

Phase 0

CleanSpace One Gripper Report

Prepared by:

Irina Gavrilovich

Checked/Approved/Signed by:

Herbert Shea

Muriel Richard

•
Swiss Space Center EPFL
Lausanne
Switzerland
•
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References

- [1] Arianespace, «Ariane 5 User's manual Issue 5 Revision 1,» 2011.
- [2] W. J. Larson, Space Mission Analysis and Design, Third Edition, Microcosm Press, 2005.
- [3] W. Fehse, Automated Rendezvous and Docking of Spacecraft, Cambridge University Press, 2003.
- [4] B.N.J. Persson, On the theory of rubber friction, Surface Science 401 (1998) 445–454
- [5] M. T. Petralia and R. J. Wood, Fabrication and analysis of dielectric-elastomer minimum-energy structures for highly-deformable soft robotic systems, The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, October 18-22, 2010, Taipei, Taiwan
- [6] P.Brochu, Q. Pei, Advances in dielectric elastomers for actuators and artificial muscles, October 27, 2009; DOI 10.1002/marc.200900425
- [7] R. Pelrine, High-field deformation of elastomeric dielectrics for actuators, Materials Science and Engineering C 11 _2000. 89–100
- [8] B.N.J. Persson, On the theory of rubber friction, Surface Science 401 (1998) 445–454

Terms and abbreviations

ADCS	Attitude Determination and Control System
ADR	Active Debris Removal
CM	Centre of mass
EAP	Electroactive Polymer
DEA	Dielectric Elastomer Actuator
DEMES	Dielectric Elastomer Minimum Energy Structure
PDMS	Polydimethylsiloxane (silicon-based organic polymer)

1 Introduction

Space is a fast developing field of exploration. Every year dozens of rockets launch with different missions, new satellites reach the orbits and with it new debris appears in space. Every year this problem becomes more and more urgent. Various approaches are proposed till now to solve the space debris problem.

The CleanSpace One is the project of the satellite-catcher with the goal to find and grab space debris. Grasping system (gripper) is the important part of the satellite which grabs, fixes and holds a target during the mission. General solution for this system is mechanical arm. But it has a few key disadvantages for space application; there is heavy weight, large volume and amount of moving elements that often operate with difficulty in space environment. Alternative solution is soft manipulator made of compliant materials and providing octopus-like grasping.

Soft robotics is an emerging field, which recently appear and rapid progress due to ample opportunities for its application. The very significant line of development of soft robotics is dielectric elastomer minimum energy structure (DEMES). DEMES usually consists of two parts: dielectric elastomer actuator (DEA) giving relatively high displacement when voltage (typically on the order of kV's) is applied and flexible frame which experiences out-of-plane bending when bonded to pre-stretched DEA. Applied to DEA voltage provokes an electrostatic pressure between compliant electrodes on the surfaces of DEA. This pressure causes elastomer contracts in thickness direction and expands its area; as a result frame tends to return to planar state. This effect allows getting large actuation stroke in DEMES.

Use of DEMES actuators for space application is advantageous due to lightweight and flexible nature that allows storing DEMES gripper rolled before its operation on the orbit and reducing required volume. Besides that grasping system with DEAs is energy efficient, it needs voltage exclusively for the deploying process (few msec) but not for all operation time on the orbit. Grasping and holding the target goes owing to the actuators return to passive state. Thereby DEMES and DEA applications for space mission look very promising and can find wide spread occurrence as more efficient equivalent for robotics part.

The object of this paper is gripper design based on DEMES. In order to prove possibility of use DEA and DEMES for satellite grasping system and its robustness for this application some calculations and tests are presented.

2 Satellite structure

The CleanSpace One is a microsatellite intended for removing space debris from the orbit (). Its architecture shall allow finding debris on the orbit, tracking, grasping and holding it till the end of the mission. The subsystems providing data communication with ground stations and controlled satellite re-entry are required for the mission success.

The CleanSpace One represents a cube structure with sizes 30x30x33cm and mass 30kg.

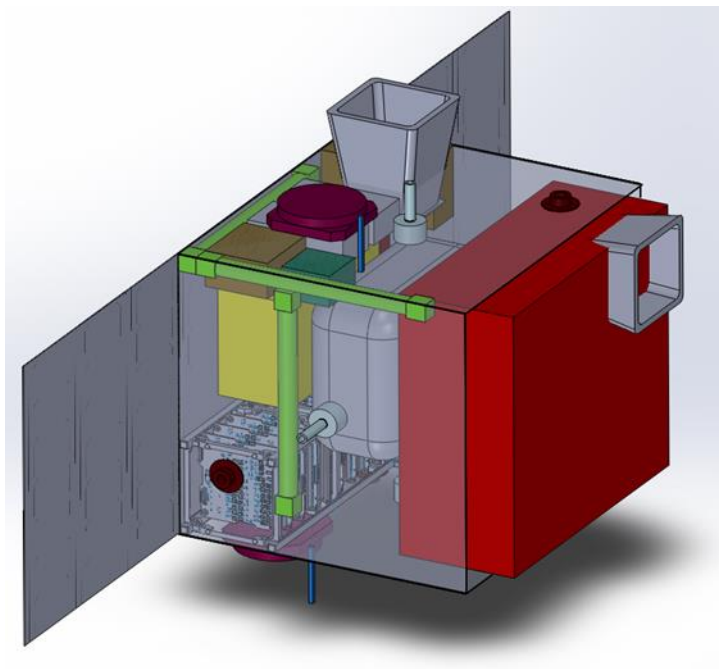


Figure 1 – CleanSpace One

3 Debris

For the CleanSpace One mission two objects are considered as targets, there are Vespa upper structure and the SwissCube satellite.

Vespa is cone-cylindrical shape as shown in Figure 2 with sizes presented in Table 1.



Figure 2 Vespa upper structure

Table 1 – Vespa dimensions

H	1340 mm
Small diameter	937 mm
Large diameter	2084 mm
Mass	150
$I_x = I_y$	85.43 kg·m ²
I_z	132.31 kg·m ²

SwissCube (Figure 3) is a single unit CubeSat built by Space Center EPFL and launched in 2009. SwissCube mission was focused on the observation of the airglow phenomena. The spacecraft successfully operates on the orbit for more than 3 years and already achieved its goals. In December 2011 the SwissCube project was officially closed and become a good probable target for Orbital Debris removal. SwissCube properties taken into account in this paper presented in Table 2.

