600 kg/m^3
Estimated Total Mass	1.3614 x 10^{12} kg
Detection Time	2085
Expected Impact Time	2020
Type of impact	Resonant hit
Orbital parameters	as 2010RF12

Definition of threat scenarios

2010 RF12

- 2010 RF12 is a small Near Earth Asteroid; its absolute magnitude H is 28.4 corresponding to a diameter between 5 m and 12 m
- Currently it has the highest probability of hitting the Earth: in both the risk pages of NEODyS and of Sentry the impact probability is estimated to be around 6% for an impact on 6 September 2095
- The energy liberated by such an impact will be of the order of the energy of the Hiroshima bomb
- 2010 RF12 was discovered on 5 September 2010, and observed for 3 days, until 8 September, during a close encounter with the Earth that brought it, on 8 September, within 79 400 km from the centre of the Earth

- http://newton.dm.unipi.it/neodys/index.php?pc=1.1.2&n=2010RF12
- http://neo.jpl.nasa.gov/risk/2010rf12.html

Definition of threat scenarios

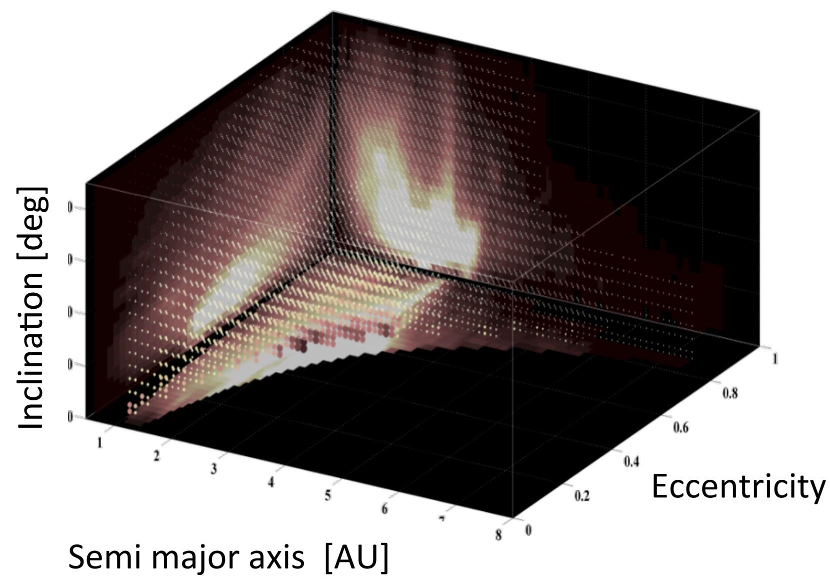
2010 RF12

- Near Earth Asteroids (NEAs) move on a wide variety of orbits; no particular choice can be considered representative of the whole population

- 2010 RF12 will lead to either an impact the Earth, or a very close encounter with it, at the end of the current century

- It can be considered a “realistic" impactor orbit, and is as good candidate for testing and preparing the simulation tools

Theoretical NEO distribution, probability density in a, e, i



- Sanchez, Colombo, “Impact Hazard Protection Efficiency by a Small Kinetic Impactor”, JSR 2013

