Uncooperative Rendezvous and Docking for MicroSats[1]

The case for CleanSpace One

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***Abstract*— This paper proposes a solution to perform active debris removal with a cost effective microsatellite. A complex aspect of debris removal in space is the detection and positive identification of the debris, medium to close approach as well as the orbital rendezvous and following on-site operations. These aspects will require a mix of several technologies, some of which already exist, and some of which will need to be miniaturized and adapted for programs such as CleanSpace One. The rendezvous phases in particular will require a good knowledge of the position of the chaser as well as that of the target. In the CleanSpace One concept, the approach and in-orbit maneuvering will be performed by a micropropulsion system based on miniature thrusters. This concept also proposes that grabbing will be done by means of a robotic claw, which will adapt itself to the form of a non-cooperating object. These are key technologies that currently being developed in EPFL laboratories. The overall microsatellite uses CubeSat and COTS technologies.**

Keywords*— Space debris ; active debris removal; microsatellites, nanosatellites; micropropulsion ; capture systems ; rendezvous sensors.

I. INTRODUCTION

Producing and launching satellites is an activity pursued by many countries and institutions, Switzerland being one of them. Recent analysis has shown that in too many instances (intended or not intended), once the useful life of a satellite or rocket body has been spent, it becomes a debris in space [1, 2]. Since early 2012, the Swiss Space Center has proposed to develop a microsatellite (~ 30-40 kg), called CleanSpace One (CSO), whose primary mission is to rendezvous with the SwissCube CubeSat, to attach to it by means of a grabbing system and to perform a de-orbiting maneuver. The motivation behind the CleanSpace One project is to increase awareness and start mitigating the impact on the space environment by acting responsibly and removing our "debris" from orbit. This project is benefiting from debris removal research activities at EPFL in a program called "Clean-mE" since late 2009. The CleanSpace One project is currently in Phase A of its development.

Although the "real" debris threats are rather large rockets bodies (R/B) and large satellites (from about 1.5 tons up to about 9 tons), some of the technologies needed for Active Debris Removal (ADR) can be scaled down and demonstrated with a microsatellite. In addition, in the realm of all possible mission architectures that would remove large debris, some architectures have relatively low mission lifetimes (in order of months to a few years [3]), which reduces the reliance on expensive rad-hard components and even allow considering COTS technologies.

It is important to note that the project's approach in this first part of Phase A has been the evaluation of possible hardware solutions to the design of CleanSpace One's platform. The sizing requirements have been based on first order analysis in most cases. The objectives of this approach have been to establish hardware feasibility first. During the next steps, more complex simulations and analyses will be performed, from which will be derived detailed subsystem and sensor requirements.

This paper thus describes the CleanSpace One mission and conceptual design, but is also meant to propose discussions and solutions for a larger community of cost effective nano- and microsatellite builders. It will therefore sometime propose alternative technologies as options. This paper also provides preliminary requirements for the rendezvous, capture and de-orbiting for the CleanSpace One mission. And last a short description of the CleanSpace One microsat is presented with preliminary mass and power budgets.

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In this paper, CleanSpace One and SwissCube are also referred to as Chaser and Target respectively.

II. Active debris removal functions

The goal of CleanSpace is to demonstrate rendezvous and capture technologies and operations. This goal is extremely challenging, and probably even more challenging for a microsatellite. Table 1 summarizes the functions that will need to be performed to remove debris. It outlines which of the functions have already been demonstrated in space, which ones still remain to be demonstrated to fetch large debris (rocket bodies, old satellites…), and which may be specific to operations of a microsatellite.

The demonstrations that can be expected from a microsatellite and that will be addressed by CleanSpace One can be classified in three categories:

1) The new (not yet demonstrated by large satellites missions) ADR functions that are at least partially scalable to the capture of large debris:

a. Debris detection in the far-to-medium range operations.

b. Debris close-range approach and autonomous formation flying with a non-cooperative debris: although the formation flying techniques have been demonstrated between collaborative objects, the non-cooperative aspect of the demonstration will be new and at least partially scalable to the capture of larger debris.

c. Debris distance and motion estimation: the PRISMA mission has demonstrated navigation based on both a passive optical system [4] and an RF system [5]. The passive optical system has shown relatively precise reconstruction of the distance to target [4]. It has also demonstrated the reconstruction of the “pose” of the target, meaning the reconstruction of its quaternions (based on predefined target geometry). The proposed demonstration will aim at linking this reconstruction with the synchronization with the motion of the debris and of its autonomous use during the capture phase.

d. Synchronization with the debris motion: depending on the capture system, this function can be quite complex. The approach for CleanSpace One will be to align with the main axis of rotation, not necessarily to synchronize the chaser/debris rotations. Some control aspects should be applicable to large debris capture.

e. Debris capture: grasping system and control of the chaser during the maneuver. Here the demonstration will be based on a semi-rigid link between the chaser and debris.

2) ADR functions specific to CleanSpace One:

a. Debris-Chaser system stabilization: detumbling after capture; this function will be simplified compared to large debris capture as CleanSpace One’s mass-inertia will be much larger than the target-SwissCube.

b. Debris-Chaser system de-orbiting: it is not expected that a controlled re-entry will be performed with the CleanSpace One mission, but the system will still be de-orbited to have SwissCube comply with the 25-year disposal guidelines.

3) Functions those are (in addition) new to microsatellites:

a. Large ΔV propulsion and operations.

b. Orbital planes changes, transfers and navigation.

c. 6 DOF propulsion and control.

It is recognized by the project that many of these functions will require complex modeling, simulations, algorithms and on-board software developments, and tests. The details of the AOCS and GNC algorithms will be addressed in future work.

The next sections will discuss the proposed/selected technical solutions for each of these functions.

III. Debris target: SwissCube

SwissCube is a 1-Unit CubeSat (Fig. 1). Its dimensions are 100 x 100 x 113.5 mm^3, and it weighs 820 g (maximum moment of inertia of 2.45 x 10-3 kg.m2) On orbit, it has two deployed antennas (180 and 610 mm long), which will be rotating during capture. All faces are covered with solar panels, thus optical reflectance is similar from each face. SwissCube has completed its primary mission and is in good health. Operations are now shared with the Swiss Radio Amateurs association.

