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SIMULATION AND PROTOTYPING OF THE CLEANSPACE ONE CAPTURE SYSTEM

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Abstract

The objectives of the CleanSpace One mission are to raise the awareness of the orbital debris problem, develop and test technologies for non-cooperative rendezvous, and as a demonstration, de-orbit the SwissCube satellite. The capture system is a "Pacman"-style mechanism composed of five deployment units unrolling bi-stable reelable composite (BRC) booms with a net attached to them. The system is actuated by two motors. The shape and behavior of this net has proven to be critical for the functionality and reliability of the capture. In order to address these concerns, simulations based on net characterizations, as well as full-scale prototyping have been achieved. This paper describes the analysis of the target-net simulations and the functionality test of the prototype. The initial part presents the design of the capture system, including the net, and the capture scenario. The resulting simulation process and net design are then discussed in the main part. The key shape parameters of the capture system (opening angle, length and curvature of the BRC booms) have been defined via the simulations results. To support those results, a full prototype of the net, BRC booms and actuation mechanisms has been realised.

The prototype showed that the design was feasible and viable. The targeted shape could be achieved within the stowing space allowed to the mechanism. It appears that a fully representative test of the capture system must be run under micro-gravity conditions. Test plans evaluations are under further investigation to select the most appropriate means of testing. The research platform of the ISS is currently evaluated as possible candidate for this purpose.
Keywords: Space debris; active debris removal; space mechanisms, debris capture

Acronyms/Abbreviations

BRC: Bi-stable Reelable Composite
CSO: Clean Space One
DoF: Degree of Freedom
DU: Deployment Unit
GNC: Guidance, Navigation and Control
HD: Harmonic Drive
SC: SwissCube
SLS: Selective Laser Sintering
TRL: Technology Readiness Level

1. Introduction

This paper is a follow up of the CleanSpace One capture system design activities presented in [R1]. Since Fall 2015, teams of students at EPFL have been perfecting the capture system, and creating a new version of the prototype. In this paper, we describe the advancements done on the optimization of the shape, design and integration of the net around the structural booms. Additional simulations and tests of the possible rebound of SwissCube within the net are discussed. And finally, the new elements of the prototype are presented. Lessons learned are multiples and show that the integration of the net requires further design work.

2. Capture system requirements

The driving requirements for the capture system can be summarized as:

DR1: The mechanism shall capture SwissCube with a possible rotation rate of up to 50 [°/s] (SwissCube has 2 communication antennas, one of which is a thin 610[mm] long strip).

DR2: The capture system shall be able to retract to enable a second capture trial,

DR3: The mechanism shall capture the target with a reliability of at least 98%.

DR4: The capture mechanism stowed allocated volume envelop has outer dimensions 400 x 400 x 100[$mm^{3]}$, and inner cylindrical dimensions Ø250 x 100[mm^3].

DR5: The capture operations shall generate no new debris of any kind.

DR6: The capture system shall accommodate a maximum relative velocity between Chaser and Target in the final capture phase less than or equal to 10[cm/s].

Greater details on these requirements are provided in reference [R1].

3. Design presentation

The capture subsystem is composed of a set of Bi-stable Reelable Composite (BRC) booms that form the spokes of a basket, completed with a net. The BRC booms are deployed and actuated with the use of the Deployment Units (DU).

Two mechanisms control the deployment and the opening of the net via the DU. The deployment mechanism allows to unroll the BRC booms, while the closing mechanism controls the opening of the net. The conjunction of those two mechanism permits to control the configuration of the capture system as seen in Fig. 1. The net is not shown for illustration purposes.

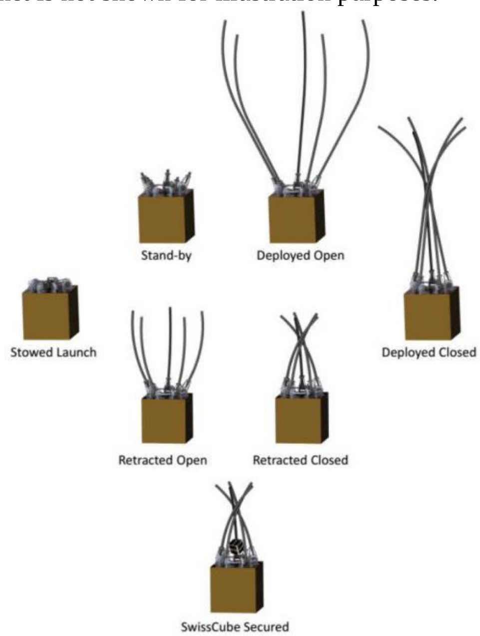

Fig. 1. Nomenclature and illustration of the different configurations of the capture system

3.1 Deployment Unit

The main mechanism of the capture system is composed of five Deployment Units (DU). They can be decomposed in three distinctive parts, depending on their relative motion, as seen on Fig. 2. They control the opening and closing of the net as well as its deployment. Only two motors are used to achieve these functions, with their respective subsystems: The closing mechanism and the deployment mechanism.