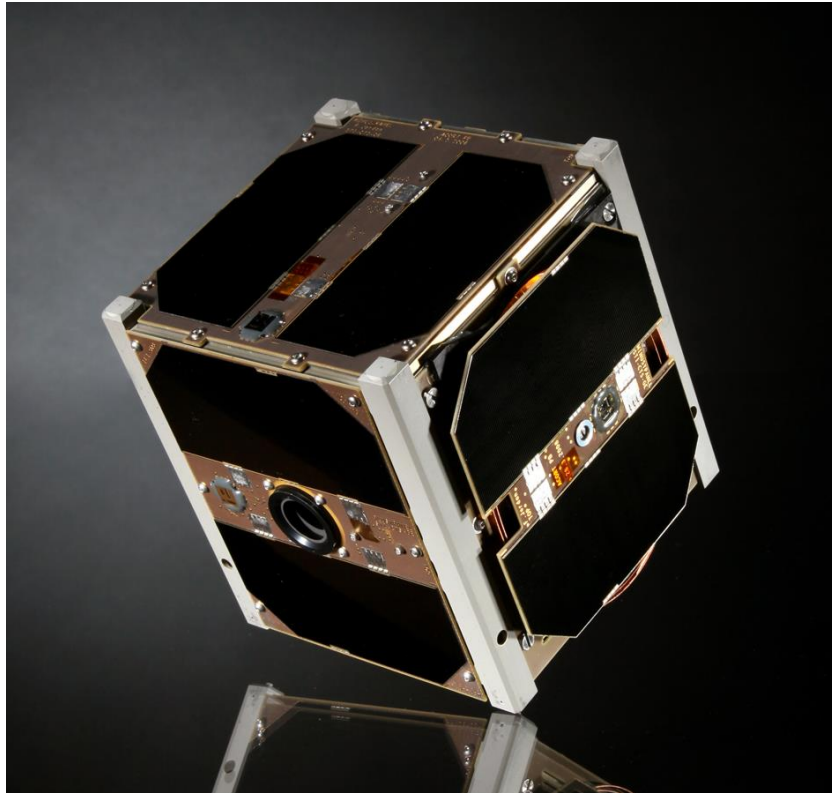


Figure 3 - SwissCube satellite

Table 2 - SwissCube dimensions

Sizes	100 x 100 x 100 mm
Mass	0.822 kg
I_x	$0.00192 \text{ kg}\cdot\text{m}^2$
I_y	$0.00246 \text{ kg}\cdot\text{m}^2$
I_z	$0.00234 \text{ kg}\cdot\text{m}^2$

4 Gripper overall description

The gripper shall be able to grab and hold on the target until the end of the mission; as well it shall have enough length to embrace given target.

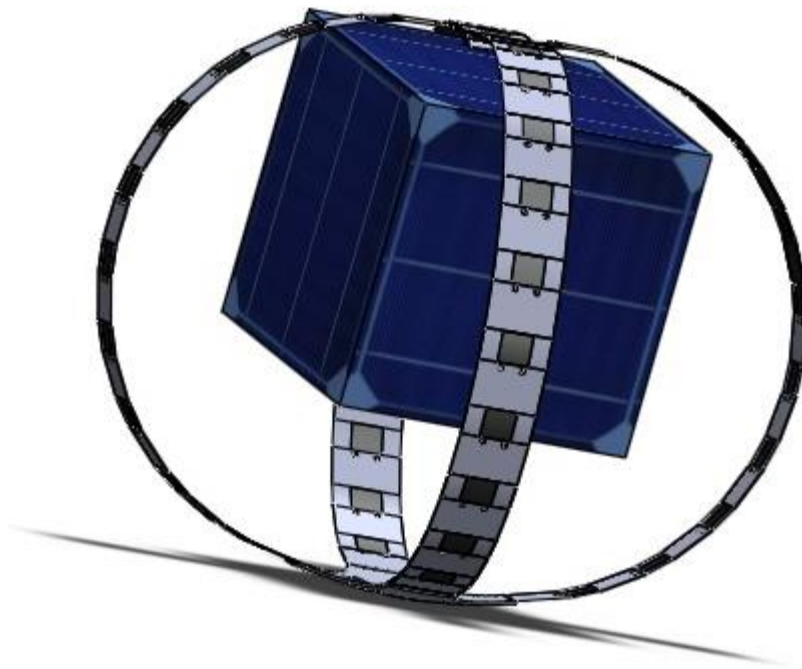


Figure 4 – The gripper with grabbed SwissCube

The gripper consists of 3 main parts; there are arms, base structure and controller. The arms represent chains of DEMES actuators connected one by one mechanically and electrically. Both surfaces of the actuators are protected by very thin (in order of a few μm) insulated layer of elastomer to prevent break down between electrode on the actuator and any conductive part of the debris. Minimum number of the arms is 3 to have got 3 contact points needed for steady fixation of the object, but 4 arms ensure better robustness (in case of malfunction of one arm) and symmetry of the system. The base structure provides mechanical connection for all arms as a whole structure and interfaces between gripper and satellite. The controller adjusts applying voltage and controls on/off modes of the actuators. The gripper is sketched in Figure 4.

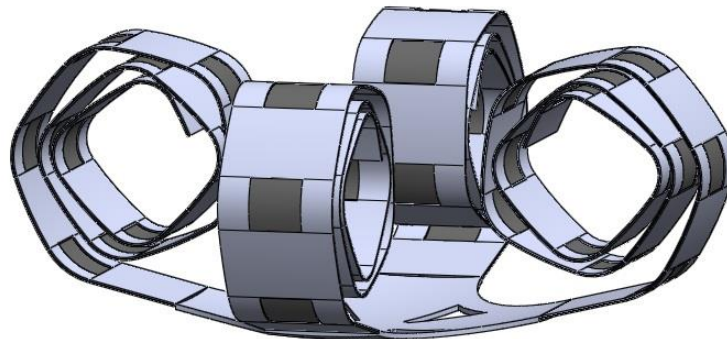


Figure 5 – The gripper stored in rolls

The gripper made with DEMES could be stored in rolls that reduce required volume on board of the satellite (Figure 5). The gripper reverts to the passive (closed) state after deployment as shown in Figure 6 and voltage shall be applied to open it. In actuated (opened) position (Figure 7) the gripper is able to envelope the target and so total actuated angle of all actuators in the arms depends on sizes of given target and shall be large enough to contain it. When the target within the gripper arms applied voltage takes off and the arms grab the debris returning in passive state. Thereby initial total angle of the arm shall be enough to grab the target tight and hold on it for a long time (in order of hours).