Direct hit scenario

DEFLECTION STRATEGY DESIGN

Direct hit scenario

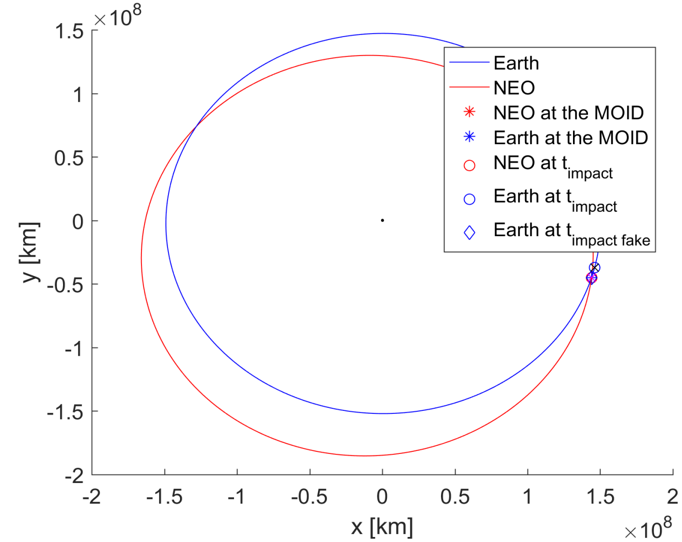
Problem formulation

Expected impact time 2095

Asteroid detected 10 year in advance

$$t_{0,\min} = t_{MOID} - 10 \text{ years}$$

Earth and NEA trajectory



The design parameters for the deflection mission

$$x = \begin{bmatrix} \eta_{t_0} & \eta_{DSM} & ToF & \Delta v_0 & \alpha_0 & \delta_0 & m_{s/c0} \end{bmatrix}$$

ToF: time of flight for the interplanetary trajectory

Δv_0, α_0, δ_0 : magnitude, in-plane and out-of-plane angles of the of the delta velocity at departure from Earth, with respect to the heliocentric velocity

m_{sc0}: wet mass of the spacecraft at launch

η_{t0}, η_{DSM}: timing of departure and deep space manoeuvre

Direct hit scenario

Problem formulation

Minimise spacecraft mass at launch (i.e. cost of the mission)

Maximise radius of the perigee at the hyperbolic passage of the asteroid from Earth during the close approach of 2095.

$$J = \begin{bmatrix} m_{sc0} & \Delta r_p \end{bmatrix}$$

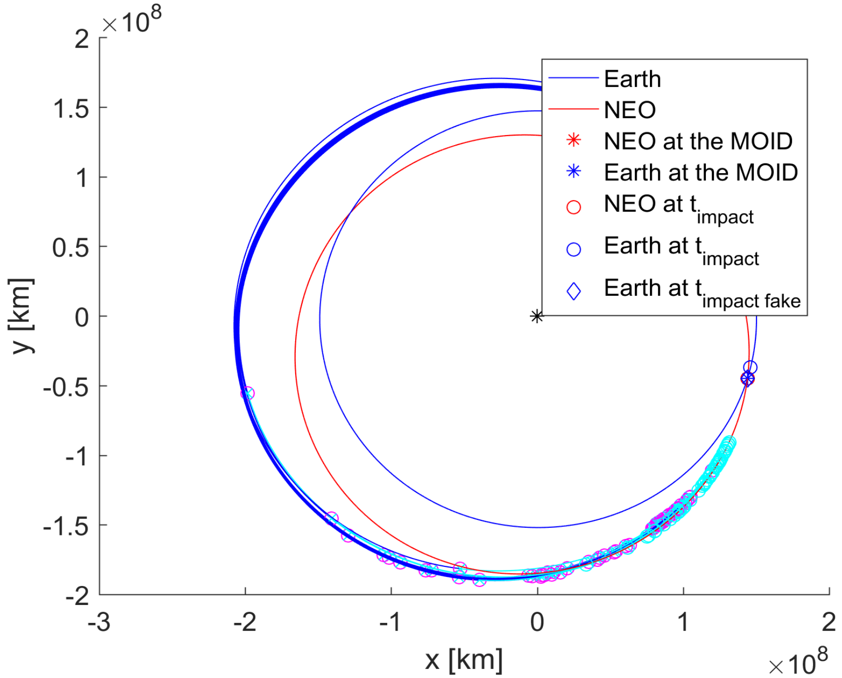
Deflection manoeuvre

$$\delta v_{NEA}\left(t_d\right) = \beta \frac{m_{sc,d}}{m_{NEA} + m_{sc,d}} \Delta v_{s/c}\left(t_d\right) \qquad \delta \mathbf{r}\left(t_{\text{impact}}\right) \approx \mathbf{\Phi}\left[t_{\text{impact}}, t_d\right] \delta \mathbf{v}\left(t_d\right) \qquad r_p = \sqrt{\frac{\mu_\oplus^2}{v_\infty^4} + b^{*2}} - \frac{\mu_\oplus}{v_\infty^2}$$