SwissCube was launched in 2009 and is one of two Swiss satellites in Orbit. It is operating in a sun synchronous orbit at about 720 km altitude and 98.4 degrees of inclination. It has an orbital period of 99 minutes. Its RAAN drift is very close to 1^o/day. SwissCube’s orbit is crossing the debris field from the Cosmos/Iridium collision in 2009. The project typically receives 3 to 5 warnings a year regarding a possible collision. That is currently its highest probability of failure.

Futhermore, right after ejection from the PSLV launch vehicle, SwissCube has experienced a large rotation rate (tumbling). Early 2011, a detumbling procedure was successfully implemented and SwissCube’s rotation has been low and stable since [6]. However, the on-board attitude controller is not active by default, and over the last 2 years, several sudden and sharp increases in the rotation rates have been observed. Actions were taken and SwissCube was re-stabilized. Figure xx shows the observed peaks in rotation. Once non-operational, it is to be expected that SwissCube may experience similar peaks. Thus CSO shall accommodate tumbling rates of SwissCube up to 50^o/s.

TABLE 1: SUMMARY OF NEEDED FUNCTIONS FOR ADR (CSO: CLEANSPACE ONE).

Operational phases	**Far Range Operations**		**Medium Range Operations**		**Close Range Operations**		**De-orbiting**		**Controlled Re-entry**	
Distance to target	**> 10 km**		**10 km -> 20 m**		**< 20 m**		**Flexible, rigid link**			
Functions	***Function***	***Demo-ed***	***Function***	***Demo-ed***	***Function***	***Demo-ed***	***Function***	***Demo-ed***	***Function***	***Demo-ed***
	Change of orbital plane	ATV OK- Microsat?	Debris detection	ATV, applicability to un-cooperative debris?	Debris distance and motion estimation	Prisma	Alignment with debris Cg (rigid)	End-of-life deorbit boosts	Chaser-debris trajectory + re-entry planning	
	Orbital synchronisation	ATV OK- Microsat?	GNC Approach	ATV OK - need adaptation	Autonomous free flying - collision avoidance	Prisma	Dynamically stable system during thrust (flexible)			
					Debris autonomous interception/ capture	CSO	De-orbit burn	Many		
					Debris-chaser stabilisation	CSO				
Navigation method and sensors	GPS (absolute)	Many	Optical/IR far range camera (relative)		Optical/camera (relative)	Prisma	GPS (absolute)	Many	GPS (absolute)	Many
	Star Tracker (absolute)	Many	On-board far range Lidar	Miniaturization needed	On-board radar/lidar	Miniaturization needed	Star Tracker (absolute)	Many	Star Tracker (absolute)	Many
			On-board far range radar	Miniaturization needed	GNC: Autonomous maneuvers	Prisma	GNC: Multi-body dynamics and control	Partial demo with CSO		
Debris localisation from ground	Ground TLE's	Many	Specific ground optical / radar observations	Uni-Bern	Specific radar observations	Uni-Bern			Specific radar observations	
Propulsion technologies	Chemical/ electric propulsion for large satellite	Many	Chemical/ electric propulsion for large satellite	Many	Cold gas propulsion for large satellite	ATV, Prisma	Chemical/ electric propulsion for large satellite	Many	Propulsion (controlled thrust to ensure re-entry)	Many
	Chemical/ electric propulsion for microsatellite	CSO	Chemical/ electric propulsion for microsatellite	CSO	Cold gas propulsion for microsatellite	6 DoF	Propulsion (any type, propellant or propellant-less)	CSO	Precise drag and entry modelling	
Legend:	Proven function:		Semi-proven:		New function:					
	Proven tech:		Semi-proven:		New tech:					

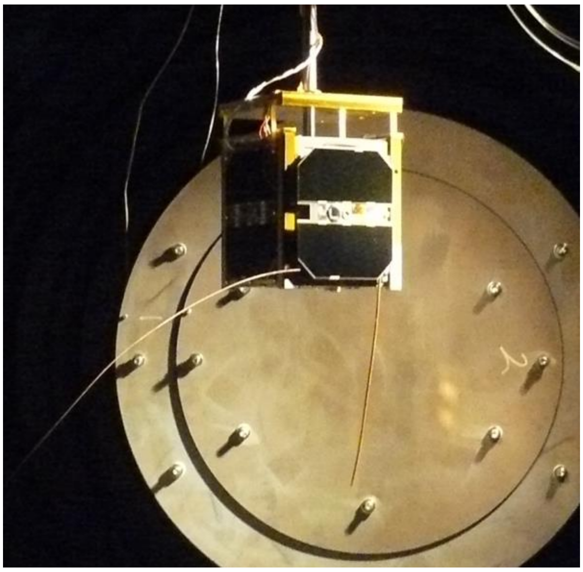


Fig. 1. SwissCube satellite in deployed configuration (in thermal vacuum chamber).

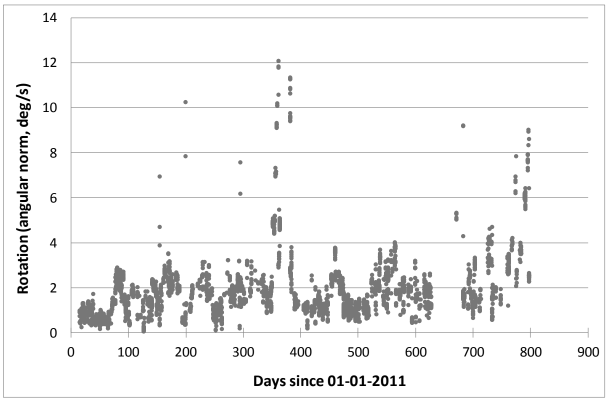


Fig. 2. Measured angular speed magnitude of SwissCube as a function of mission days since January 1, 2011. When angular speed goes above 2°/sec, on-board controller is used to reduce rotations. Controller is "off" by default.