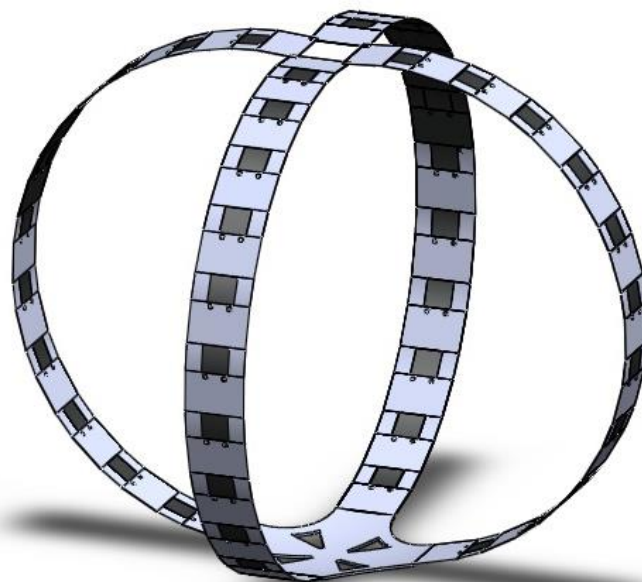


Figure 6 - The Gripper in passive (closed) position

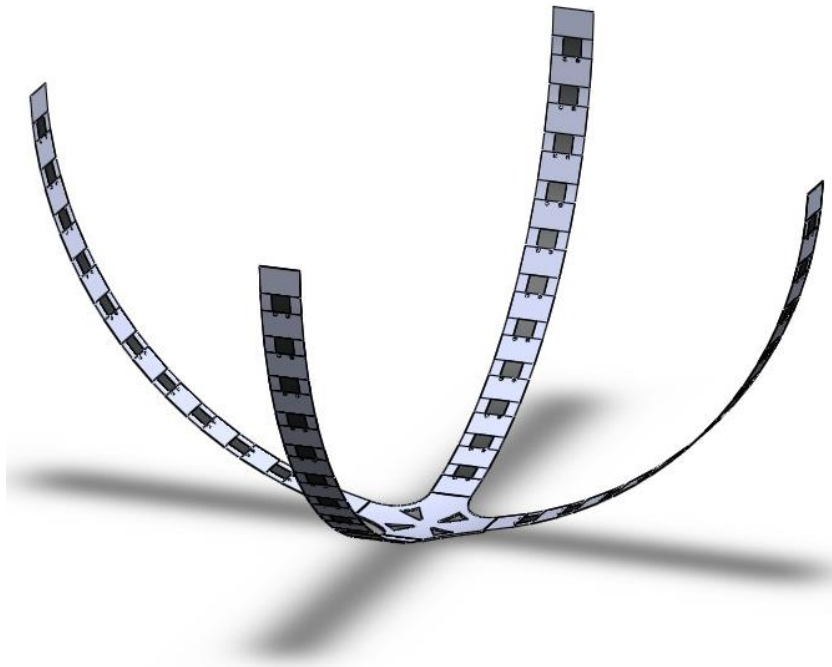


Figure 7 - The Gripper in actuated (opened) position

Required grabbing force depends on the target and de-tumbling time of the satellite-debris system. Calculations of grabbing forces are presented below in section 5.

The controller shall convert board voltage 12V into 3kV, be lightweight and have small sized. Recommended controller PICO 12VV4 is shown in Figure 8, its properties is presented in Table 3.

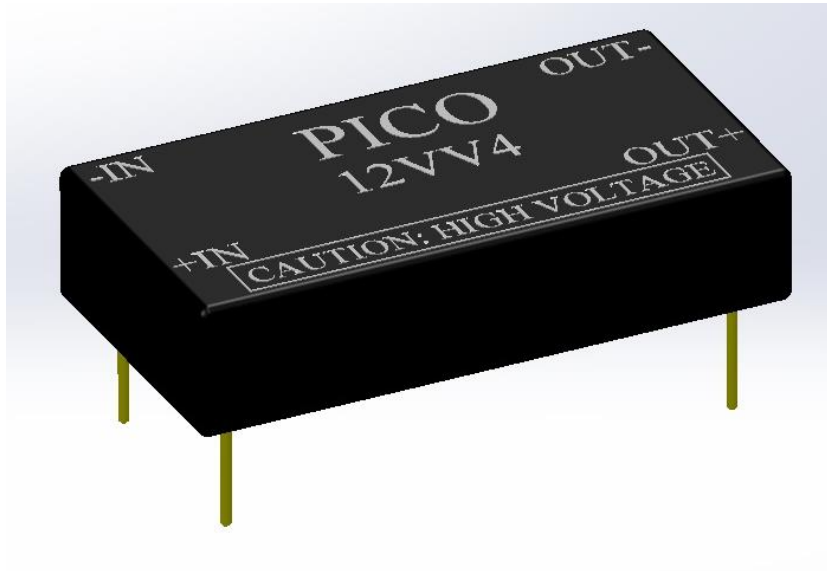


Figure 8 – Controller PICO 12VV4

Table 3 – Controller PICO 12VV4 properties

Sizes	60 x 30 x 15 mm
Mass	0.045 kg
Operating t° range	-25°C to +70°C
Input voltage	4V – 12V
Output voltage	525V – 4000V
Output power (max)	7Watt
Efficiency	70%

The mass budgeted for the grasping system is shown in Table 4.

Table 4 – The grasping system mass budget

Arm	0.045 kg
Base structure	0.015 kg
Controller	0.045 kg
Connectors and fasteners	0.03 kg

5 Dynamics

5.1 General

The grasping dynamics of the gripper with DEA differs from the dynamics of the mechanical arms. For flexible arms deceleration and grabbing the target are the result to a considerable degree of friction between the arms and the target. The compliant nature allows reducing grasping force but requires longer time of grasping manoeuvre (in range from ms to min).

The inertia of the target is highly important in this process and it defines required force in the arms: the larger inertia of the target and the shorter capture time, the larger should be grasping force. Size of the imposed target defines length of the gripper's arm and required bending angle. Actuator's geometry makes no effect on calculated force because friction doesn't depend on a contact area.

The dynamics of the system with compliant gripper is very complicated and the required force cannot be defined exactly on the design phase, but it can be estimated with sufficient accuracy. The safety coefficient compensates error of the calculated result.

The phases of target de-tumbling and grabbing are shown in Figure 9. The target is rotating around the arbitrary axis with constant angular velocity ω_t^* . If this axis is not coincided with the longitudinal axis of the satellite with the gripper, the rotating target would touch the gripper's arms one by one. In the moment of contact the undefined force is applied to the target in normal direction. This force will produce the torque moment around the center of mass of the target. After some touches with the arms the rotating axis of the target will take more stable state. Then the grabbing force of the gripper de-tumbles and catches the target. This grabbing force required for successful mission is defined in calculations below. Some assumptions were applied in the estimating calculations.

Assumptions:

1. I_t and I_{sys} are the maximum moments of inertia of the target and the satellite;
2. The deceleration of the target induced by touching with one arm is negligible, so $\omega_t^* = \omega_t$;
3. The process of the change of the rotation axis is short;
4. The angular velocity acquired by the Satellite with the gripper in this process is negligible;
5. The rotation axis can take two stable states depends on initial orientation – parallel or perpendicular to longitudinal gripper axis. Those cases require slightly different forces. The case with parallel axes is calculated below and the difference for other case is compensated with safety coefficient;
6. The gripper grabs and de-tumbles the target due to friction force only. Normal forces could help to grab and reduce required grabbing force, they are not considered in worst case.