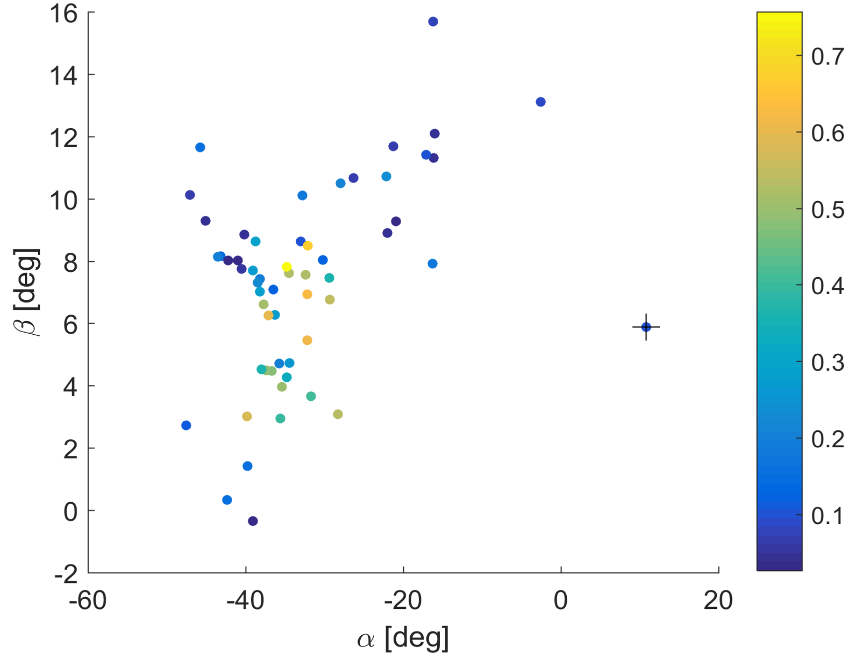
- Gauss equations, relative motion equations, gravitational focusing factor
- Deflection measured on the b-plane

➢ Vasile, Colombo, "Optimal Impact Strategies for Asteroid Deflection", JGCD 2008

