Executive Summary

of

ESA Contract Nr. 4000116950/16/NL/LF/ as

"Assessment of an Anchoring Device for CubeSat Landers"

	Name (function)	Date	Signature
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Document Revision History

Issue	Section	Change Description	Date
1.0		Document created	10.02.2017
1.1		Added recommended trajectories (section 4) Added remarks on requirements derived from D2 (sections 4, 6) Added remarks on release mechanism tests (section 7)	10.03.2017

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1. Introduction

The current study has evaluated the feasibility of a CubeSat anchoring device in the context of AIM mission. By enabling this capability on a Cubesat type nanosatellite, the overall AIM mission will be further augmented with in-situ scientific measurements such as close surface visual observations, on site plume ejecta monitoring, impact induced accelerations and seismic wave propagated through asteroid body, etc. Moreover, the anchoring device has a strong reuse potential in the context of SSA by the utilisation of Cubesats or small platforms for debris removal techniques.

The purpose of using an anchoring device on a small celestial body (comet or asteroid) is to ensure the fixture of the lander to the surface of the body, in order to achieve proper position and attitude at rest or to prevent intensive mechanical experiments (drilling, scooping of samples etc.) from changing the attitude/position of the lander. Furthermore, sensors integrated in a harpoon can provide subsurface data, augmenting the scientific objectives of the mission.

CubeSats, arguably the spacecraft type with the best reliability/cost ratio, are an ideal solution for adding value to the AIM mission by recording data from the ideal place during the DART impact - the surface of the target asteroid. The advantage of such advantage point is the detection of the impact and its aftermath using on-board accelerometers. Under this scenario, the main requirement for best data collection is that the sensors are firmly attached to the target.

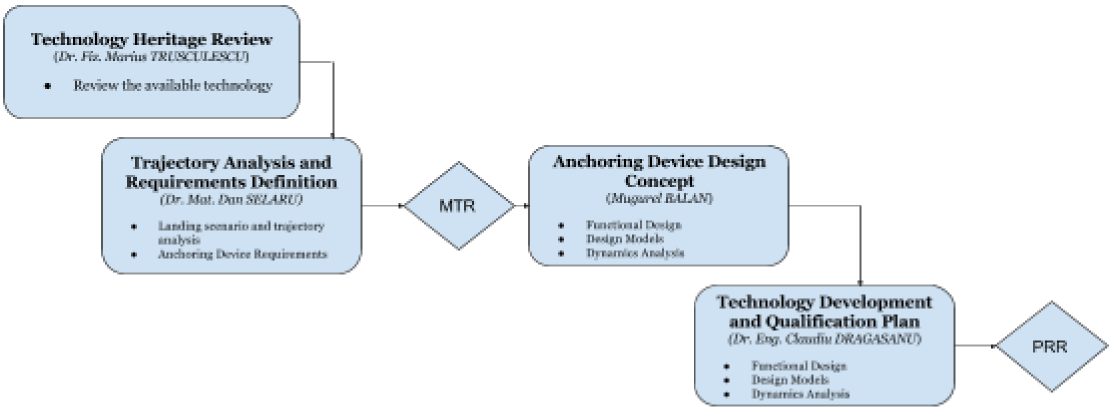
The study considered the anchoring device as a standalone subsystem, compatible with a CubeSat type satellite. The minimum components of such subsystem are: the anchor, the anchor actuator, the electronic control box. The first two of these components are heavily dependent on the anchoring method selected, while the electronic control box, as the interface with the rest of the spacecraft is more dependent on the command requirements and the host lander.

In the proposed mission scenario, the lander separates from the AIM spacecraft on a descent trajectory towards the secondary body of the Didymos system. During the descent phase, the anchoring device is armed by the OBDH of the lander. In the armed configuration, either an automatic reading from an accelerometer at the first impact or a range measurement device can trigger the engaging of the mechanism. A scenario in which the OBDH has the final decision of the triggering, which would allow flexibility in terms of the desired orientation at the landing site, is not recommended as it is considered too complex and risky for the spacecraft.