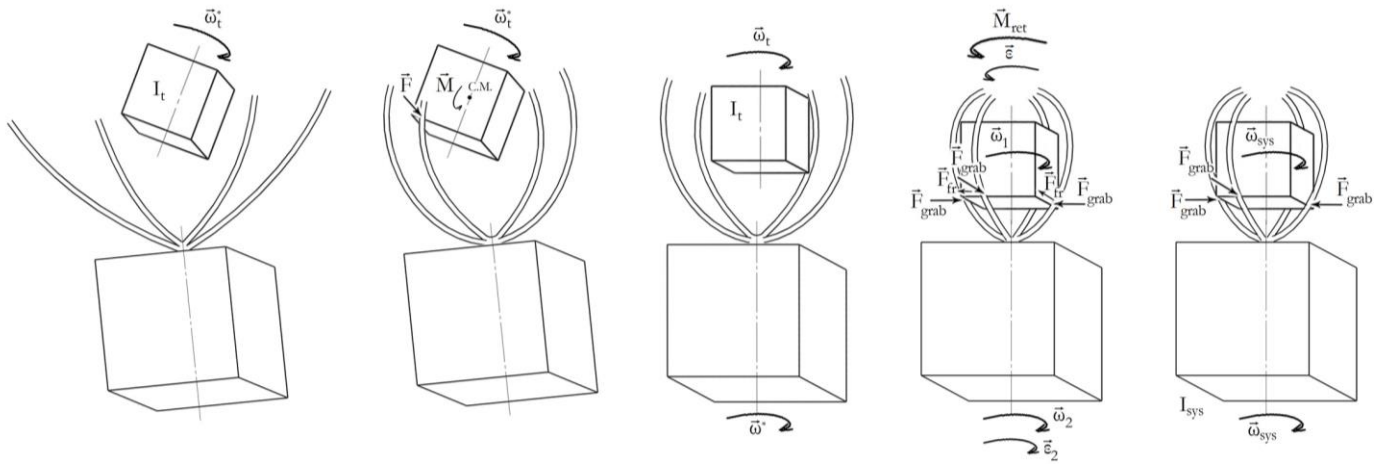


Figure 9 – Diagram of forces in the system of bodies

The grasping process described below is illustrated with phases 4 and 5 on Figure 9. Friction force between the arm and the target is related with the force which the arm provides in normal direction to the target surface in contact spot:

$$F_{fr} = \mu F_{grab}, \quad (1)$$

where μ - friction coefficient between surfaces, F_{grab} - grabbing force of the gripper's arm.

No external torque on the system of the target and the CleanSpace One satellite during grasping manoeuvre so law of conservation of angular momentum can be applied:

$$\sum \frac{dL}{dt} = 0, \quad (2)$$

where L - angular momentum.

For the target-satellite system (2) transforms into:

$$I_t \omega_t = I_{sys} \omega_{sys}, \quad (3)$$

where I - moment of inertia, ω - angular velocity, subscripts "t" and "sys" correspond to the target in free motion and the target-satellite system rotating around its CM.

Angular velocity of the system can be defined with ε - angular acceleration. The system slows down because of added moment of inertia and causes negative ε . Therefore:

$$\omega_{sys} = \omega_t - \varepsilon t, \quad (4)$$

where t is time of grasping manoeuvre.

Retarding torque produced by one arm and acted in the system can be expressed in terms of force:

$$M_{ret} = 4F_{fr} l, \quad (5)$$

where l - arm of friction force;

or in terms of angular acceleration:

$$M_{ret} = I_t \varepsilon \quad (6)$$

These expressions (5) and (6) give relation between friction force and acceleration:

$$F_{fr} l = \frac{I_t \varepsilon}{4} \quad (7)$$

With (1) we find relation for grabbing force:

$$F_{grab} = \frac{I_t \varepsilon}{4 \mu l} \quad (8)$$

The only unknown parameter in (8) is ε , which can be given by combination of (3) and (4):

$$\omega_{sys} = \frac{I_t \omega_t}{I_{sys}},$$

$$\varepsilon = \frac{\omega_t - \omega_{sys}}{t} = \frac{\omega_t - \frac{I_t \omega_t}{I_{sys}}}{t} = \frac{\omega_t (I_{sys} - I_t)}{t \cdot I_{sys}} \quad (9)$$

Considering (9) and (8) final equation for required grabbing force:

$$F_{grab} = \frac{\omega_t I_t (I_{sys} - I_t)}{4 \mu \cdot l \cdot t \cdot I_{sys}} \quad (10)$$

Note:

General values:

- $\mu = 3.3$ Kinetic coefficient of friction for rubber materials on aluminum surface according to [4] is 2.1..4.5 for different rubber surface energy. In calculation take mean value.
- $\omega_t = 0.20$ deg/s or 0.035 rad/s for Vespa;
- $\omega_t = 0.50$ deg/s or 0.087 rad/s for SwissCube.

5.2 CleanSpace One - Vespa dynamics

5.2.1 System description

Considering Vespa's dimensions presented in Table 1 gripper's arm shall be 3m long. The moments of inertia of the bodies presented in TBD and Table 1. For calculations the moment of inertia of Vespa I_t should be equal $I_z = 132.31 \text{ kg}\cdot\text{m}^2$ as maximum.

The positional relationship of the bodies has an influence on the moments of inertia of the system. Possible options include 2 cases of positioning with one common axis and 2 cases of

positioning without common axis. The moment of inertia of the system I_{sys} depends on the distance and the angles (for 2 last cases) between the bodies, so it cannot be precisely calculated for generalized model. But the analysis of the models for all cases presented below gives good estimation for range of I_{sys} .

There are two possible situations when Vespa has one axis coincided with satellite's axis at the moment of grasping maneuverer. Vespa could turn to satellite with one of its end like shown at Figure 10 and Figure 11. For every case system has different moments of inertia and CM position presented at Table 5 and Table 6.