IV. MISSION AND OPERATIONS CONCEPT

A. Launch, orbital synchronisation with, transfer to SwissCube's orbital plane and phasing (Far range operations)

To reduce mission time and requirements, CleanSpace One will have to be inserted into an SSO orbit, with an inclination relatively similar to SwissCube's. As it will most probably be launched as a piggy-back, the expected range of inclinations will be between 97.3^o (at 500 km) to 99.3^o (at 900 km). The assumptions for further mission design analysis are that the launch vehicle will inject CleanSpace One into a 500-km circular SSO orbit with an inclination of 97.3^o. This represents a lower bound for the orbital altitude and an average inclination change of 1^o. Thus the launch shall be selected based on its ability to deliver CleanSpace One on an orbit within 1^o inclination to SwissCube's, and with altitude between 500 and 900 km.

After launch, CleanSpace One will have to wait for RAAN synchronization (natural drift due to the J2 effect). At 500 km SSO, a passive synchronization may take several years to several decades. Furthermore, any delays in launch date may prove critical to the mission. To reduce the risk of missing the "optimum" launch date, CleanSpace One will proceed by default to a drift orbit, which require as a first assumption either a 1.1^o change of inclination at a constant altitude (stays at 500 km) or a 220-km change in altitude at a constant inclination (initial inclination 97.3^o). Once the drift orbit is reached, the relative drift rates will be approximately 0.1^o/day or 0.15^o/day respectively. A RAAN difference between the launch and SwissCube's orbits of 90^o would be effectively and passively reduced to zero in about 2-2.5 years. The launch shall thus be selected to allow for a difference in orbit RAAN at launch within +/- 90^o (launch within 3 months of planned date).

The ΔV to reach the drift orbit, to synchronize RAAN and reach the final SwissCube's orbit is close to 350 m/s (computed with the Edelbaum's low thrust equation [7]), for both types of drift orbits. This ΔV will be performed, in the current design, with an electric micro-propulsion system. The detailed trajectory design, especially using low-thrust, remains to be performed. The expected pointing accuracy and stability needed during thrust is respectively on the order of 1^o and 0.1^o/s.

Furthermore, during this phase, the (absolute) navigation will be done with an on-board GPS, sun sensors, Earth sensors, and with optical/radar measurements from the ground. It is assumed at this point that CleanSpace One will be brought to about a few tens of kilometers (30-50 km) from its target. Test with the observatory site in Zimmerwald [8] are currently on-going. The requirements imposed by the use of these facilities on the selection of the orbit or timing of the approach (for illumination purposes) still needs to be defined.

B. Approach and rendezvous (Medium to close range operations)

The approach and rendezvous consists of several phases, which are evaluated here for ΔV and for navigation requirement purposes. The design of CleanSpace One's Guidance, Navigation and Control (GNC) system shall allow performing the following phases:

- Phasing and Homing (Forward Phasing): this phase will start between 30-50 km away from the target. At this point, a cold gas system will be utilized for further operations. Optical/radar ground tracking [8] should support orbital position determination. Navigation should assume absolute measurements. This phase shall end at about 5-10 km from the target.

- Target detection: This phase starts at the boundary of the uncertainties in the TLEs and/or on the precision of the ground observations available. At this point, the target needs to be found and locked upon. Three technologies are being investigated for the detection of the debris, and to confirm location and lock on the target: optical/IR cameras, a miniaturized imaging Lidar, and an X-Band radar system. These systems should fit within 2 CubeSat Units and utilize a maximum of 10 W. This phase may last a few days to a few weeks.

- Closing (Forward Phasing): once the target has been locked upon, this phase will bring CleanSpace One from 5-10 km down to about 300 m. Navigation should assume both absolute and relative measurements. Control should be elaborated to stay in closed loop with the target.

- Final approach and target inspection (Straight Line Approach): this phase will include the close approach from 300 m to approximately 10-20 m from the target and a fly-around to an inspection point. At this point on, the GNC shall provide autonomous formation flying and collision avoidance algorithms up until the capture is initiated. The inspection point will provide the right illumination for the vision system to reconstruct the target's attitude. Based on this information, the main rotation axis of the target will be reconstructed both on the ground and on-board. The selection of the "grasping point" will be done on ground, and the motion reconstruction will be compared to the on-board prediction. The maneuvers will subsequently be uploaded from the ground. The capture mechanism will be deployed to its full extent. The planned trajectory path for the capture mechanism will also be uploaded from the ground. These maneuvers will be based on the relative position provided by the rendezvous sensors. They will have to be performed autonomously.

- Preparation for capture: during this last phase, CleanSpace One will maneuver to about 1-2 m from the target, potentially synchronize with and along the target's main rotation axis (or in a configuration defined by the rotation of the antennas). An additional very small camera located at the end effector of the grasping mechanism will be engaged in the control loop. CleanSpace One is then ready for capture.

It is planned that at the end of each phase, a check/GO/NO-GO from the ground will be performed before starting the next phase.

During final approach, target inspection and capture phases, the ground shall be in contact with CleanSpace One constantly for verification and safety. The current design includes an on-board S-band telecommunication system will allow a downlink of 2 Mbps with ground stations. Since this radio-amateur link may not be sufficient for live operations, the on-board GNC system shall include autonomous safety checks, reconfiguration and collision avoidance capability. An evaluation about the use of the TDRSS network is still on-going.

Estimations of the propulsive ΔV needs during these phases have been performed. There are many different possibilities to approach the target and many different aspects will contribute to the decision of the final approach maneuver. Important aspects to respect will be: the orientation if orbit of the target and corresponding illumination conditions, the available time to perform maneuvers, available data rate and communication possibility to ground stations, the capabilities of on-board actuators and sensors, safety issues (e.g. collision risk by failure of GNC), target rotations and grasping plans. The exact trajectories and distances for each maneuver should be determined.

Using the Clohessy-Wiltshire (CW) equations, preliminary delta-V estimation all of these parameters have been calculated. In Table 2 three different cases are shown. For each case slightly different parameters have been used. The result is that the needed delta-V for one single approach and grasping maneuver lies around 10 m/s. It should be noted furthermore, that this delta-V calculations assume a perfect controller, which uses the minimum amount of fuel. However especially in closed loop control, depending on the sensitivity of the controller, much more delta-V is used. To size the systems of CSO, given all uncertainties, a ΔV of 20 m/s has been assumed.