Taking into account the relatively short time frame and the overall AIM mission requirements, the current study will start by focusing on deep space missions that have targeted/landed on comets or asteroids, and have proven deep space heritage (Rosetta - Philae’s Harpoon, NEAR Shoemaker, Hayabusa Minerva, Phobos Hopper, MASCOT (2), Rosetta (soft landing)).

Although all those missions offers precious information about the asteroid and comets outer surfaces characteristics, only Philae's anchoring system can be considered a proven technology with deep space heritage.
Several anchoring approaches for surface retention have been investigated including harpoon, auger anchor, screw anchor, drive anchor, surface adherent landing gear etc. However, the study has not been restricted to the space used devices, several other industrial technologies also being investigated for their potential of spin-off into space.

The work under this project had been structured as in the WBS below:



Work Breakdown Structure

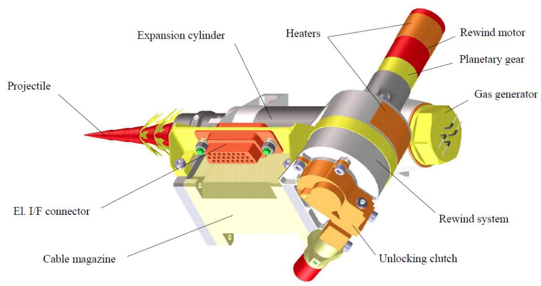
The following sections resumes the work performed under the current contract emphasizing the results and proposing follow-up actions.

2. Technology Heritage Review

Starting from the above mentioned premises, a literature survey study has been conducted on the attempt to find the best suited anchoring technology. The potential technologies evaluated for use on the COPINS CubeSats are:

A. Harpoon technology
   a. Pyrotechnics harpoon
   b. Cold gas harpoon
   c. Springs driven harpoon
   d. Electromagnetic driven harpoon
B. Telescopic spear
C. Soil screws/auger anchor
D. Microspine gripper

E. Gecko-gripper

	
Rosetta mission: Philae's anchoring device [1]	Microspines-gripper mechanism[2]

The studied anchoring systems/technologies have been parameterized against the following criteria:

1. Flight heritage
   - Graded from 1 (no heritage) to 10 (flight proven); intermediate values are for technological developments towards space use.
2. Cost of implementation/spin-into space
   - Graded from 1 (low cost) to 10 (high cost).
3. Reliability
   - Graded from 1 (low reliability) to 10 (high reliability).
4. Availability
   - Graded from 1 (unavailable) to 10 (easily available)
5. Technology maturity
   - Graded from 1 (low TRL) to 10 (high TRL).
6. Flight safety
   - Graded from 1 (unsafe) to 10 (safe).
7. Critical issues for space qualification.
   - True/False assessment that disqualify the technology (e.g. pyrotechnics).

The Philae harpoon philosophy has been considered the most appropriate in the current study, mainly due to CubeSat integration aspects. However, the pyrotechnic

[1] Markus Thiel, Jakob Stöcker, Christian Rohe, Norbert I. Kömle, Günter Kargl, Olaf Hillenmaier, Peter Lell; "The Rosetta Lander Anchoring System";
[2] Gripping Foot Mechanisms for Anchoring and Mobility in Microgravity and Extreme Terrain, Jet Propulsion Laboratory, California Institute of Technology

arrow propelling system had been replaced in the conceptual design phase due to the “no pyrotechnics” restriction imposed by the Agency.

3. Analyzing the target surface

Additionally to the launch conditions, the expected environment on the asteroid is the greatest unknown of the mission.

- Soil type: rubber pile + rocks
- Likelihood of rocks as rocks/m^2
- Velocity restitution coefficient unknown - simulation values 80%

Data on the soil’s strength of low gravity bodies is limited. In this case, the ranges of the parameters are greater and so, margins are more conservative. What the limited investigations of the low gravity bodies indicate is that in terms of surface properties there is no single category but a cumulus of multiple regions that are easily distinguishable (e.g. Itokawa, 67P/Churyumov-Gerasimenko).