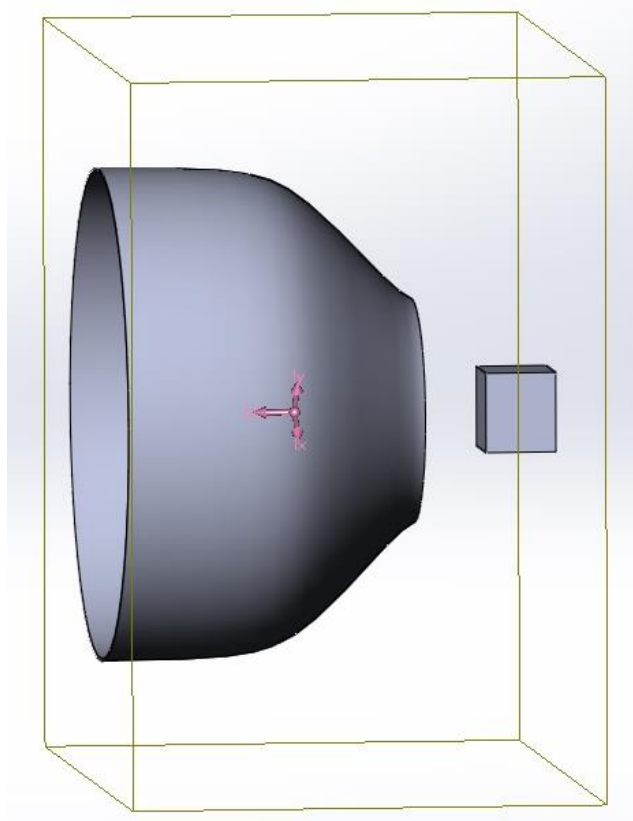


Figure 10 – Vespa-SleanSpace One system. Case 1

Table 5 – Moment of inertia taken at CM of the system. Case 1

I_x	120 kg·m ²
I_y	120 kg·m ²
I_z	132 kg·m ²

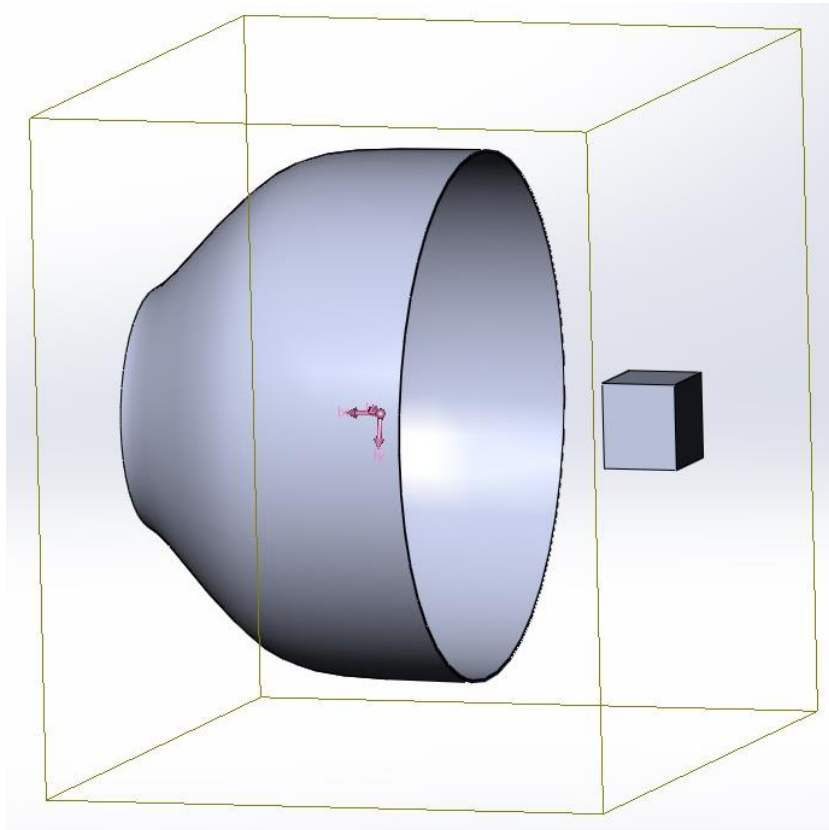


Figure 11 - Vespa-SleanSpace One system. Case 2

Table 6 – Moment of inertia taken at CM of the system. Case 2

I_x	132 kg·m ²
I_y	133 kg·m ²
I_z	133 kg·m ²

Two other cases of positioning, when Vespa and the satellite do not have common axis (Figure 12 and Figure 13), gives another sets of moments of inertia for the system presented at Table 7 and Table 8.

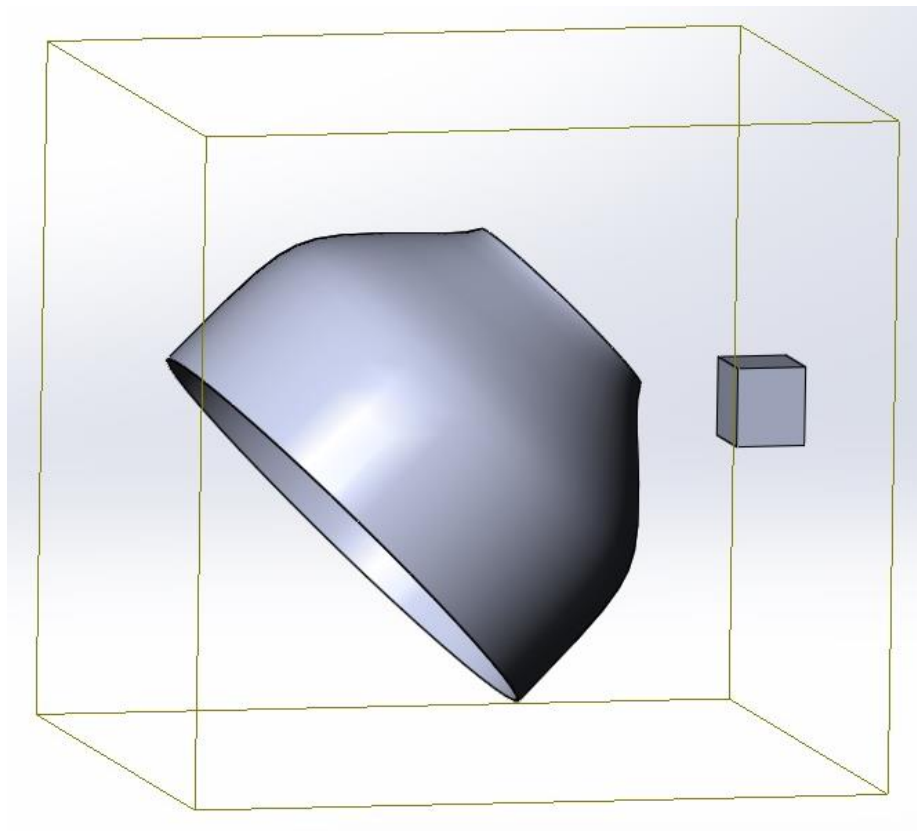


Figure 12 - Vespa-SleanSpace One system. Case 3

Table 7 – Moment of inertia taken at CM of the system. Case 3

I_x	102 kg·m ²
I_y	136 kg·m ²
I_z	166 kg·m ²

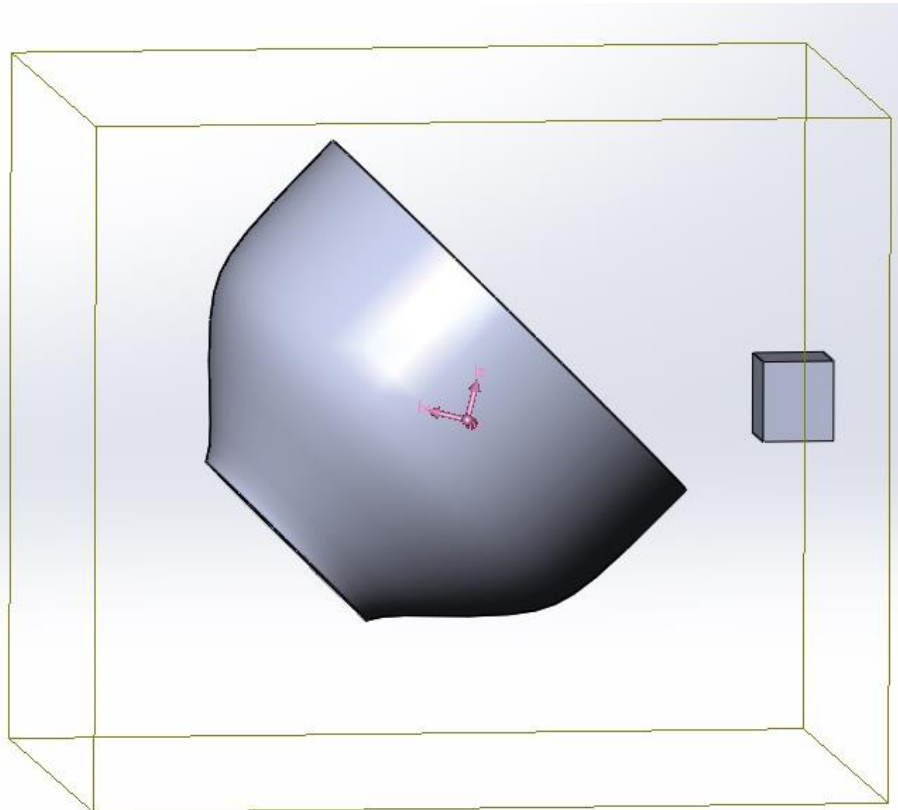


Figure 13 - Vespa-CleanSpace One system. Case 4

Table 8 – Moment of inertia taken at CM of the system. Case 4

I_x	105 kg·m ²
I_v	157 kg·m ²
I_z	185 kg·m ²

As results show the moment of inertia of Vespa-CleanSpace One satellite is 185 kg·m² in the worst case, that should be used in the calculations.