C. Capture

The concept of operations and associated maneuvers are tightly linked to the choice of capture system. In general, three main categories of capture systems have been identified:

1) Capture with a rigid link: typically robotic arms and grasping mechanisms;

2) Capture with a flexible link, such as nets and harpoons;

3) Contactless capture systems, such as foam projection, or the Ion-beam shepherd concept.

All three of these concepts have pros and cons, especially to remove large debris. The rigid link will imply more complex approach and capture scenarios, with at least some motion synchronization with the target during grasping, and requires Chaser-Target Cg alignments for deorbit thrusting. However, robotic arms benefit from flight heritage [9] and also relatively high TRL developments in Europe [10]. The flexible link provides lighter approach operations, but in general has the potential of creating breakups and small debris during the contact with and/or handling of the debris. The management/control of the flexible link during attitude control or de-orbit thrusting also remains to be verified. And finally the contactless options are attractive from an approach operations point of view, but may not provide the ability to perform a control re-entry in the atmosphere (for large debris removal).

TABLE 2: RENDEZVOUS ANALYSIS RESULTS.

Phase / Parameter	**Cases**		
	Nominal	***Nominal with margin***	***Worst***
Forward Phasing			
Distance [km]	30	50	100
Time [hours]	10	10	10
Delta-v [m/s]	0.4	0.8	1.6
Straight line			
Distance [km]	0.2	0.3	1
Time [sec]	1500	3000	6000
Delta-v [m/s]	0.7	0.8	2.4
Fly around to inspection point			
Time [sec]	1000	500	200
Radius rcirc [m]	20	20	20
Alpha α [deg]	180	180	180
Delta-v [m/s]	0.3	0.6	1.6
Target Inspection			
Time [sec]	1000	3000	8000
y-distance [m]	20	20	20
z-distance [m]	20	20	20
Delta-v [m/s]	0.1	0.3	0.7
Fly around to grasping point			
Time [sec]	1000	500	200
Radius [m]	1	1	1
Alpha α [deg]	180	180	180
Delta-v [m/s]	0.02	0.03	0.08
Grasping			
Time [sec]	1000	3000	8000
y-distance[m]	1	1	1
z-distance [m]	1	1	1
Delta-v [m/s]	0.01	0.01	0.04
Atmospheric Drag			
k [-]	0.016	0.016	0.016
Delta-v [m/s]	0.01	0.02	0.03
Total Time and ΔV			
Far range [hrs]	10	10	10
Close range [s]	5500	10000	22400
ΔV [m/s]	1.6	2.6	6.5
ΔV + 40% margin [m/s]	**2.3**	**3.7**	**9.1**

For CleanSpace One, the selection criteria included the following considerations: expertise and interests available in Swiss partner laboratories, implementations and operational complexity, manufacturability and ground test potential within the university environment and design capabilities in an educational context. The evaluation of these criteria led to the selection and design of a relatively simple capture mechanism. It is understood that the complexity will lie within the GNC design, and an appropriate European partner will be selected when funding is secured.

A preliminary design of the grasping mechanism has started, with currently the evaluation of three different types of gripper/end-effectors. The simplification of the mechanisms lies in the reduction of the number of DoF (5 DoF) compared to a full robotic arm, and in a simplified end-effector. With the current approach, only an axial angular synchronization is required (also because SwissCube's inertia is much smaller than CleanSpace One).

Figure 3 shows the concept for the grasping arm as well as the more detailed design of a mechanical wrist and gripper [11]. The wrist and gripper as shown are currently overdesigned to grasp SwissCube. They are tailored to grasp a launch vehicle adapter "passing by" with a rotational speed of 10o/s, and to damp the loads at the grasping moment. The currently preferred gripper for CleanSpace One inherits from developments of artificial muscles for medical applications. It is based on Dielectric Elastomer Actuators (DEAs), which are a class of electroactive polymer (Fig. 4). They are an emerging actuation technology based on the deformation of thin elastomer membranes under the application of a large electric field. The DEA membranes thin in the thickness dimension and expand in the planar dimensions as a result of the electric field, leading to potentially large actuation deformations [12, 13].

The inherent flexibility and lightweight nature of the Dielectric Elastomer Minimum Energy Structures (DEMES actuator) is advantageous for space applications where volume and mass are limited. The use of DEMES actuators will enable the gripper to be stored in a curled or rolled state to minimize volume and then be deployed when needed. The current drawbacks of this technology are the low TRL and the relatively high operations voltages, which will require specially designed power electronics. In the current capture scenario, the DEMES gripper shall open up when actuated in a cone of at least 45^{o} half angle and comply with the high rotation rates of SwissCube. The forces needed to keep SwissCube enclosed during de-orbiting are very small but shall be taken into account.

D. De-orbiting

The de-orbiting will be performed with the same electric micropropulsion system as for orbital synchronisation. It is assumed that the de-orbiting will be done from 720 km altitude down to 200 km altitude. At that point, the propulsion system will be turned off and re-entry studies will be validated with the GPS and accelerometers from the IMU. The de-orbiting ΔV is computed with the Edelbaum's low thrust equation [R7].

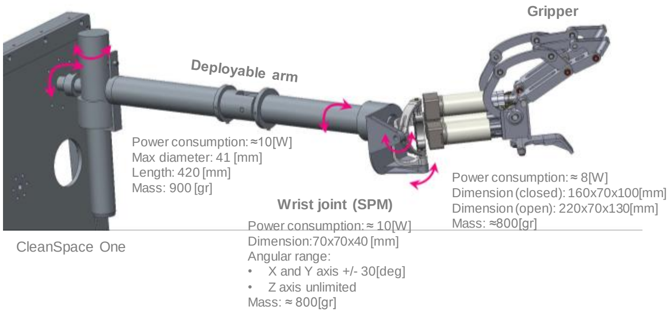


Fig. 3. Under-actuated gripper, wrist and arm design [R11].

Fig. 4. Concept diagram and proof-of-concept of DEMES gripper.