Direct hit scenario

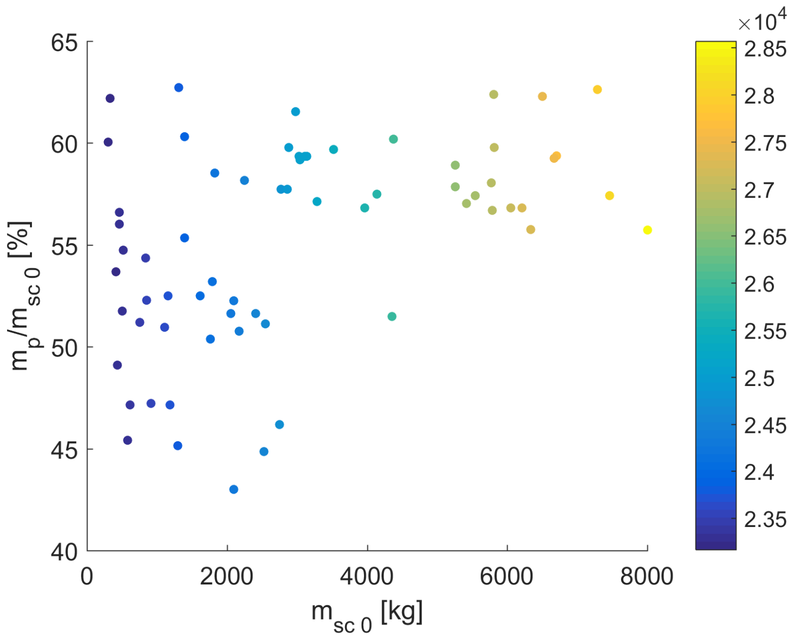


Sample of deflection trajectories

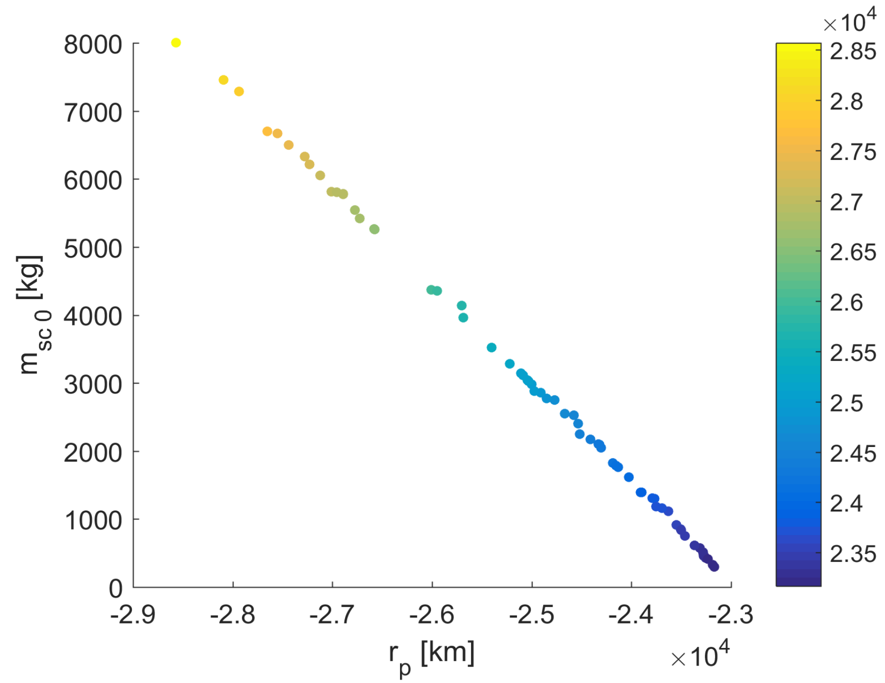


Direction of the deflection manoeuvre applied to the asteroid

Direct hit scenario



Spacecraft initial mass vs propellant mass ratio



Spacecraft initial mass as function of the achievable deflection at the MOID

Agreement with previous studies

Probability of a deflection system to deflect a generic impact threat

Seriousness of an impact based on the impact energy

Impact hazard categories

Combination of relative frequency of impact and size

Type of event	Approximate range of impact energies (MT)	Approximate range size of impactor	Relative event frequency
Airburst	1 to 10 MT	15 to 75 m	~177,000 of 200,000
Local Scale	10 to 100 MT	30 to 170 m	~20,000 of 200,000
Regional Scale	100 to 1,000 MT	70 to 360 m	~2400 of 200,000
Continental Scale	1,000 MT to 20,000 MT	150 m to 1 km	~600 of 200,000
Global	20,000 MT to 10,000,000 MT	400 m to 8 km	~100 of 200,000

Type of event	Warning time				
	20 year	15 years	10 years	5 years	2.5 years
Airburst	99.4%	99.0%	98.1%	88.8%	26.9%
Local Damage	92.5%	88.3%	**80.7%**	51.4%	9%
Regional Damage	43.0%	31.7%	22.8%	9.5%	0.6%
Continental Damage	3.9%	1.8%	0.6%	0.03%	0%
Global Damage	0%	0%	0%	0%	0%

- Sanchez, Colombo, "Impact Hazard Protection Efficiency by a Small Kinetic Impactor", JSR 2013