The grabbing force equation (10) requires to know the minimum possible distance between the target's axis of rotation and the point of force application on target's surface – arm of the force l . The contact points of the gripper cannot be predicted properly, so it's reasonable to take value l equal to half of Vespa's small diameter – 468mm.

Table 9 – Values for Vespa - CleanSpace One dynamics calculations

I_t	132.31 kg·m ²
I_{svs}	185 kg·m ²
l	0.468 m
μ	3.3
ω_t	0.20 deg/s
t	0.5..60 sec

5.2.2 Forces

The results of the calculation from Section 5.1 with data from Section 5.2 presented below.

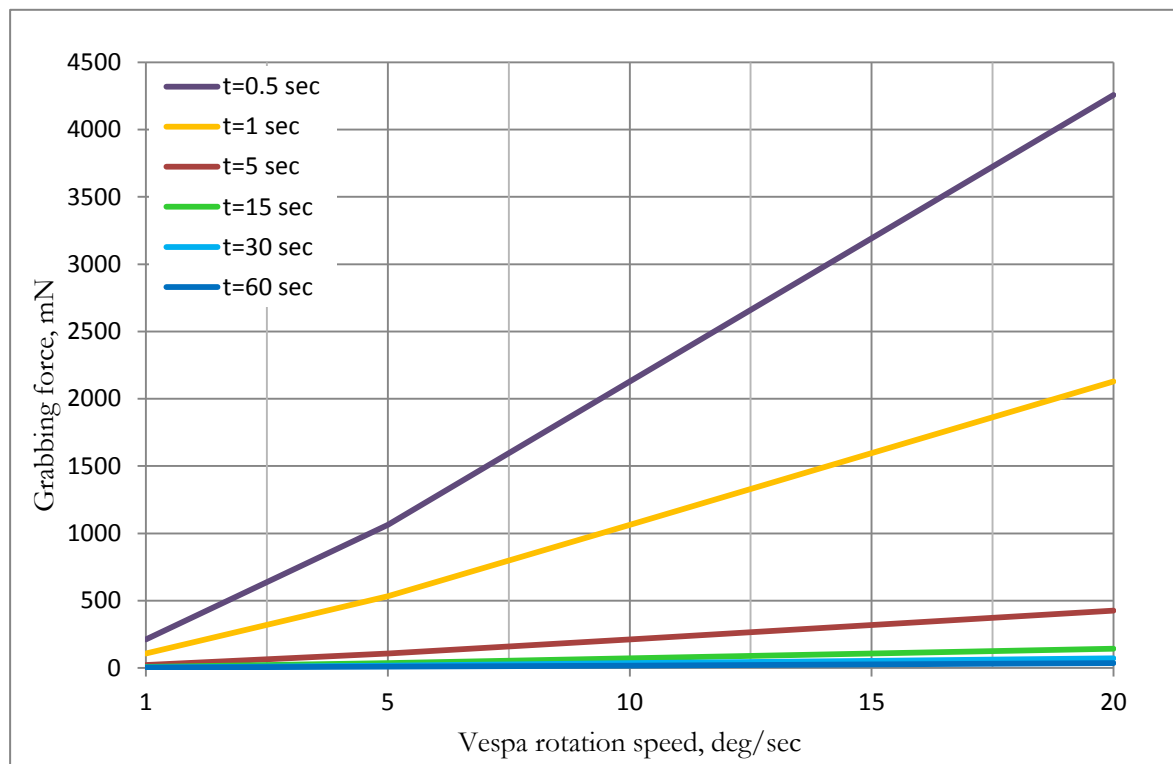


Figure 14 – Required grabbing force

Table 10 – Required grabbing force, t = 1..60s

ω		t, sec					
deg/s	rad/s	0.5	1	5	15	30	60
1	0.02	213	106	21	7	4	2
5	0.09	1064	532	106	35	18	9
10	0.17	2128	1064	213	71	35	18
15	0.26	3192	1596	319	106	53	27
20	0.35	4256	2128	426	142	71	35
		Required grabbing force, mN					

Required forces presented in Table 10 can be compared with forces of the solid (not compliant) arm; geometry of the system is same. Forces of the arm calculated for full transition time in CAD software PTC Creo.

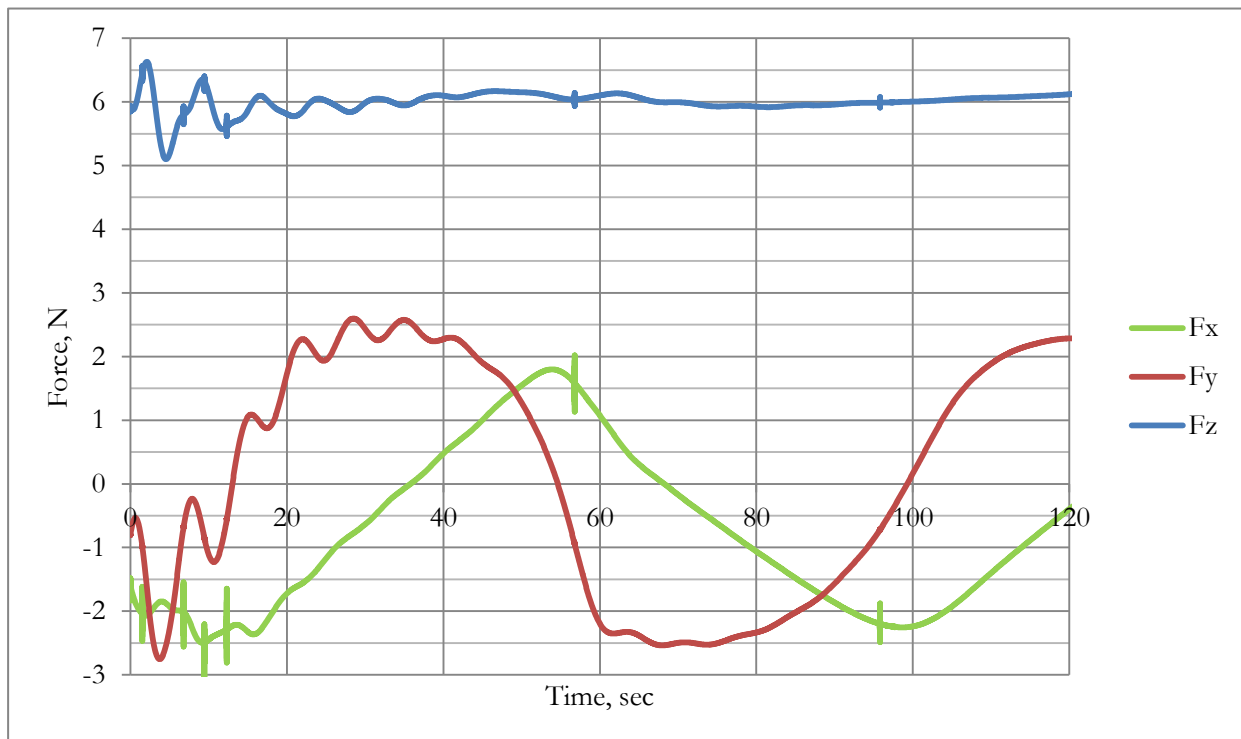


Figure 15 – Forces in the arm. Angular velocity of Vespa 20deg/s

Comparison between the results shows that ranges of required forces are quite close to each other and results presented in Table 10 are valid.