V. CLEANSPACE ONE CONCEPTUAL DESIGN

CSO is currently a 27 Unit CubeSat (or micro-satellite, see Fig. 5 and 6) with a mass of about 35-40 kg. Besides the structure, which is not compliant with CubeSat standards, all technologies used on-board are either from the CubeSat shop or COTS, or student designs. The avionics uses mostly GomSpace [R14] or AAC Microtech [R15] subsystems. Fig. 7 shows the hardware block diagram with the GomSpace avionics. The system architecture is divided in two parts:

• The core electronics is used for the essentials spacecraft functions as communication, CMDS and simple ADCS with magneto-torquers for detumbling. The boards are integrated in a 2U structure and connected together through the CubeSat kit connector.

• Mission dedicated electronics, like cameras, radars, proximity sensors, reaction wheels, etc. are distributed on the satellite structure. Power supply for this equipment is separated from the core electronics one and is inserted into a 1U structure.

Table 3 gives the preliminary mass budget.

A. Command and data management

The main OBC is based on A712D board from Gomspace, this board contain a ~40 MHz ARM microprocessor and 2 GB of data storage. To increase the number of interfaces a NanoHub from Gomspace is also used. Three data bus are implemented:

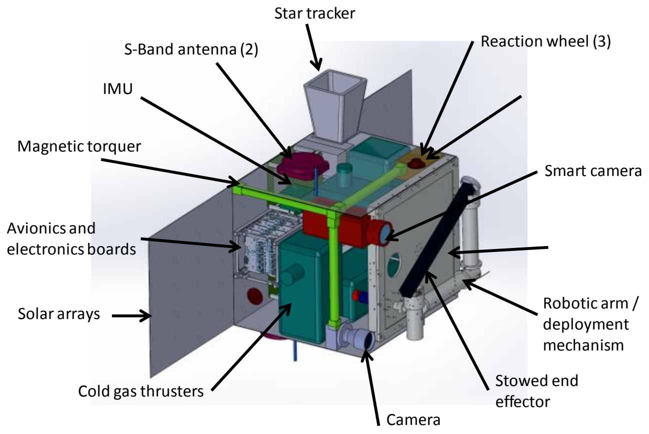


Fig. 5. CleanSpace One configuration with stowed grasping system.

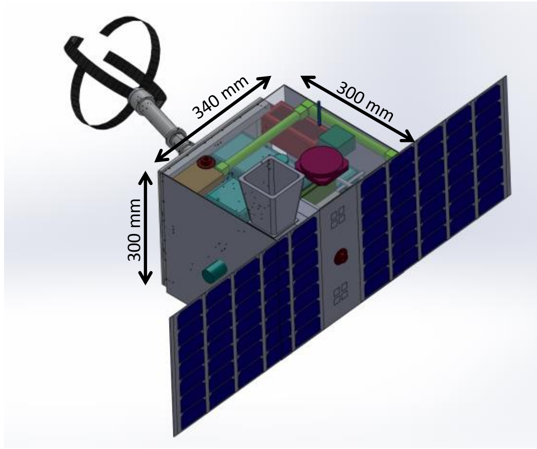


Fig. 6. CleanSpace One configuration with deployed grasping system.

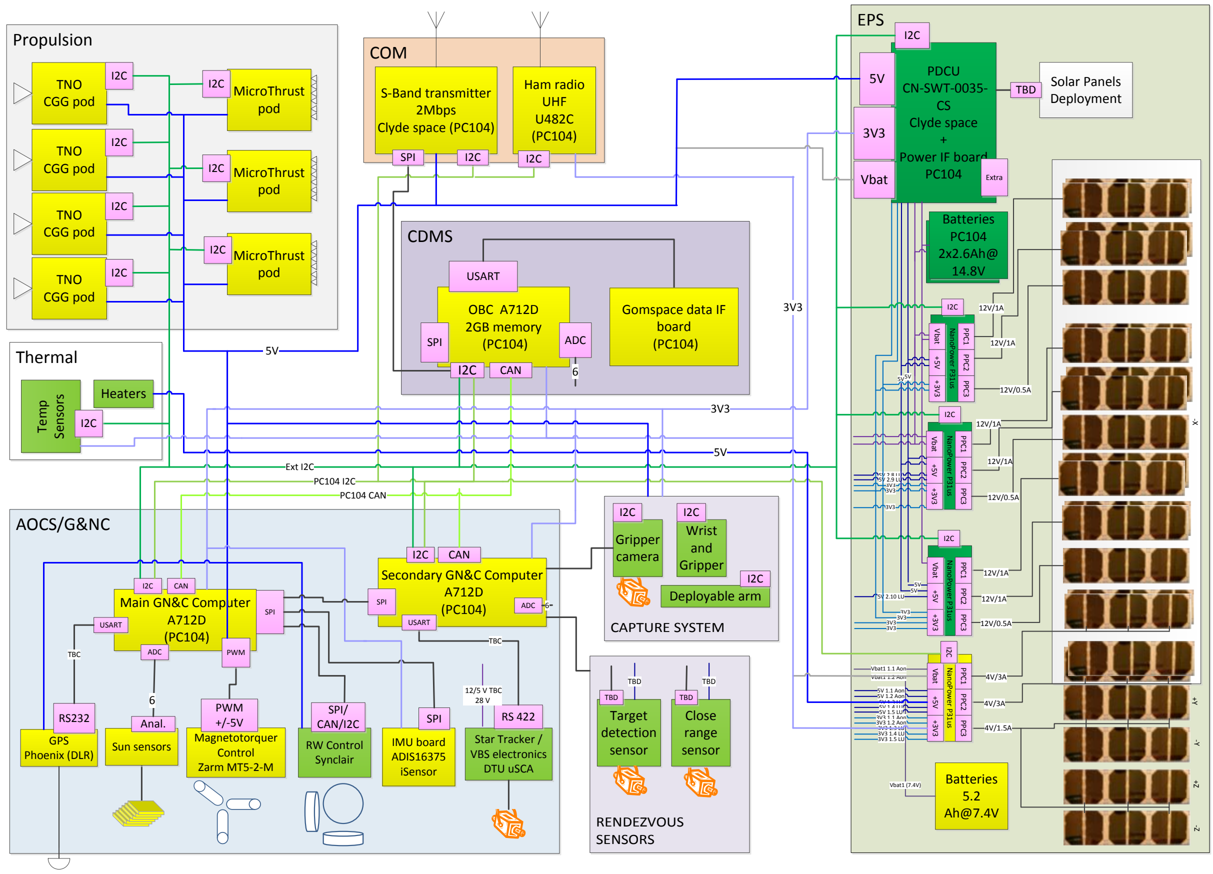


Fig. 7. CleanSpace One preliminary hardware block diagram.