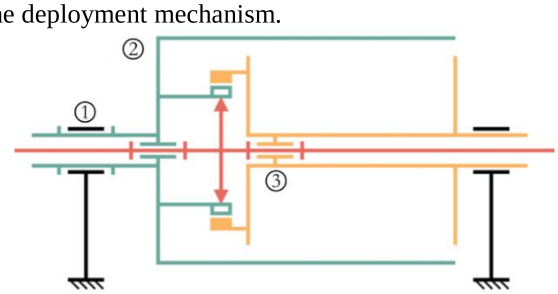

Fig. 2. Linkage diagram of an individual DU

The black part number 1 on Fig. 2 supports the whole unit. The axis in red is linked to the other DU via a set of flexible axis, forming the deployment mechanism. The part 2 is the boom support, as it holds the "neck" that is containing the BRC boom. It is linked via its "Pulley" part to the Closing mechanism and thus is the part that moves when the net is closed.

The Part 3, in orange, is the boom spindle. It is on this part that the BRC boom is rolled. This part is situated at the output of a Harmonic Drive (HD) that is actuated through the deployment mechanism. The high transmission ratio ensures the irreversibility of the rotation, such that only a rotation of the axis will allow to deploy the boom.

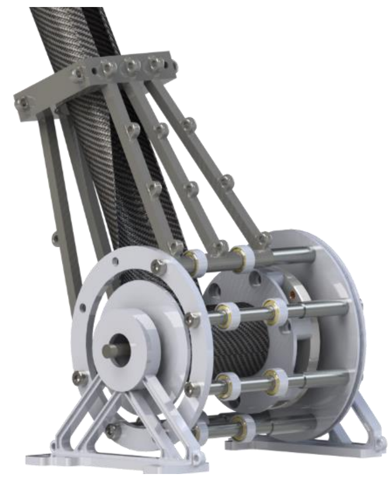

Fig. 3. Rendering of a deployment unit

Fig. 3 shows a rendering of one DU. The neck that is holding the BRC boom is visible in darker gray. For prototyping purposes, some attachment points, in the shape of little extruded cylinders on the surface of the neck, were added to test different net attachment configurations.

As part of the deployment mechanism, a flexible axis transmits torque to the different DU. This type of axis has some advantages regarding the absence of need for lubrication and the high tolerance to axis alignment angle and placement error.

The closing mechanism is composed of a cable running through all DU that controls their orientation. It is actuated by a linear spindle drive and a brushless electrical motor.

3.2 *BRC* boom

The BRC booms have two distinctive parts, the linear part and the curved one. The respective lengths of the different parts are subject to optimisation, that is discussed in section 4.1, while the manufacturing process is presented in previous work, available in Reference [R1].

3.3 Net

The net consists of two main parts. A static protective net that keep the vision subsystem on the face X+ of CSO from being impacted, and the Pacman net, that is weaved around the BRC booms and guided by an upper and lower telescopic stiffener ring. Within the design process, the focus was on resolving the complex net motions under the constraints of protection and vision requirements mainly. The Fig. 4 shows the skeleton on which the net will be weaved, as described in Section 6.2.

Fig. 4. The five BRC booms held by the DU and the two stiffener rings

4. Simulations

To give an insight on the performance of the capture system, simulations of the system's dynamics have been implemented. This allowed the testing of different geometries without the time and resources a hardware implementation would require.

Based upon a 2D simulation in Matlab, which was the source of the dimensioning for the actual prototype described in this paper, two different types of 3D simulations types were implemented and are presented later in this section. Their common goal is to increase the reliability and compactness of the capture system. The first one uses Simulink and Simscape, a set of tools accessible from the Matlab software suite, while the second simulation is a standalone program developed in C++14.

As for the scenario used for the basis of the simulations, only the capture was modelled, namely the closing motion of the BRC booms from Deployed Open position, to Deployed Closed position.

4.1 Matlab 2D simulation

A simple model of the BRC booms allowed obtaining a rough dimensioning already in [R1]. The probability of SC leaving the basket, depending on the point of impact on the net, is estimated through a simple elastic interaction in two dimensions, as shown on Fig. 5.

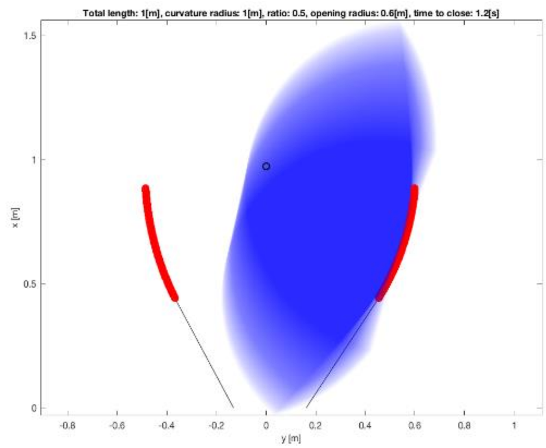

Fig. 5. Visualisation of impact points resulting in escape of SC (red) and statistical dispersion of trajectories (blue)

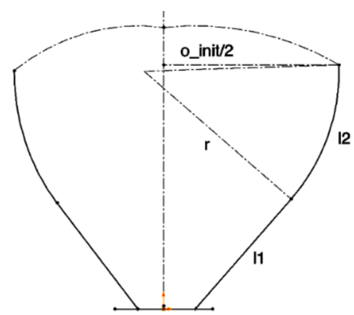

Fig. 6. Schematics of main definition parameters of the net

Fig. 6 presents the parameters that characterize the net. Another indicator of interest is the *ratio*, that can be deducted from l_1 and l_2 as the percentage of linear part over the total boom length. From r, the curvature of the curved part and the opening angle, the diameter of the circumscript circle of the pentagon opening at the beginning of the capture o_{init} can also be derived.