5.3 CleanSpace One – SwissCube dynamics

5.3.1 System description

The gripper shall be possible to grab the SwissCube with sizes given in Table 2 and length of the arm shall be 30 cm to provide efficient grasp.

SwissCube position relative to CleanSpace One satellite doesn't have significant influence on value of the moment of inertia of the system I_{sys} , because SwissCube is much smaller than the satellite-hunter.

The system of bodies is shown in Figure 16 and calculated moments of inertia are given in

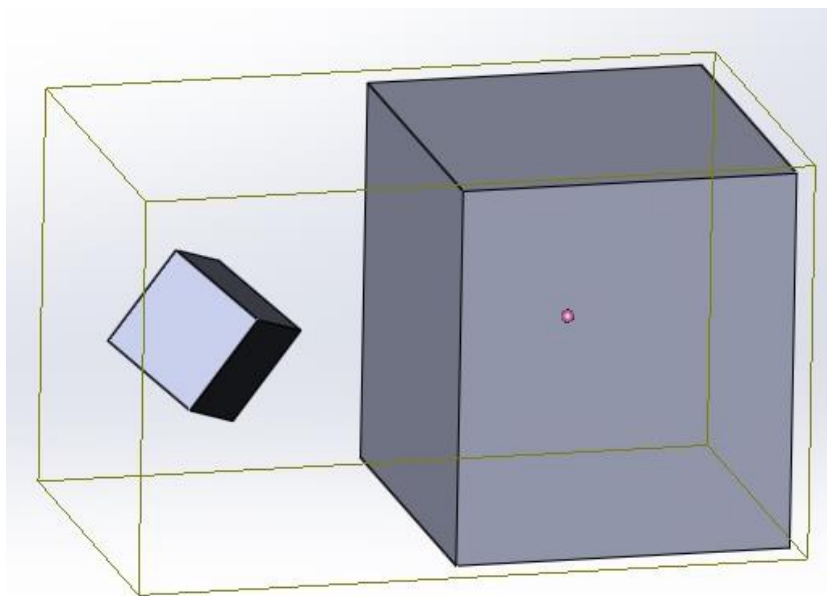


Figure 16 – SwissCube-CleanSpace One system

Table 11 – Moment of inertia taken at CM of the system

I_x	0.52 kg·m ²
I_y	0.61 kg·m ²
I_z	0.61 kg·m ²

The minimum arm of the force could be approximated to most possible value – half side of the cube. Therefore $l = 50$ mm.

All values required for grabbing force calculations given in Table 12.

Table 12 – Values for SwissCube - CleanSpace One dynamics calculations

I_t	0.00246 kg·m ²
I_{svs}	0.61 kg·m ²
l	0.05 m
μ	3.3
ω_t	0..50 deg/s
t	0.5..60 sec

5.3.2 Forces

Calculated forces presented in Figure 17 and Table 13 - - Required grabbing force, $t = 1..60s$.

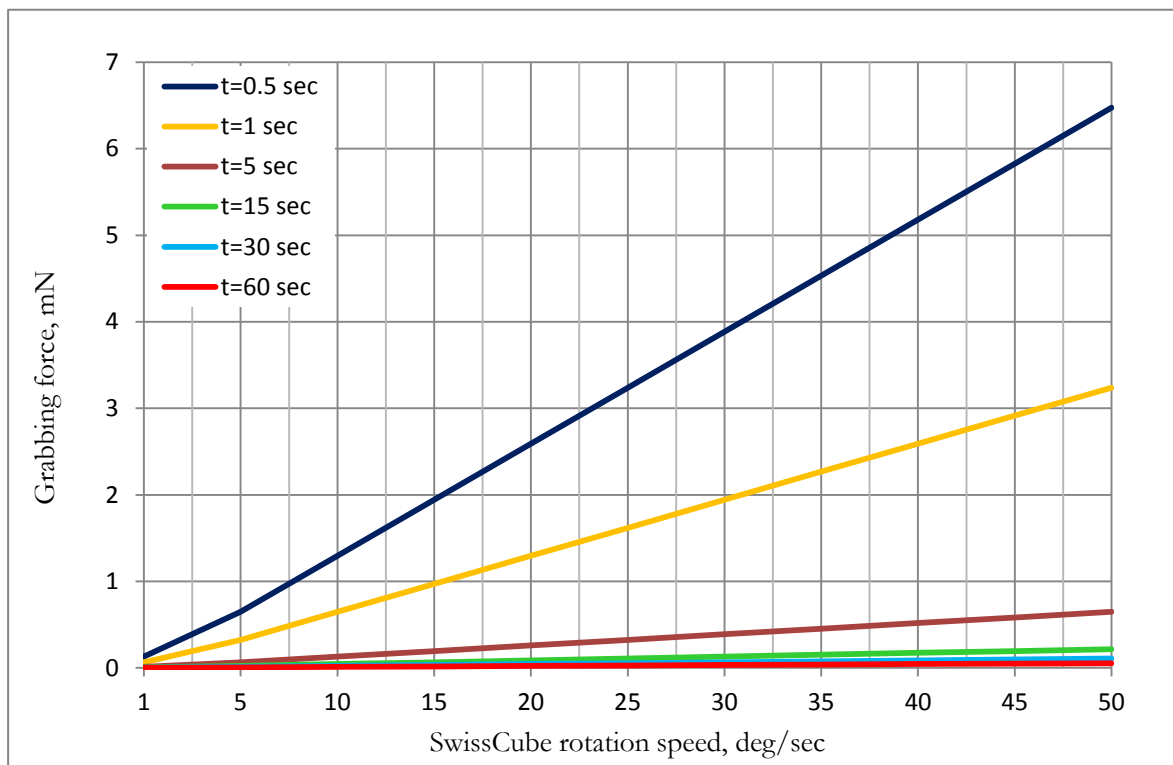


Figure 17 – Required grabbing force

Table 13 - - Required grabbing force, t = 1..60s

ω		t, sec					
		0.5	1	5	15	30	60
deg/s	rad/s						
1	0.02	0.130	0.065	0.013	0.004	0.002	0.001
5	0.09	0.648	0.324	0.065	0.022	0.011	0.005
10	0.17	1.295	0.648	0.130	0.043	0.022	0.011
15	0.26	1.943	0.971	0.194	0.065	0.032	0.016
20	0.35	2.590	1.295	0.259	0.086	0.043	0.022
25	0.44	3.238	1.619	0.324	0.108	0.054	0.027
30	0.52	3.885	1.943	0.389	0.130	0.065	0.032
35	0.61	4.533	2.267	0.453	0.151	0.076	0.038
40	0.70	5.181	2.590	0.518	0.173	0.086	0.043
45	0.79	5.828	2.914	0.583	0.194	0.097	0.049
50	0.87	6.476	3.238	0.648	0.216	0.108	0.054
		Required grabbing force, mN					

5.4 Recommendations

According to results time of grasping process have a significant influence on the required grabbing force. If the process lasts a few minutes, in zero-gravity environment the gripper doesn't need to provide large force to grab big and heavy object like Vespa. However, long de-tumbling process causes the problem of the buckling resistance. The gripper's arm has large elongation and weak equilibrium state at some angles. The longer the arm applies force to tumbling object the bigger possibility of buckling.