- A CAN bus to connect the main OBC with the two AOCS and G&NC computers;
- An internal I2C on CubeSat kit connector to connect all the core systems;
- An external I2C connected to the tree computers and all the external components.

Dedicated (SPI, PWM, RS-232,…) point to point connections are used to connect sensors and actuators.

TABLE 3: CLEANSPACE ONE PRELIMINARY MASS BUDGET. CBE: CURRENT BEST ESTIMATE.

Subsystem (SS)	Mass in kg (best estimates)	
	CBE	***CBE + SS contingency***
CDMS	0.8	0.9
TM/TC - COM	1.1	1.3
Power - EPS	3.9	4.7
ADCS/GNC	3.0	3.6
RV sensors	2.0	2.4
Capture system	3.1	3.7
Propulsion AOCS	7.5	9.0
Propulsion EP	2.1	2.5
Structure & Thermal	5.2	6.2
Total DRY	**28.6**	**34.4**
System contingency (20%)	5.7	6.9
Propellant	1.2	1.2
TOTAL [kg]	**36**	**43**

B. *Electrical Power System (EPS)*

The power system is divided in two separated power systems, one that handles core and safe mode functionalities (CDMS/COM/Basic ADCS), and one that handles all functions related to the rendezvous, capture and de-orbiting phases. The core system is supplied by 6 x 3U solar panels (one to two on each face) generating between 7 and 14 watts (on a 4V solar panel bus). This system provides power at all spacecraft attitudes. The core system also has a set of 38 Wh batteries for eclipse. The ADR dedicated EPS is supplied by two deployable solar panels (7 x 3U solar panels each) and one located on one of the faces (1 x 3U solar panel). This system can produce up to 90 watts and it carries batteries with an energy storage capacity of 78 Wh. This system can provide up to 1h of autonomy for the approach and grasping if the main solar panels are not illuminated. The overall EPS system uses four P31us power supplies with 3 BP4 batteries boards from Gomspace and a distribution unit CN-SWT-0035-CS from Clyde Space. These 4 boards can process up to 120 W. Table 4 gives the preliminary power budget.

Note that the current configuration of the solar panels needs to be changed and improved to fit better plumes and needs for the propulsion systems.

C. *Telecommunication system*

Two communication systems are implemented on CleanSpace One:

- The main one is based on A482C board from Gomspace. It use UHF amateur band and allow half duplex communications at 9.6 kbps. This link will be used to send command and downlink housekeeping data.

TABLE 4: CLEANSPACE ONE PRELIMINARY POWER BUDGETS.

Subsystem	Power in W (best estimates)		
	Peak	***Capture mode***	***Orbital transfer***
CDMS	0.35	0.35	0.35
TM/TC - COM	11	6.5	0.5
Power - EPS	10	10	9
ADCS/GNC	31.9	23.4	16.9
RV sensors	10	10	-
Capture system	32	15	-
Propulsion AOCS	10	8	-
Propulsion EP	35	-	35
Thermal	5	5	5
Contingency (30%)		23.5	20
TOTAL [W]		**102**	**87**

- A fast downlink for pictures and videos is based on an S-Band transmitter from Clyde space. This link allows increasing the data rate up to 2 Mbps. This board will have a dedicate data link with the main OBC.

UHF will have an omnidirectional canted turnstile antenna based on ANT430 from Gomspace. This antenna consists of four monopole antennas combined in a phasing network in order to form a single circular polarized antenna. S-band will use two patch antennas to be omnidirectional.

D. *Propulsion*

Propulsion is one of the least developed technologies for CubeSat due to their size. This subsystem is a major driver on the overall design, not only for ΔV and impulse-bit performance but also for power, mass and volume.

Table 4 summarizes the preliminary ΔV results per phase. Margin is included in the results.

Several micro-propulsion technologies have been evaluated, and several may fit the ΔV requirements. For AOCS, solutions are available in the cold gas and micro-PPT fields. The major driver quickly becomes the volume available within the 27 Units. The best compromise found between volume/complexity/mass and ΔV capability was the solution proposed by TNO (Cool Gas Generators). CGGs are very modular in their design and performance capability, and with 4 pods of 100 x 100 x 200 cm, all 6 DoF and a ΔV of 20 m/s can be reached. In addition, the tank, feed system and 5 thruster heads are all integrated within a pod, which makes testing and integration simpler than more conventional cold gas systems. As the propellant is stored as a solid, safety procedures with respect to the launch vehicle are also eased.

TABLE 4: ΔV RESULTS PER PHASE FOR CSO.

Phase	ΔV in m/s (allocation, includes margin)		
	Primary - Electric	***Secondary – Cold gas***	***Duration***
Orbital Phasing	350		2-2.5 yrs
Homing		3	Hours-days
Final approach and inspection		10	Hours
Capture		4	Few hours
Maintenance		3	-
De-orbiting	300		Few months
TOTAL	**650**	**20**	

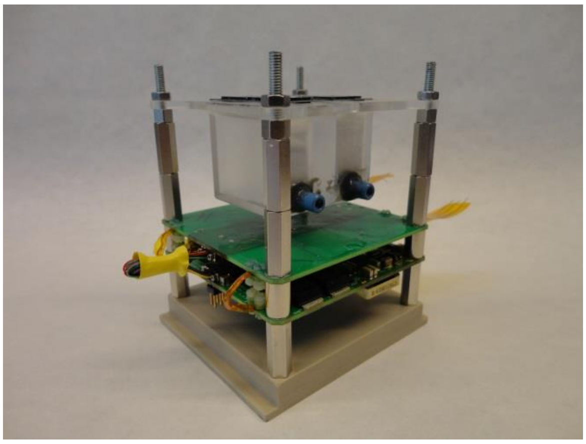
For the primary propulsion (large ΔV), one of the best solution in Europe is the micro-colloid propulsion system called MicroThrust [16] (Fig. 8). This system is under development through an FP7 activity with several European partners and EPFL. Although quite a few thruster technologies have been miniaturized, very few so far have demonstrated to fit the mass, power, volume and large ΔV requirements for CubeSats (target for CSO: 1-2 kg dry, 30-50 W of power, 2-3 CubeSat Units of volume). The other alternative is the system proposed by ALTA, which is a miniaturized version of the Ionic liquid FEEP system [17].