This model allows to give a rough dimensioning for the prototype that is presented in Section 6. As there are multiple parameters that influence each other, some values have been arbitrarily fixed following an example found in Nature, in the shape of the arms of an animal depicted in Fig. 7. The ratio was chosen and it was fixed to 0.55 [-]. The results of the analysis are given in Fig. 8, with a time to close of 1.2 [s].

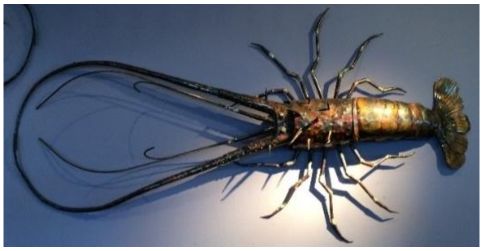

Fig. 7. Warm water lobster

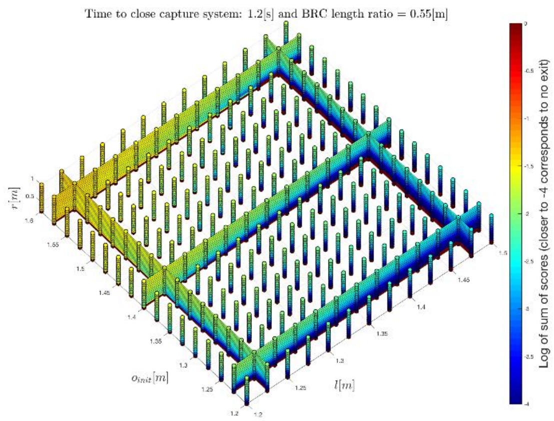

Fig. 8. Results of sweeping opening (*o*), length (*l*) and radius of curved part (*r*) of BRC booms with score in colour

With the aforementioned fixed parameters, it can be observed that factors favouring a capture are: high length, low curvature radius and small opening diameter. After a trade-off based on this results, the parameters chosen as basis for the prototype and the 3D simulations are: a *total length* of 1.4 [m], a *ratio* of 0.55 [-] for the linear part, a *curvature radius* of 0.5 [m] an *initial opening diameter* of 1.2 [m] and a *time to close* of 1.2 [s].

4.2 Simscape 3D simulation

Simscape is a module part of the Simulink package of Matlab. It adds acausal features to the model-based approach of Simulink. This allows the modelisation of systems through equations, giving a larger freedom of interaction management.

With its building blocks, mechanisms can be modelled using multiple Degree of Freedom (DoF) joints as well as springs and dampers. It can handle 2D and 3D collisions and friction forces between simple components such as spheres, planes and tubes.

However, the library only allows contact between the sphere-and-plane or sphere-and-tube configurations. To bypass this limitation, SC was modelled as a sphere with a diameter slightly larger than the edge length of SC rigidly connected with 16 smaller spheres located on the corners and middle of edges of the cube, as seen on Fig. 9. The total inertia of SC was added to the central sphere.

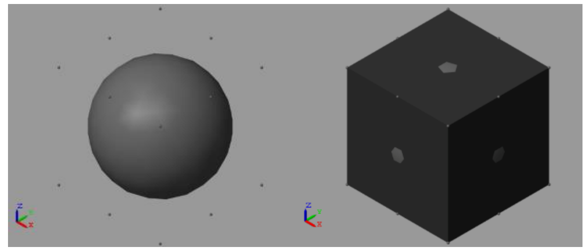

Fig. 9. Modelisation of SC in Simscape

Still, this kind of modelisation remains an approximation, as the contact will only occur on the different spheres and not on the planes, added exclusively for illustration purposes.

CSO could, however, be modelled using tubes and planes for the bus, the BRC booms and the net. Its main bus was set as the reference frame, as its projected mass being two orders of magnitude greater, movements of CSO upon impact with SC were neglected.

The booms are modelled with a linear part, and 5 linear segments to approximate the curved part, as the library does not support curved tubes. Revolute joints are placed between the different segments to account for the elasticity of the BRC boom. The joints at the base of the BRC boom can be actuated to embody the closing motion of the mechanism.

The result of this simulation is a stable basis for a dynamic model of the dynamics of CSO's capture system in the Simscape environment. In the future, it is hoped that these models will be further developed such that a full and validated simulation may be configured. Indeed, the multi-domain functionalities of Simscape would allow to merge the model described here with a Guidance, Navigation and Control (GNC) Simulink model for example, thus allowing to simulate the complete capture procedure.

However, to establish a model with good correlation with physical test results, the model should be adapted and validated extensively. Due to time constraints, there was no possibility to do multiple runs of the model with different initial conditions and to compare with the prototype's tests. Moreover, the computational cost of the model necessitated a computer cluster when it achieved a point where multiple initial conditions had to be tested to validate the different stiffness and damping parameters.