Direct hit scenario

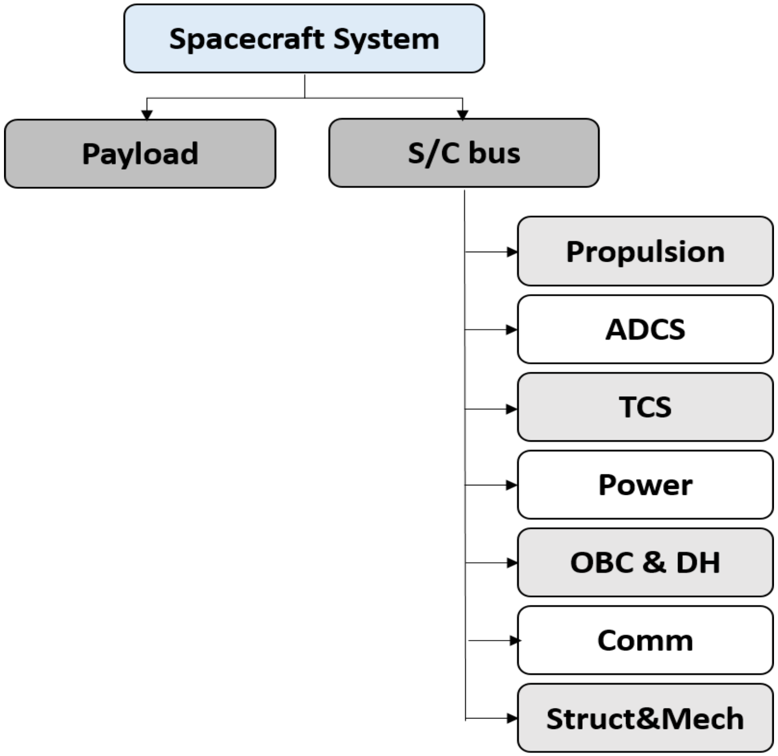
SYSTEM DESIGN

System design

Requirements

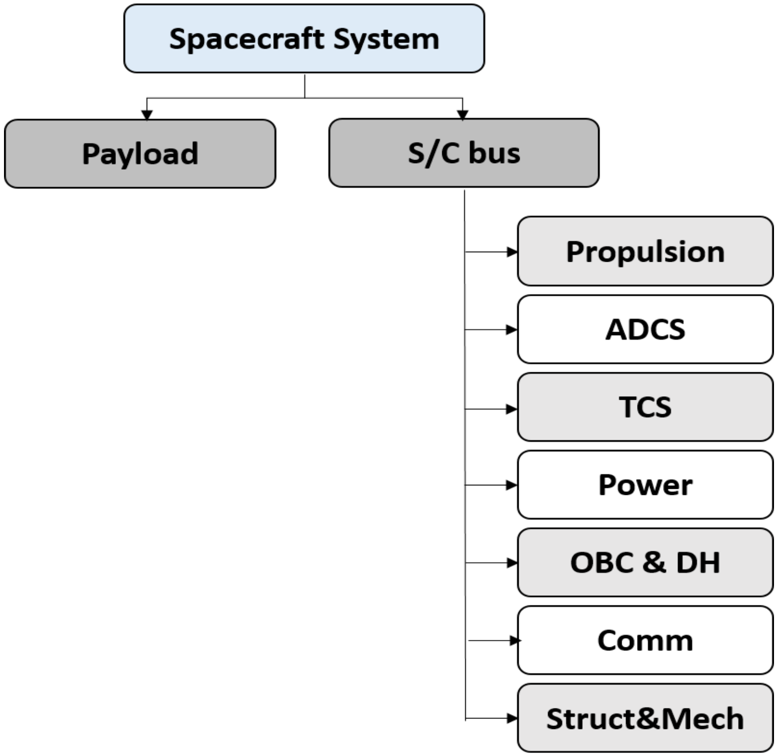
- The spacecraft shall be able to perform autonomously the navigation toward the asteroid and the final targeting of the impact point by use of OBC and high resolution images;
- The spacecraft shall be able to operate at a maximum distance of 1.5 AU from the Sun and to communicate with Earth at a maximum distance of 2 AU;
- Low cost technologies with a TRL ≥ 7 shall be adopted for the spacecraft design and integration to reduce the time required by the spacecraft development phase
- The spacecraft shall be configured in order to assure a high level of AOC performances, mainly in the targeting and approaching phase