Philae’s impact with the surface of the comet is a valuable dataset for estimating the scenario in which the anchoring device does not engage. The initial velocity was almost normal with respect to the surface. The small lateral component of the velocity was on a north-south component and it remains mostly unchanged after impact. However, most of the energy lost in the normal component went to an east-west velocity that was mainly caused by the rotation of the lander at impact. Analyses performed indicated two touchdown craters of up to 20 cm maximum depth. The estimation for the damping coefficient of the surface at the first touchdown indicates 50% to 80% of the initial kinetic energy dissipated to the soil. A damping element accounts for 10 - 40% of the initial energy, while the rest of 10% went into the rotation and velocity after impact [3].

Rosetta’s Philae lander ran experiments for measuring these properties but, besides discovering a thin outer layer of dust, the experiments have only put lower limits on the value of the strength of the hard surface. A distinction must be made between the estimates at the first touchdown site and at the rest position since there seem to be differences in their properties. The MUPUS penetrator from Rosetta mission estimates the uniaxial compressive strength at more than 2 MPa. Temperature measurements conducted by the same instrument indicate a soil inertia consistent with a compacted dust-ice crust under a thin layer of dust.

[3] Biele, J. et al., 2015. The landing(s) of Philae and inferences about comet surface mechanical properties. Science, 349(6247). Available at:: http://science.sciencemag.org/content/sci/349/6247/aaa9816.full.pdf?ijkey=hbPJM3IFYkDzg&keytype=ref&siteid=sci

The analysis of the two Hayabusa touchdown events at Itokawa put estimates on the coefficient of energy restitution at 84% [4]. According to the same results, the surface of this asteroid, estimated to be very similar to Didymos, is represented by a model of a regolith with multiple fragments, rather than by the dust model. The temperature readings, correlated with models for the thermal inertia, also favor the interpretation.

In the design of the anchoring system, the asteroid surface initial assumptions are extremely important. According to the elaborated Didymos reference model, Didymoon surface rock distribution is derived from scaling the rock size distribution on Itokawa model. Although the distribution of pebbles, cobbles, and boulders can be estimated, the anchoring system design requires additional information regarding the material strength, local density and porosity. A bulk density of Didymoon of 2400 Kg/m3 is assumed, mainly considering the characteristics of S type objects.

Jens Biele et al. [5] treat the problem of surface material strength for 67P/Churyumov–Gerasimenko comet, the Philae lander target, as part of the Rosetta mission. The tensile strength of several kPa and compressive strength one order of magnitude greater are estimated for soft surfaces. Furthermore, for the design of the Philae harpoon system, according to Thiel, M. et al. [6], an upper limit for target material strength of 5 MPa is considered. Also, in the design of an anchoring device for small bodies performed by Jingdong Zhao, the maximum surface strength of 5 MPa is considered.

On the other hand, the estimations of Thiel, M. for the lower limit of the surface strength significantly vary starting at hundreds of Pa. Also, many analyses have been conducted over the data provided by the Deep Impact mission. The DI ballistic model favours a strength of at most 1–10 kPa, with 1–5 kPa being more likely; on the other hand, even values up to 100 kPa seem to be consistent with the data in the same paper.

4. Cubesat Landing Trajectory Analysis

For evaluating the separation descent and landing of the CubeSat, a dedicated software simulation program has been created. It includes the gravitational and geometrical model of the asteroid binary system. The motion of the CubeSat as a material point was considered to be completely passive under the influence of external gravity fields. The movement of the CubeSat was assumed to be under

[4] Yano, H. et al., 2005. Touchdown of the Hayabusa at the Muses Sea on Itokawa. *Science*, 312(5782), pp.1350 – 1353, available at: http://doi.org/10.1126/science.1126164

[5] Biele, J. et al., 2009. The putative mechanical strength of comet surface material applied to landing on a comet. Acta Astronautica, 65(7-8), pp.1168–1178. Available at: http://dx.doi.org/10.1016/j.actaastro.2009.03.041

[6] Thiel, M. et al., 2003. The Rosetta lander anchoring system, European Space Agency (Brochure) ESA BR, (215), p.16, available at: http://www.esmats.eu/esmatspapers/pastpapers/pdfs/2003/thiel.pdf

gravitational forces of the planets and moons in the Solar System in the vicinity of the binary system Didymos. The reference system is J2000. The planets and bodies considered in the simulation are detailed in the following sections.