It is hoped that this may be resolved soon, such that the net model in Simscape may be further validated. It indeed offers promising results, but the accurate values for the different stiffness and damping coefficients at the different joints should be adapted. Still, the code of the models established in this project have been implemented with a high number of modifiable parameters, such that it will be straightforward to adapt them should an important design change take place, e.g. the BRC boom shape or their layout on CSO's main structure.

4.3 3D C++ Simulation

To complete the Simscape model and to offer a possibility for comparison, a second 3D simulation was conducted in the form of a C++ program. It was capable of simulating the dynamics of the capture of SC in the net of CSO and was developed using a staged development approach starting from simple environments, with a focus on unitary testing to ensure consistency and correctness from early on. Techniques such as Monte Carlo simulations and Velocity Verlet integrators, have been used to reach the desired result.

Additionally, the tests described in this section show that the program behaves correctly and approximates well enough the capture system net dynamics. Simulations also show physically realistic results, as presented in Table 1. For each test, initial and final velocities (v_0, v_f respectively), incidence angle α and angular speed ω are measured in the real test. The initial conditions are configured in the simulation and the final four columns are the difference between the real test results and the simulation output.

Table 1. Comparison between real tests and simulation results. Velocities are in meters per second, angles in degrees and angular speeds in degrees per second

Net collisions

Description	v_0^x	v_0^y	α_0	ω_0	v_f^x	v_f^y	α_f	ω_f	Δv_f^x	Δv_f^y	$\Delta \alpha_f$	$\Delta \omega_f$
Planar collision	0	-0.35	90	0	90	0.34	0	0	0	0.098	0	0
Rotating collision	0.01	-0.35	92	50	-0.01	0.33	93	50	0.002	0.006	0.877	1.579

Curved boom collisions

Description	v_0^x	v_0^y	α_0	ω_0	v_f^x	v_f^y	α_f	ω_f	Δv_f^x	Δv_f^y	$\Delta \alpha_f$	$\Delta \omega_f$
Planar collision	0.17	-0.98	100	0	-0.17	0.98	100	0	0.002	0.001	0	0
Edge collision	0.07	-0.09	127.875	0	-0.08	0.08	135	50	0.004	0.006	-2.66	4.01

During the simulations, it has been observed that although the antenna can deviate the path of SC, it rarely changes the final capture result: if SC ends out of the net after a collision with the antenna, most probably it would also have escaped without that collision.

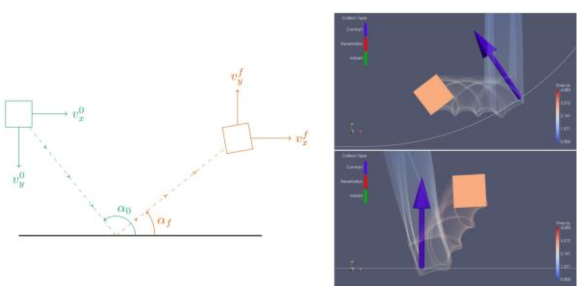

Fig. 10. Collision schematic and respective parameters (left) with examples of results visualization (right).

On Fig. 10 it is possible to see a schematic of the collision, as well as examples of results visualization with collisions in the curved or linear parts of the boom on the right picture. The arrow indicates the normal of the boom at the impact point.

The standalone simulation is useful in determining the behavior of the capture in certain special cases, such as exploring what happens when SC approaches the upper border of the net and whether it can escape capture or not. Fig. 11 shows a visualization of one of these simulations, in which SwissCube's antenna bounces in the curved part of the net without taking an escape trajectory.

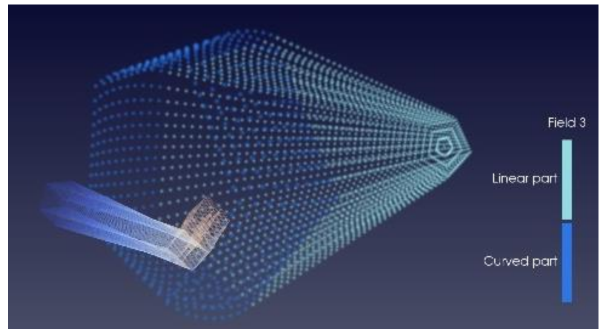

Fig. 11. Visualization of the simulation results of CSO capturing SC with C++ program

Simulation visualization also helped in the observation of the influence of the antenna in SwissCube's movement. Given its flexibility, it does not usually change significantly the trajectory of the satellite, although in some cases it causes a secondary collision that indeed changes considerably the movement.