System design



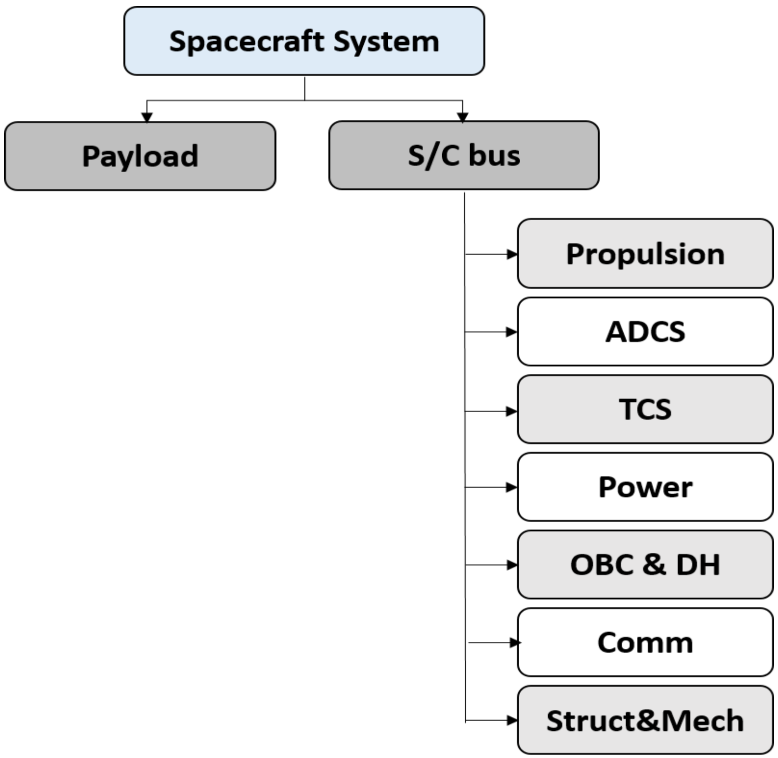
- Payload: instruments devoted to the asteroid imaging and the optical S/C navigation
- Real-time navigation and guidance is performed on-board with a high degree of autonomy.
- Traditional orbit determination by means of DDOR technique during the cruise phase making use of the on-board telecommunication sub-system
- Real-time navigation and guidance with optical camera and on board data processing system (e.g. Deep Impact NASA)

System design



- The spacecraft equipped with two cameras: a wide-angle medium resolution instrument and a high resolution instrument with a quite narrower field of view
  - (Wide Angle Camera (WAC) on ExoMars Rover 2020)
  - High resolution camera, ECAM-C50
- A laser altimeter, light detection and ranging (LIDAR) for the final approach (e.g. like the one mounted on-board of Hayabusa 2 S/C)

System design



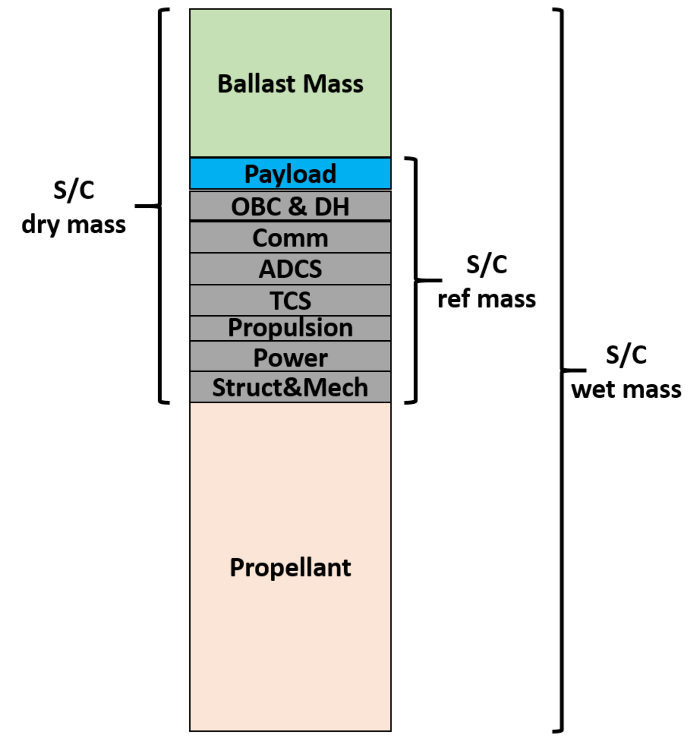
Spacecraft subsystem through statistical approach, depending on spacecraft mass at asteroid, through margins