Geometrically, the primary (Didymain) is considered a spherical object, while the shape of the secondary (Didymoon) is a three axis ellipsoid with characteristics mentioned in the Didymos reference model. The shapes are considered in evaluating the touchdown with either of the bodies in the system. Furthermore, the parameters of the reference documents are fixed (e.g. mass, size etc.), the nominal values are considered.

The software evaluates the deployment conditions and the probability of touchdown with statistics on the number of contacts with the surface and that of remaining on Didymoon's surface. In terms of initial conditions, at the moment of CubeSat deployment, the AIM's distance with respect to the DCM (Didymos Centre of Mass) is greater than the distance to Didymoon. The orbits of Didymain and Didymoon are considered circular (unperturbed by external forces) and no libration was taken into consideration.

The system is propagated 12 hours forward and 12 hours backwards in time with respect to the touchdown event. If the time between deployment and final rest on Didymoon's surface is longer than 24 hour, we considered a negative outcome for the iteration. The figure below presents the impact point's reference system together with the Didymoon's reference system.

The software is built around 6 modules:

1. initial data;
2. backward time integration - using 4th Runge-Kutta method;
3. perturbation of the launch conditions - uniformly distributed random number generator used;
4. forward time integration - using 4th Runge-Kutta method;
5. Touchdowns and impact;
6. Statistics.

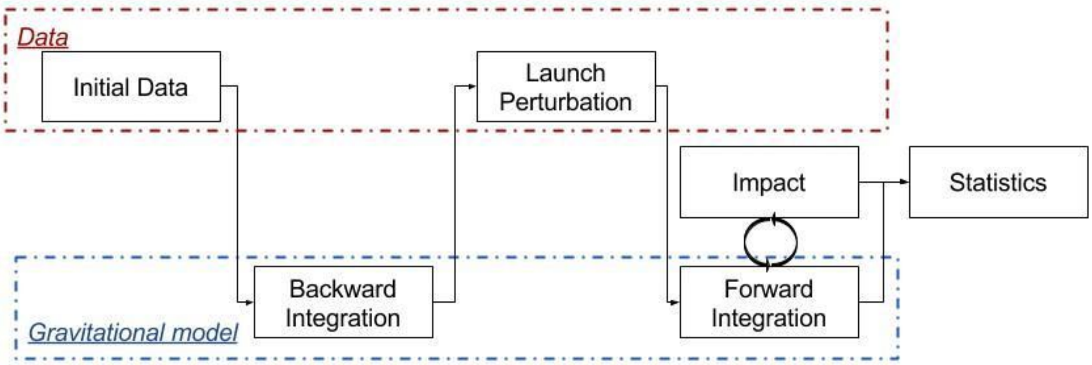


Fig. 6 - Software modules interaction

Fig. 6 presents the interaction among the modules at each iteration. The initial data set for the angles and parameters is used to calculate the ideal launch conditions, which are later perturbed with random errors. The perturbed launch conditions are used to calculate the new trajectory to touchdown and the velocities after impact. The last segment is looped until: the satellite stops on the surface of the secondary or it touches the primary or the Cubesat bounces at least 1 km away from the surface of Didymoon or more than 24 hours have passed since the release from AIM. It is considered that the CubeSat has stopped on the surface of Didymoon if the height of the last jump is smaller than 2 cm. The maximum duration of the software model integration is 24 hours.

The analysis conducted resulted in the identification of several trajectories of high hit and stay on the surface probabilities within the constraints of the accuracy estimated for the AIM mission. The solutions having a probability higher than 90% for a touchdown and higher than 70% for resting on the surface of Didymoon are summarized in the following table.

No	TD (lat., long.) [º]	Angles (Incidence, Heading) [º]	Vernal angle [º]	Altitude [km]	V_{TD} [cm/s]	Hit [%]	Stay [%]	Distance wrt Didymos CM [m]	Velocity wrt Didymos CM [cm/s]	Time of Launch	Flight time [h]
1	(0,0)	(75,30)	277	0.2	4.55	95.22	83.88	1445.190	17.940	2022-8-14 21:53:07	2.12
2	(0,0)	(75,30)	277	0.3	4.55	90.77	80.55	1506.276	17.579	2022-8-14 21:10:38	2.82
3	(0,0)	(75,30)	267	0.2	4.55	93.66	80.55	1438.054	17.967	2022-8-14 21:48:01	2.2
4	(0,0)	(75,300)	277	0.2	4.8	97.88	78.77	1440.935	17.769	2022-8-14 22:05:35	1.91
5	(0,0)	(75,300)	277	0.3	4.8	93.55	77.22	1500.719	17.420	2022-8-14 21:24:18	2.6
6	(0,0)	(75,300)	277	0.2	5.55	91.22	85.22	1411.426	19.130	2022-8-14	3.25