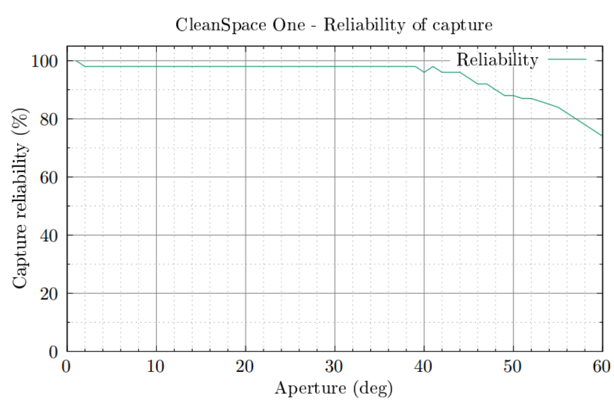

Fig. 12. Reliability of the capture when varying the aperture of the net

Additionally, the Monte Carlo aggregate simulator helps to measure the impact of the change of certain parameters of the net in the capture reliability. For example, image Fig. 12 shows a simple example in which the capture reliability is measured against the aperture of the net. It can be seen that SwissCube only starts to exit in a significant number of the simulations when the aperture is at 40 degrees or higher.

The development from a simple starting point (a point and a cylindrical net) up to the complete SC – CSO model has also been proven useful, as it has allowed to ensure correctness and obtain preliminary results from the beginning of the development.

The use of simple shapes in the modelling made a fast collision detector possible, that works with analytical formulas and not point-by-point sampling, thus reducing the running time.

Future work on this simulator could include further performance improvements to reduce the time needed to collect data from a set of simulations. Collision mechanics, although accurate enough for our current purposes, should also be improved with realistic simulation of multiple collision points and accuracy assessments with results of the inertial model in more situations, such as collisions with a strong lateral component where the strings and knots might play an important role.

5. Validation through net characterisation

As presented in [R1], the parameters of the impacts between SC and the net can be evaluated through testing with a test bench consisting of a 3-meter pendulum on which an inertial model of SC swings to simulate micro-gravity. A camera is used to track the movements of the cube, and the rotational and translational velocities are therefore determined before and after net impact. The damping and other behavioural characteristics of the net could be compared to the simulations presented in Section 4. The estimation of the angle of rebound depending on the direction and amplitude of the initial velocity vector was also one of the parameters of interest.

An image processing method has been developed to enable a more reliable tracking of the cube. There exists however a margin of improvement that can lower the error on the measurements.

Fig. 13. Inertial model of SC with LED for image tracking

Experiments of impacts of the cube on the different set-ups gave a first insight of the dynamics of the rebounds. The first results have to be considered with caution, but it seemed that the net was able to dissipate more rotational energy than the boom. In the boom tests, the fact that rotational velocity energy could be converted into translational energy should be considered in the further development of the capture system, as seen in Table 2. For comparison, the maximal expected rotational velocity for SC reaches 50 [°/s].

Table 2. Examples of increasing exit translational velocity

Test name	v_i [mm/s]	v_f [mm/s]	rot_i [°/s]	rot_f [°/s]	contact duration [s]
Boom.rot2	387	407	162	36	0.4
Boom.rot5	329	370	198	-68	0.39
Boom.rot20	254	280	352	-3	0.44
Boom.rot27	304	322	207	147	0.43

More tests should be performed on representative set-up to allow for a statistical treatment of the results. This would allow a better understanding of the dynamics of the impact of SC with the capture system.

6. Prototyping

To confront the concept presented in reference [R1] to reality, the DU, the BRC booms and the net were manufactured and integrated on a dedicated platform. Different processes were used. The parts seeing the most stress have been manufactured in aluminium, while the most intricate parts were realised through additive manufacturing using the selective laser sintering (SLS) method. The choice of materials has been based on availability and machinability. However, the material selection for the flight model will profit from the results of this prototype.

This section presents the different approaches for the prototyping of the DU and the net subsystems, as well as the respective preliminary results and lessons learned.

6.1 Deployment units and its mechanisms

The Fig. 14 presents the laid-down components of the DU and the Deployment mechanism. One DU is composed of just under a hundred components.

Fig. 14. Layout of the DU before integration

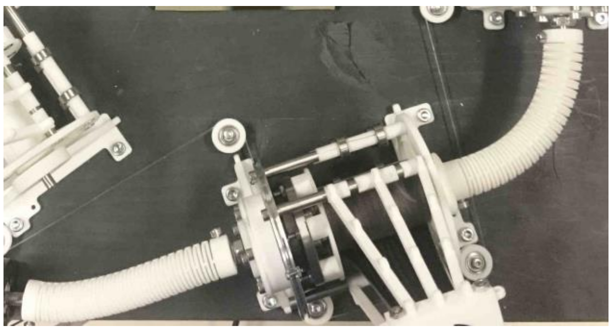

Fig. 15. Top view of a DU with two flexible axis and the cabling of the closing mechanism

The closing mechanism is composed of a cable running through all DU that controls their orientation, visible on Fig. 15. It is actuated by a combination of a linear spindle drive and a brushless electrical motor.

The spindle drive is managed by a field bus that can be controlled through CANbus. The motor position unit is the [qc]. With 380'000 [qc] total possible length, 5181 [qc] give 1 [mm] displacement of the spindle. To close the DU, 80'000 [qc] displacement is necessary, as seen in Fig. 16. For testing purposes, the control was not put in the loop of the automatic capture control linked to the vision subsystem.