As shown in Figure 8, the MicroThrust propulsion system (pod) is composed of the thruster micro-fabricated emitter arrays (on top, view B), the thruster module (tank and feed system, electronics) and the power conditioning system. Two electrical boards generate the high voltage (HV) and drive the power to the thruster module and arrays. The central Power and Control Board (CPCB) generates the high voltage, interfaces with the satellite's OBC via an I2C bus, and controls the switching of the HV lines while in bipolar mode of operation. The second board ensures the regulation of the THC voltages, the THC voltages feedback, and provides routing to the thruster module. The thruster module holds the tank and feed system (propellant is fed via capillary forces), and the emitter arrays.

The overall pod weighs about 700 gr dry, and for a ΔV of 650 m/s, about 1200 gr of propellant is needed at an Isp of 3000 sec. The thrust generated is about 0.6 mN. To spread out propellant loads and reduce thruster lifetime requirements, three MicroThrust pods will be integrated into the CSO platform. Each pod will be run sequentially with about 35 W input into the power conditioning system. Each pod will use 1 Unit of volume.

E. AOCS

The AOCS system has to perform detumbling at the beginning of the mission as well as right after capture. It has to provide orbit position knowledge and sufficient controllability to perform all phases of the rendezvous (from launch to de-orbiting).

A)


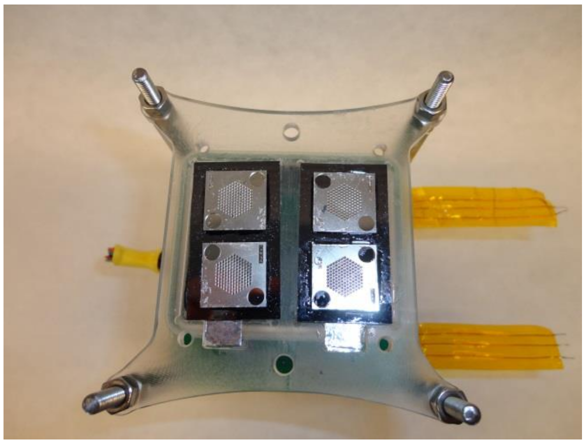
B)


Fig. 8. Example of a miniaturized micropropulsion system (height = 10 cm). A) power electronics fits on 2 electronics boards, tank and feed systems integrated with structure. B) upper view of 4 MEMS emitter arrays. The total system mass is less than 1 kg.

In the current configuration (after a first iteration on the requirements), CSO is equipped with 6 Sun Sensors (from CubeSat Shop, 0.5 deg. accuracy), one 3-axis AMR digital magnetometer from Zarm Technik, one Star Tracker (Micro-Advanced Stellar Compass from DTU), and one ADIS 16375 IMU. The attitude control is done via three MT5-2-M magnetotorquers from Zarm Technik and three RW-0.060 reaction wheels from Sinclair Interplanetary. Further description of the ADCS system can be found in [18].

For absolute navigation, the DLR Phoenix-XNS GPS receiver is currently envisaged. As quoted by the manufacturer, this receiver offers advantages as it extends the functionality of the basic receiver version by a built-in navigation filter for LEO satellites. It also provides a dynamically smoothed and continuous navigation solution even in case of limited GPS satellite visibility. The measurement processing inside the Phoenix-XNS provides a rigorous elimination of ionospheric path delays and enables a real-time navigation [19]. This GPS receiver has also flight heritage on the Proba-2 mission [20].

RV sensors

The Rendezvous sensors suite comprises all the hardware related to the medium range target detection and close range observation of the target, including any active or passive sensing device and the image processing unit. As mentioned in the “mission and operations concept” section, the system is activated upon approaching the target within sensing range and is used until the target is secured. As far as the CSO is concerned several options are being currently investigated.

For the close range observations, meaning range and motion reconstruction, the first option is the use of a commercial High-Dynamic Range camera. This property is important in order to handle the large changes in luminosity due to variation in reflectivity of the target and the relative position of the sun. The 2D-images are used to reconstruct the relative motion and the attitude of the target through key-point matching or optical-flow-based algorithms that are being developed at EPFL. A more hardware extensive option is to use two cameras to determine the 3D dimension information through more traditional stereo-vision algorithms.

For this first option, PhotonFocus [21], a Swiss SME active in the field of HDR cameras has been approached and one of the SMART camera has been tested on-ground in a realistic setting and the images have been fed to the motion and pose estimation algorithms (Fig. 9). The promising results have led us to now to further consider space qualification issues. A qualification test will be conducted in the near future on a micro-satellite platform designed by Beihang University. This mission, which shares similarities in terms of target observation with CSO, will also provide a stress-test for the algorithmic aspect. Eventually a custom built variant might be used for CSO.

A second option, DTU has developed a vision-based system (VBS) derived from one of its star-trackers in the context of the Prisma mission involving the demonstration of orbital rendezvous (Fig. 10). The system involves up to four image sensors which allow target detection and pose estimation covering all the required operational range of the vision system. If the hardware's performance is as advertised, it could also be a potential candidate especially since it has been flown.

A third option involves 3D Camera which are based on active sensing techniques either LiDAR or infrared light. The active component brings several advantages over the standard image sensors. First, the dependence on sun light and varying illumination issues is non-existant. Secondly, it avoids the increased processing requirements needed to reconstruct depth. The drawback however is the limited range of such devices, up to a few hundred meters and the increased power consumption due to the active component. A passive mode or second passive imaging device is therefore required.