- Chemical hydrazine monopropellant propulsion system (e.g. Planck, Herschel and METOP 1 missions).
- Attitude determination with star-trackers. Four reaction wheels are foreseen in a skewed configuration for 3-axis control (e.g. GOSAT-2 2018). In addition, hydrazine-based thrusters are provided for wheels desaturation and for redundancy in case of wheels failure (e.g. Cosmo Skymed and Sentinel satellites)

System design

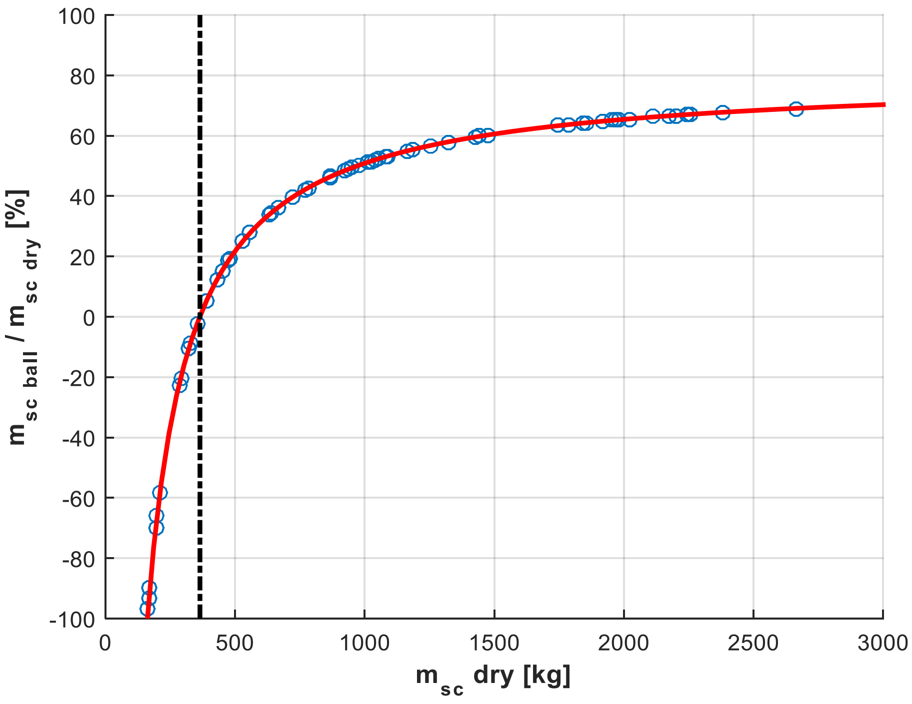
	Max. Value (including 25% margin) [kg]
Payload	12.5
S/C Subsystems	279
ADCS	25
OBC&DH	12
Power	190
Propulsion	17
Thermal	10
TT&C (Comm)	25
Structures & Mechanisms	20% of S/C dry mass