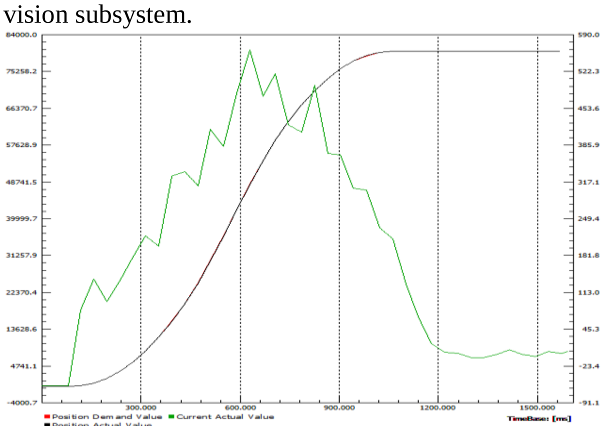

Fig. 16. Position (left in motor reference scale) and Current consumption (right scale in mA) of the closing sequence

The cable show the need of a tension mechanism to ensure proper functionality of the closing mechanism. A loss of tension will result in unwanted behaviour of the closing mechanism.

As for power consumption, the Fig. 17 shows the point of view of the EPOS2 field bus driving the Spindle drive. The parameters to achieve this performance were a maximal velocity of 7000 [RPM] with a maximal acceleration of 10'000 [RPM/s].

With a motor nominal tension of 24 [V], it is possible to compute the power consumption of the closing, as seen Fig. 17. The peak power is at 14[W] and the total energy consumption for the 1.2 [s] closing is 7.9 [J] or 2.2 [mWh]. In order to provide enough power in such short burst, the use of a bank of ultracapacitor can be envisioned in case the power subsystem does not allow for this.

It can be noted that, while closed in upright position under Earth gravity, the assembly generates a position-keeping power consumption of up to 0.2 [W]. It could be measurement noise, but the position-keeping power need to be considered in case of strong attitude manoeuvers are executed, in the last instants before the capture for example.

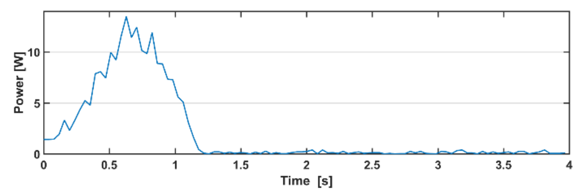

Fig. 17. Power consumption for 1.2 [s] closing

Concerning the deployment mechanism, as using one motor per DU is not optimal, it is desirable that all units can be actuated using a single motor. The motion transmission between units must compensate the misalignment of the units due to their pentagonal arrangement.

As with the closing mechanism, the motor is linked to the different DU in a serial way. Thus, any problem at the interface will result in a loss of functionality of the whole mechanism.

A complete test of the mechanism could not be fully performed, as some issues were encountered. The BRC booms were brittle and nearly broke when entering the neck of the DU, the net got entangled in the flexible axis, and the interface between the DU and the flexible axis was not optimal. Moreover, due to procurement and budget constraints only three HD were available for the prototype.

The power consumption at 300 [RPM], motor side, was nearing 22 [W]. This value can be optimized by fine tuning the motor used to actuate this mechanism.

6.2 Net

The net design includes the determination of the net attachment and the folding mechanism in such a way that the net can be retained during launch and deployed in the mission, can be closed, retracted and opened for at least two times and is able to secure the target for deorbit.

The emphasis of the development is set to resolve the four functions "Close net", "Retract net", "(Re)open net" and "Unfold (redeploy) net", as not all functions relating to the net assembly are active at all mission phases and as the most complex configuration arises during the capture as seen on Fig. 18.

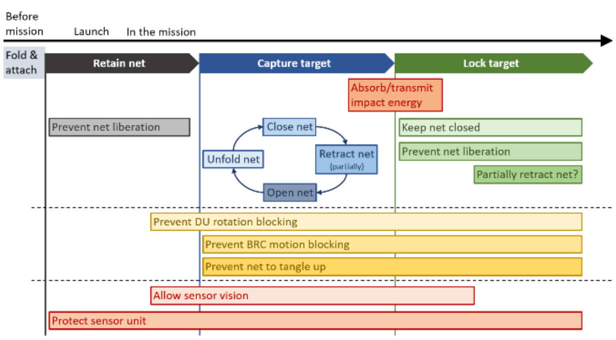

Fig. 18. Chronological functional decomposition of the net assembly throughout the CSO mission phases

As proposed by precedent project work the capture of the target and the protection of the sensor unit is functionally decoupled by realising a Pacman net and a Protective net respectively. Also, the net is placed outside of the BRC booms because it forces the net to follow the boom geometry and naturally causes tension and stability to the deployed capture system. As baseline net materials serve a Polyethylene fiber known as Dyneema and Aramid fibers as a solid alternative.

A sequential design approach exploiting the possibilities of mock-up prototyping and 3D-printing was applied by increasing the complexity by adding new functionalities stepwise.