										20:45:09	
7	(0,0)	(60,0)	247	0.2	4.55	95.33	82.66	1453.991	17.949	2022-8-14 21:56:37	2.06
8	(0,0)	(60,0)	237	0.2	4.55	94.44	82	1449.299	17.940	2022-8-14 21:54:12	2.1
9	(0,0)	(60,0)	217	0.2	4.55	94.11	83.66	1443.587	17.984	2022-8-14 21:48:13	2.2
10	(0,0)	(45,0)	247	0.2	4.55	93	84.44	1470.159	18.269	2022-8-14 22:12:15	1.8
11	(0,0)	(45,0)	237	0.2	4.8	97.55	84.33	1468.841	18.208	2022-8-14 22:12:49	1.79
12	(0,0)	(45,0)	237	0.3	4.8	93.44	80.22	1546.619	17.546	2022-8-14 21:37:11	2.38
13	(0,0)	(45,0)	237	0.4	4.8	91.44	77	1612.755	17.042	2022-8-14 21:10:22	2.83
14	(0,0)	(45,0)	237	0.2	4.55	92.22	84.44	1464.698	18.049	2022-8-14 21:55:14	2.08
15	(0,0)	(45,0)	227	0.3	5.05	97.11	74.66	1550.603	17.623	2022-8-14 21:50:58	2.15
16	(0,0)	(45,0)	227	0.6	5.05	94.11	72.55	1739.110	16.242	2022-8-14 20:45:10	3.25
17	(0,0)	(45,0)	227	0.2	4.8	97.66	85.88	1467.581	18.159	2022-8-14 22:12:35	1.79
18	(0,0)	(45,0)	227	0.3	4.8	94.77	82	1543.635	17.522	2022-8-14 21:36:44	2.39
19	(0,0)	(45,0)	227	0.4	4.8	90.88	76.33	1608.610	17.030	2022-8-14 21:09:42	2.84
20	(0,0)	(45,0)	227	0.5	4.8	90.11	76.66	1667.032	16.606	2022-8-14 20:47:17	3.21
21	(0,0)	(45,0)	227	0.2	4.55	93.77	88.22	1462.911	18.033	2022-8-14 21:54:38	2.09

There are multiple criteria for selecting a best case and they are dependent on the mission requirements. Those are better to be iterated from the mission requirements. For example, if we assume just the stay probability as important, the worst and best case conditions can be identified:

	Incidence [º]	Heading [º]	Vernal angle [º]	Distance [km]	TD velocity [cm/s]	Hit prob. [%]	Stay prob. [%]	ToF [h]
Min	45	0	227	0.6	5.05	94.11	72.55	3.25
Max	45	0	227	0.2	4.55	93.77	88.22	2.09

The best probability of landing is on the point located on the Didymoon equator on the opposite side of the primary. Furthermore, for increasing the landing probability at this point and resting on the asteroid surface, the trajectory of the Cubesat should have at touchdown a heading angle of $0^{o} \pm 5^{o}$ and an incidence angle of 45 ± 10^{o}.

Also the vernal angle of the AIM spacecraft at Cubesat release time should be between 197° and 257°. These parameters together with the altitude of the release between 200 and 600m and the touchdown speed between 4.55 cm/s and 5.05 cm/s increase the chance to hit and remain on the secondary asteroid.

5. Drafting the requirements

Starting from the concept mission of a Cubesat lander on the Didymodon surface and taking into consideration the trajectory analysis, three sets of requirements have been defined for each implementation level.

The first set, refers to the requirements imposed at AIM mission level. Those requirements are mainly deducted from the trajectory analysis and address the separation and the insertion into descent trajectory since, as shown in the previous chapter, the position of the AIM spacecraft in respect to the asteroid binary system and the time frame of deploying the Cubesat are very important.