Two manufacturers have been identified to potentially provide hardware based on these technologies. In Switzerland the CSEM has developed a flash-LiDAR based sensor which enables depth sensing for long and short ranges. It has the advantage of having been designed for space applications in mind, yield reduced qualification overhead as compared to the HDR camera. The Canadian firm Neptec has also been developing similar technologies albeit in the more heavy duty context for the Space Shuttle missions. Their TriDAR which combines a LiDAR with triangulation capabilities and has the advantage of providing pose estimations directly. While the hardware boasts a high TRL and heritage, it can most likely not be used directly as an off-the-shelf component due to its size and power requirements.

For the far-medium range debris detection, a combination of the DTU VBS and the CSEM LiDAR is currently being investigated.

Fig. 9. PhotonFocus HDR SMART camera and detector [21]. This detector has been used in Space Shuttle missions for docking with the ISS and presents a powerful image processing DSP.

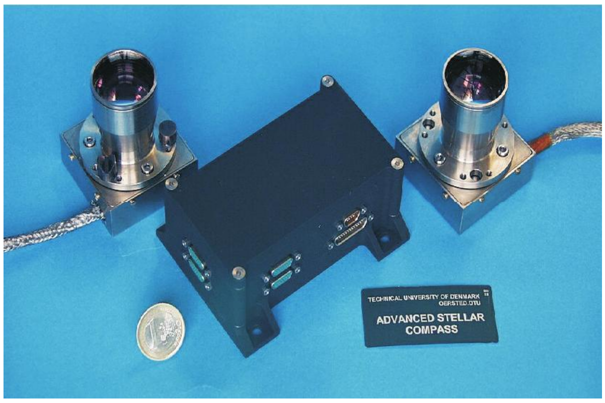


Fig. 10. DTU Advanced Stellar Compass used as the Vision Based System [4].

CSO’s attitude and position are controlled by two OBC as the CDMS based on the GomSpace A712D board (or two AAC uRTU 300). These two computers will share the algorithms to control the satellite during the approach and grasping phases using information from the various AOCS/ G&NC sensors but also from the various cameras and the radar.

Simulations are on-going to verify that preliminary selected hardware has the adequate performance capability.

VI. Conclusions

This paper presents a preliminary design solution for a micro-satellite that is designed to perform rendezvous and capture of a non-cooperative object. Although the target searched for is relatively small compared to the chaser, most functions and technologies are scalable to a large extent for the capture of large debris. It is thus possible to demonstrate critical aspects of ADR in a cost effective manner. The obvious application of such a demonstrator is to remove the SwissCube CubeSat not only for technical reasons but also for national ownership reasons.

The CleanSpace One project is in its Phase A definition and this paper presented the status of its development. A hardware selection approach has been taken in this first iteration to nail down options and identify gaps in technologies. The next phase will be the validation of the choices through detailed simulations and continued design iterations.

References

[1] Liou, J.C., "An active debris removal parametric study for LEO environment remediation", Advances in Space Research, 2011.

[2] CNES paper 6th European Conference on Orbital Debris, Darmstadt, April 2013- Paper to be published in proceedings.

[3] B. Chamot et Al., "Technology Combination Analysis Tool (TCAT) For Active debris Removal", 6th European Conference on Orbital Debris, Darmstadt, April 2013.

[4] J. L. Jørgensen, M. Benn, "VBS - The Optical Rendezvous and Docking Sensor for PRISMA", DTU Space, Elektrovej Bld. 327, DK - 2800 Kgs Lyngby, Denmark.

[5] M. Delpech, P.Y. Guidotti, S. Djalal, T. Grelier, J. Harr, "RF Based Navigation for Prisma and other Formation Flying Missions in Earth Orbit", CNES.

[6] A.E. Overlack, J.M. Kuiper, H. Peter-Contesse and M. Noca, "Analysis of the Attitude Control Instability of the SwissCube Nano Satellite, IAA, Rome, January 2011.

[7] T.N. Edelbaum, "Propulsion Requirements for Controllable Satellites", ARS Journal, August 1961.

[8] J. Herzog, T. Schildknecht, M. Ploner "Space Debris Observations with ZimSMART", European Space Surveillance Conference, 7-9 June 2011.

[9] http://mdacorp-us.com/is/robotics.html

[10] B. Sommer, K. Landzettel, T. Wolf, D. Reintsema, "The In-flight Technology Demonstration of Germany's Robotics Approach to Service Satellites", German Aerospace Center (DLR).

[11] B. Sudki, M. Lauria, « Conception d'un mécanisme de saisie de débris spatiaux », Genève, HES-SO//Master, 8 février 2013.

[12] Keplinger, C., T. Li, R. Baumgartner, Z. Suo, and S. Bauer: 2012, 'Harnessing snap-through instability in soft dielectrics to achieve giant voltage-triggered deformation'. Soft Matter 8(2).

[13] Kofod, G., W. Wirges, M. Paajanen, and S. Bauer: 2007, 'Energy minimization for selforganized structure formation and actuation'. Applied Physics Letters 90(8), 081916.

[14] Personal communications with L. Alminde, http://gomspace.com/

[15] Personal communications with J. Backstrom, http://www.aacmicrotec.com

[16] www.microthrust.eu

[17] S. Marcuccio, P. Pergola, I. Andreani, A. Ruggiero, "Ionic Liquid Field Emission Electric Propulsion for CubeSat–Like Platforms" Alta, Pisa – Italy. 4th European CubeSat Symposium Brussels – Belgium, 30 January - 1 February, 2012.

[18] S. Rossi, "CleanSpace One attitude control subsystem", SSC-master thesis, November 2012.

[19] Phoenix

[20] Spaceborne GPS Receiver datasheet; Communication with M. Markgraf, DLR.

[21] M. Markgraf, O.Montenbruck, S. Santandrea, J.Naudet, "PHOENIX-GPS Navigation System Onboard the PROBA-2 Spacecraft –First Flight results", DLR.

[22] Communications with PhotonFocus, http://www.photonfocus.com.