6.2.1. Net reinforcement and guidance: stiffeners

The upper and lower stiffener rings are 3D-printed, consist of three telescopic stiffener elements attached to the caps (upper ring) and of two telescopic elements attached to the sliders (lower ring) respectively (see Fig. 19). These rings guide and reinforce the net with spring elements that force the net to go inwards and close properly. They limit the degree of freedom of motion in- and downwards to guide the net and keep it within the shape defined by the BRC booms in any phase. The telescopic tubes are joint by snap-fits and are connected with S-shaped springs to each other and the caps or slider hinges. The springs form “heads” on one side, transforming material bending into traction and therefore increasing the bending resistance as soon as the heads touch each other. Hinges allowing for 90° rotation connect the stiffeners towards the caps and sliders by snap fits as shown on Fig. 19 and Fig. 20.

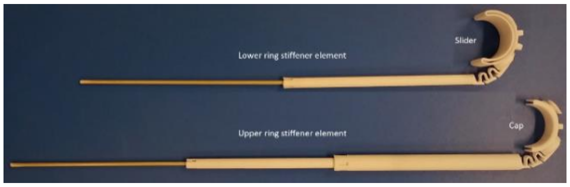

Fig. 19. Assembled lower stiffener ring element (top) and an upper stiffener ring element (bottom)

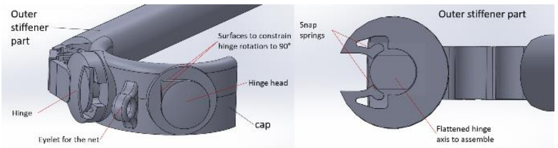

Fig. 20. -Model of the cap and outer part of upper stiffener ring (left) and clip section view on the hinges snap fit (right)

The stiffeners are especially required to prevent the formation of tunnel-like openings at the top end of the net in the closed state and sagging of the overhanging net in the retracted state of the BRC booms. This could allow the target to escape and in the latter case, the net would directly be subject to the heat of the GNC thrusters.

6.2.2. Thruster plume heat influence on the net

As some of the thrusters will be positioned on the side faces of CSO and point into X+ direction its plumes will create a non-negligible heat flux incident on the Pacman net and the BRC booms. A simplified 2D-geometry model considering the thruster plume heat field, the solar irradiation and the thermal radiation emitted is used to estimate the equilibrium temperature in the net for each configuration of thruster axis angles, BRC boom opening angle and vertical thruster position. It shows that with the current net shape and Dyneema as material, and with an opening angle of 26.5[°], the thrusters should be positioned more than 20[cm] away with a thruster angle of 30[°] or more to prevent net damages.

Even though the thruster pulses might be very short and the incident heat might may be less critical, a more detailed evaluation is suggested including a trade-off of material selection and (post-)processing to reduce the absorptivity and/or increase the emissivity.

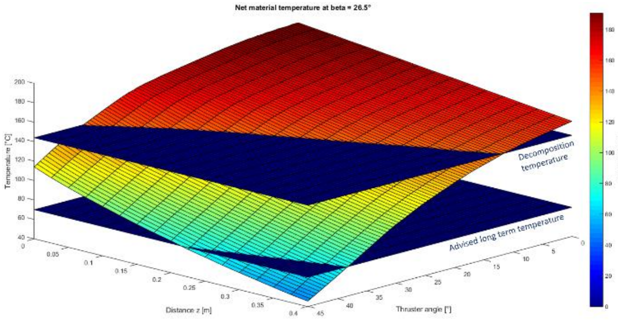

Fig. 21. Maximum equilibrium temperatures (z-axis) arising in the Dyneema net with BRC boom opening angle of 26.5[°] depending on the vertical thruster position (x-axis) and thruster angle (y-axis). Advised maximum long term operation temperature and decomposition temperature are represented by the horizontal dark blue sheets.

6.2.3. Full scale net prototype

The prototype of the net sub-assembly consists of the Pacman net, the Protective net and an upper and lower stiffener ring. The Pacman net is weaved through the booms and the stiffeners and attached through eyelets to the boom support of the DU, the sliders and the caps. Using a “mould”, the net is shaped such that the Pacman net follows closely the deployed BRC boom shape volume.

The Protective net is attached to the top of the inner boom support of the DU in such a way that the net is stretched but not under high tension at the maximum boom opening angle of 30[°], visible on Fig. 22. This guarantees protection of the sensor unit during the critical opened standby and opened deployed position while not creating a large rebound, nor blocking the DU actuations.

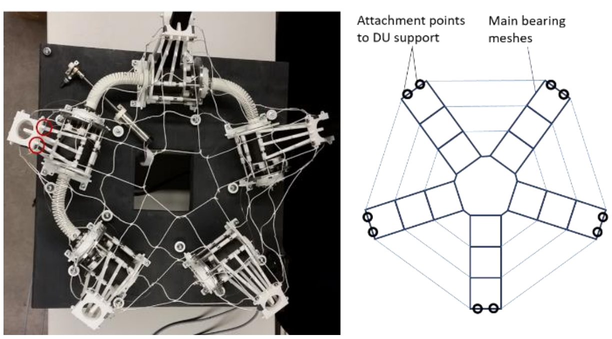

Fig. 22. The Protective net, its attachment points on the DU boom support (left) and its design principle (right)

The total weight of the net sub-assembly reaches 246.3[g]. For this prototype a rather simple, easily adaptable Nylon decoration fishing net material with a 50[mm] mesh size is used.

Eventually a full-scale capture system prototype was produced and is visible on Fig. 23.