Preliminary results of S/C subsystems mass budget estimation

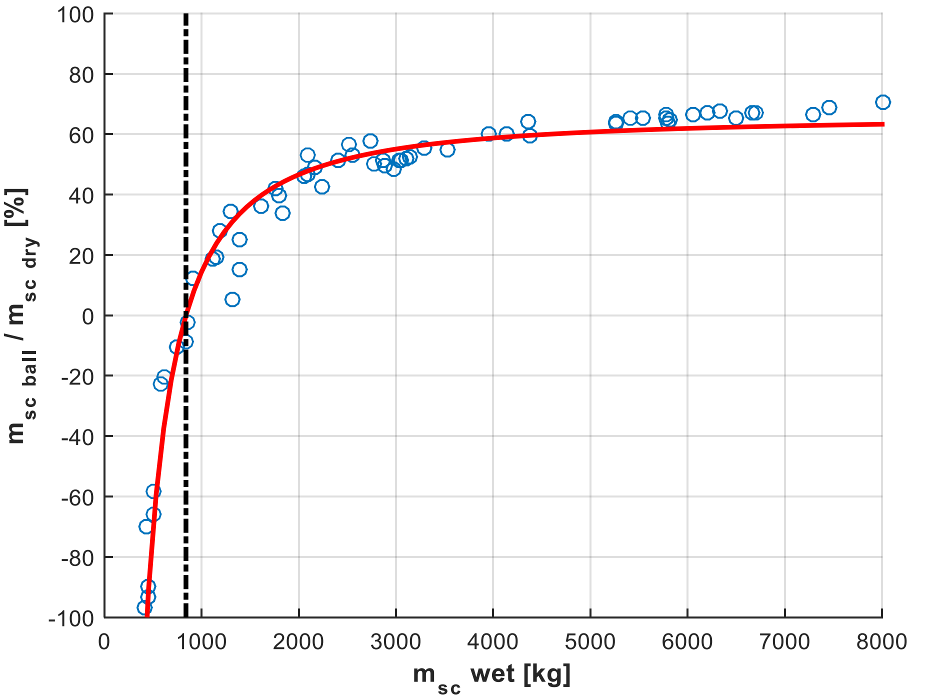


Spacecraft mass budget definitions

System design



Ballast mass percentage as function of S/C dry mass



Ballast mass percentage as a function of S/C wet mass.

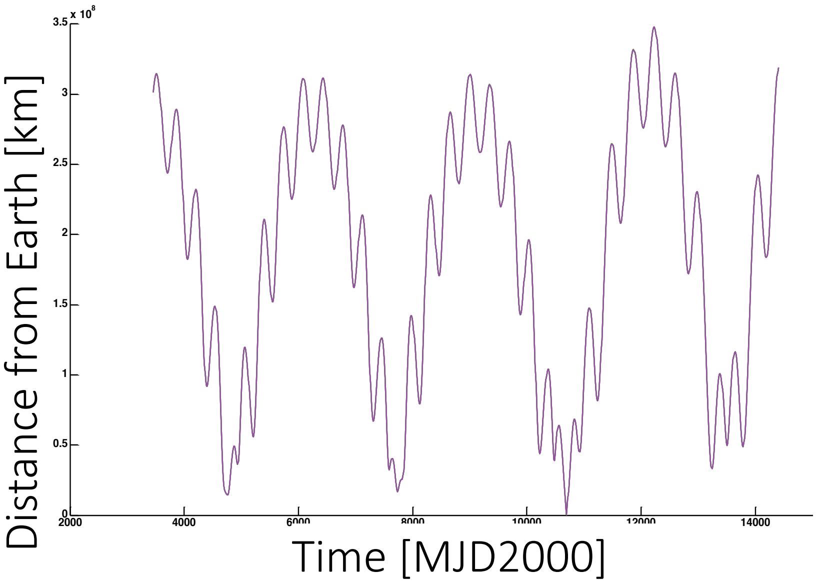
Minimum feasible S/C dry mass is about 370 kg, which corresponds to about 840 kg once equipped with propellant needed to perform orbital transfer

Conclusions

- Preliminary design of a representative deflection mission to a synthetic Near Earth Asteroid (2010RF12 with an increased mass)
- Simulation tools for parametric study of trajectory.

What's next

- Consider effects of uncertainties in the deflection manoeuvre and the asteroid's response to the deflection action
- Improve deflection efficiency by considering fly-by in trajectory and multiple kinetic impactors
- Earth's resonant encounter hit, deflect "on the long term"



➢ Letizia F., Colombo C., Van den Eynde J. P.J.P., Armellin R, Jehn R., SNAPPshot suite for numerical analysis of planetary protection, ICATT, 2016, Darmstadt, Germany.

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