Furthermore, a second set of requirements, this time imposed to the CubeSat platform, has been defined. The main driver for the requirements imposed to the satellite platform is the CubeSat standard specification. In terms of volume, the standard imposes a maximum envelope for the overall satellite including the bus and payload subsystems, hence the anchoring device is further limited. In line with the Agency's requirements the volume envelope will be restricted to half a 1U Cubesat unit. Also, the anchoring device pointing in the final descent phase has been taken into consideration.

The main set refers to the requirements defined for the anchoring device. The set covers the Deployment velocity for surface attachment, Structural requirements, the use of Pyrotechnics, Electric requirements, Verification and testing requirements and Environmental requirements.

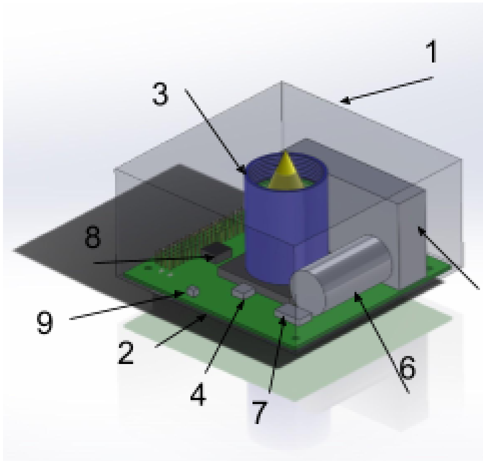
6. Design concept

Taking into consideration all three design concepts and having in mind that the exact mass of the satellite will be known only later in the AIT phase, the research team has focused on designing a spring propelled anchoring device that can be easily adjusted in terms of momentum stored after the system was installed on the satellite.

Since the design of the system is sensitive to the momentum of the satellite in the final approach phase, the system shall be able to permit fine tuning after satellite integration. For instance, in the mission scenario, the mass of the satellite considered is 4 kg, the as built mass of the arrow is 10 grams and the satellite velocity at 1 m altitude is 5 cm/s. In this case, in order to compensate the satellite momentum, the arrow must be accelerated to 30 m/s, resulting 4.5J of energy stored in the compressed spring.

Now let's consider that the as built mass of the satellite is 4.4 kg. Since the system is integrated and the mass of the arrow is fixed to 10 grams, the single way of reaching a higher momentum is to further increase the velocity of the arrow. A harpoon design

which permits this is presented below. In contrast with the Philae harpoon, this concept uses no pyrotechnics, having a compressed spring as energy storage device.
The concept design selected is the single spring propelled harpoon system. A description of the system is presented in the image below.

1. Volume restriction box (transparent) 2. PC 104 board (green) 3. Spring mechanism 4. Release mechanism drive electronics 5. Wire magazine 6. Rewinding actuator 7. Actuator drive electronics 8. Microcontroller 9. 3 axis IMU	

The proposed design is compliant with the main restriction of mass and volume respectively less than 700g and less a half of Cubesat unit. The mass of the presented design is estimated at 372g and the volume is less than 100 x 100 x 50 mm^3.

7. Design Validation Plan

A series of tests have been envisaged in order to validate the design of each component. The procedure starts with a test covering the verification of the aiming accuracy and the alignment of the arrow with the trajectory and the satellite center of mass.

In terms of arrow design verifications, a trade off on arrow head shape, arrow energy, types of material on the asteroid surface has been defined in order to consolidate the system design. Moreover, the CubeSat mission level parameters (descent trajectory, approach angle and satellite attitude) have been considered and validations tests were defined accordingly.

Validation testing plans at component level have been defined including: release mechanism, electronic command and control unit, wire magazine, rewinding mechanism and arrow launch sensors.