Fig. 23. full-scale capture system prototype

6.3 Evaluation of the Prototype

Tests of the main capture system positions included several cycles from open deployed position to closed position, one partial retraction, establishing the stowed launch position and the opened standby position. A full functional cycle was not yet possible.

The fundamental motions to close and reopen the net in the deployed position can be conducted with the current prototype. Under gravity, the upper stiffener ring conducts the wanted in- and downward motion. However, the boom endings do not coincide or overlap in the closed position due to large rotational deflections from manufacturing impurities as visible on the left of Fig. 24. Also, a sufficient overlap of the boom endings is prevented by the upper stiffener ring, as seen on the right of the same Figure.

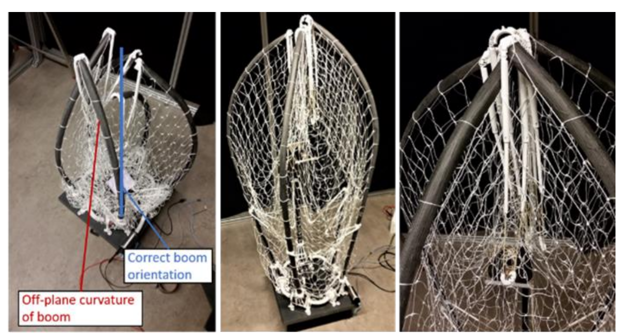

Fig. 24. Deployed closed position: BRC boom misalignment (left), established correct position (middle) and insufficient overlap due to the stiffeners (right)

Retracting the net half way in the closed position revealed that the lower stiffener ring correctly forces the lower net sections inwards. On Fig. 25, it is possible to see that the middle and upper net sections have the freedom to hang slightly loose and tangle up in the screws of the flexible axis, for example.

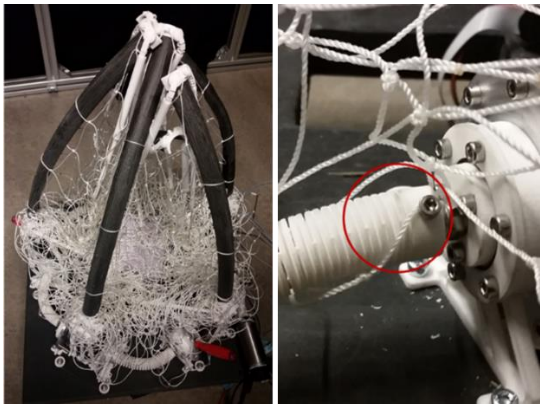

Fig. 25. Secured position with half-way retracted BRC booms (left) and tangling up of the net in an assembly screw head of a moving flexible axis (right)

When opening from the retracted closed position, the middle and upper excess net sections start forming bowls in the thruster critical area. Also, the stiffener's spring heads tend to tangle up with the net during the closing motion which leads to a deformed capture system shape in the subsequent retracted open position.

The stowed and standby positions were established successfully from the partially retracted closed positions. The stiffener rings can not only be stored within the envelope, moreover they support the stowing motion of the net by dragging it to the correct position.

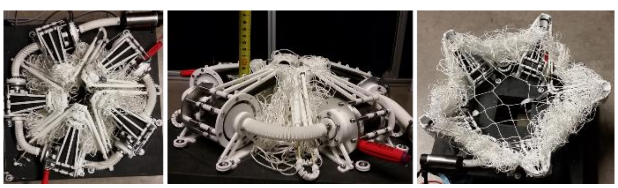

Fig. 26. Top view (left) and side view (middle) on the stowed launch position and the standby position (right).

7. Discussion

The integration of the prototype showed that the concept was viable, as the capture movement could be initiated. However, although major developments were made, there is room for improvement on different aspects of the design.

The main observation from the tests is that the net stowing was not yet successful in terms of keeping all the net inside the volume shaped by the BRC booms. This is especially the case in the retracted open position, where bowls are forming in the critical thruster plume area because of excess net due to the retraction of the BRC booms.

The closing time of 1,2 [s] could be achieved with the prototype configuration. However, a proper tension of the cable is necessary to guarantee the intended behaviour and performances. A tension mechanism and actuator could be implemented to prevent the problems due to long exposure to temperature cycling. The cable could also be stowed within the plate, allowing for compact design and temperature management.

The optimal position of the lower and upper stiffener ring should be identified, while the addition of an intermediate stiffener ring is to be evaluated.

Also, the net material properties and the net shape should be evaluated to reduce interactions with the vision subsystem.

The problematic of the net management, from manufacture to redeployability is a non-negligible and mission critical issue. Solutions can arise from the use of a finer mesh that reduces the size of the features in which it can entangle and possesses more homogeneous properties that allow for a straightforward simulation and design.

8. Conclusion

To raise the technology readiness level (TRL) of CSO’s capture system, an integration of the net on the BRC booms was necessary. This prototyping effort had a design reference frame given by different simulations of the capture system.

While the net and basket type capture system has showed to be feasible, some issues with net management have been identified and will be further addressed.

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References

[R1] M. Richard et al. «Developing a reliable capture system for CleanSpace One», IAC-16-A6.5.2, September 2016