The release mechanism is composed of a nichrome wire twisted with a nylon wire which holds in place the torsion spring of the mechanism. Several tests have been imagined as follows:

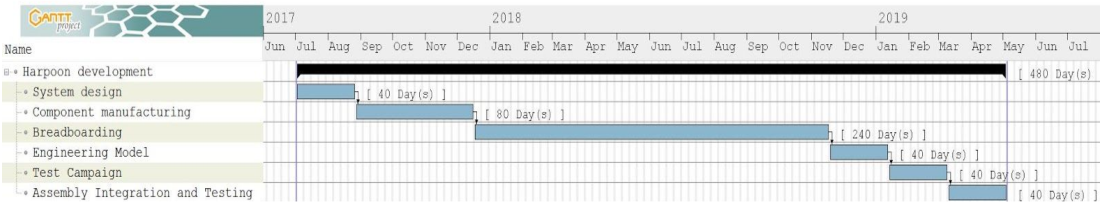
- Test the electronic command line.
- Test the two wire twisting method.
- Correlate the current in the nickeline wire with the release time.

The results of those tests shall be presented in the form of a “Release mechanism wiring procedure”.

Finally, a draft procedure for system arming including test definition for fine adjustments has been created. This procedure can be used in late AIT phase, since all the operations can be performed with the system integrated in the CubeSat.

8. Follow-up and Recommendations

In order to assess the development of the proposed conceptual design, a preliminary development plan has been put in place. It considers a time to completion of 24 months in accordance with AIM’s development plan.
A proposed Gantt chart is presented below.



Preliminary Gantt chart for anchoring device development

During the consolidated design phase, the conceptual design is detailed at component level. Moreover, in this phase different alternative components are designed/selected. For instance, in this phase, the six types of arrows are to be designed in accordance to the validation plan: 10 grams with ogive head, 10 grams with conical head, 20 grams with ogive head and so on. At least three springs, made of different material, which meet the energy storage requirements have to be selected in order to be used in the breadboarding phase. The design ends with the preliminary design review (PDR). Following this, all the designed system components shall be manufactured. Moreover, the validation test setups are to be developed at this point for further use in the breadboarding phase.
At the next step, an iterative developing - validation breadboarding process is foreseen. After the final configuration is chosen (arrow head design, release mechanism, etc.), a further optimisation iterative process is expected, including three breadboard iterations. This phase is the most consuming part of the project in terms of time and resources. It ends with a detailed design review that will allow the start of

the EM development phase. Each breadboarding iteration will also include functional verifications in order to asses required modification for the next design.

An engineering model of the anchoring device shall be assembled in the for-flight configuration. All the components used are in their last iteration of the design. The role of the engineering model is to verify the interfaces of all components (mechanical, electrical, software) and the as expected operations of the assembly. A separate flight model is recommended, but the proto-flight approach can also be used in order to decrease costs.

The engineering model test campaign shall be performed to verify the harpoon's compliance with requirements in accord with the proposed Anchoring Device Testing Plan. Besides the functional tests, the campaign will also include qualification level testing for mechanical environment (sinusoidal vibration, random vibration, shock response spectrum) and the thermal environment (bake-out, TV cycling). If the proto-flight approach is used, the model shall only be tested at qualification level. In the alternative case, the EM is tested at qualification levels, while the flight model is being tested at the acceptance levels.

The activities performed resulted in a concept for an anchoring device based on technologies of sufficient maturity to minimize development risks. Spring actuation is a safe approach in terms of risks to the spacecraft and trigger of actuation.

The mai risks identified are:

- Deployment of anchor inside the AIM spacecraft:
  - Accidental deployment command prevented by arming signal set by AIM.
  - Mechanical deployment (under stress from launch) is mitigated against by qualification tests established in the Technology Development and Qualification Plan.
- Failure of functionality:
  - Failure to deploy risks are mitigated by the trajectory analysis results leading to requirements of best approach separation scenarios that maximize the probabilities of touch-down and rest on the surface of the asteroid.
  - Failure to attach mitigated by anchor head design and by requirements of actuation timing before the first touchdown resulting in a null velocity relative to the surface of the asteroid.
- Technology development risks
  - Incorrect energy storage in spring after cruise mitigated by tests foreseen in the development plan. Deployment speed includes margin

for attachment to the surface (hence for the energy imparted by the spring).

- Single component failures mitigated by tests foreseen in the development plan and redundancy.
- Schedule slippage mitigated by flexibility in design in terms of exact components chosen (depending on availability) and by possibilities of financing the development under ESA or national grants.

The design concept defined under the current study can be developed taking into consideration the relative short AIM mission time frame.