The DEA actuation and deactivation take a short time, and it is reasonable to limit time of grasping process with 1sec. This gives limitation for required grabbing force:

- 3.24 mN for SwissCube;
- 2.13 N for Vespa.

As stated above some approximation was applied to force calculation to get results for general case. The worst case was taken into account, but real values of some parameters could increase assigned range. As well calculations made for 4 fully operable arms, but the mission shall be successfully completed in case if one of the arms is broken. To assure the gripper functionality safety factor shall be added to force requirements.

The recommended safety coefficient for systems operated in space environment is 2.

With safety coefficient 2 required grabbing forces:

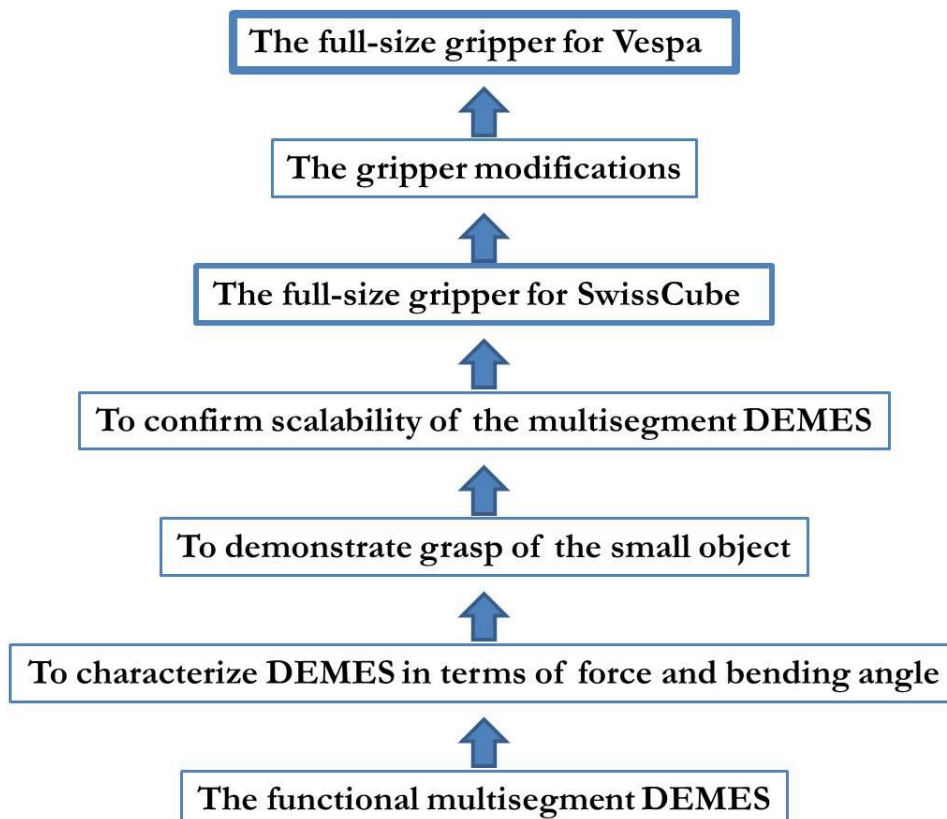
- 6.5 mN for SwissCube;
- 4.3 N for Vespa

The existent DEA samples are capable of providing blocking forces on the order of few mN. It is possible to overcome this limitation in close future, but it needs new approach to fabrication and new materials maybe.

At the moment sensibly to focus on the most practicable task for the compliant gripper – grasp a small rotating object, like SwissCube.

The design trajectory for the gripper based of DEMES is suggested in Figure 18.

Figure 18 – The design trajectory



6 Gripper technical requirements

6.1 Functional requirements

The gripper shall be stored in rolls during mounting, ground testing, launch and satellite systems check on the orbit.

The gripper shall be able to unwrap with no damage to its functionality.

The gripper's arms shall provide grabbing force 6.5 mN/each.

The gripper shall be able to grab the rotating target with angular velocity $\leq 50 \text{ deg/s}$, sizes 10 x 10 x 10mm, mass $\leq 1 \text{ kg}$.

The gripper shall be able to repeat attempt to grab the debris (open-close cycle) a few times in case of unsuccess.

The gripper shall hold on to the debris until the end of the mission.

The gripper shall manage the space environment conditions for its whole life-time.

6.2 Mission requirements

At the beginning of the mission the gripper shall be released from rolls and return to initial passive state.

The gripper shall be actuated by applying required voltage when it is located 1m away from the target.

Applied voltage shall be turned off when grabbing camera or sensors show that the gripper embraces the target.

If the gripper doesn't grab the target it shall repeat attempt until success.

The grasping shall not be longer than 1sec.

The gripper shall be able to complete the mission in case of damage to one or two arms.

The whole mission shall not take more than 2 hours to be accomplished.

The complete success criterion of the mission is: the gripper grasps the first time and holds on to the target at least 10min.

The partial success criterions of the mission are: the gripper grasps the target after few or many attempts and hold on at least 10 min; the gripper grasps and hold on less than 10 min.

6.3 Interface requirements

A physical, electrical, thermal and protocol interfaces shall be defined between the gripper and the satellite structure.

6.4 Environment requirements

Mechanical environment depends on the chosen launch vehicle.

Thermal environment during the following phases shall be considered:

- Ground operations
 - the spacecraft preparation;
 - the launch vehicle operations with spacecraft encapsulated inside the fairing;
- Flight
 - before fairing jettisoning;
 - after fairing jettisoning.

The gripper shall operate within temperature range:

- from 0C° to 50 C° on the mounting surface;
- from -80C° to 100 C° on the arms surfaces.

Radiation and electromagnetic environment during the flight shall be defined.

6.5 Operational requirements

The gripper shall be designed to operate autonomously with respond to the data from the grabbing camera.

The gripper shall accept control from ground segment in case of failure of the grabbing attempt.

6.6 Physical requirements

The gripper shall have an outside size:

- 100mm x 100mm x 50mm for the arms in wrapped state;
- 100mm x 100mm x 50mm for the controller and interfaces mounted inside the satellite.

The mass of the whole gripper shall not be more than 0.3kg.

6.7 Product assurance (PA) induced requirements

The gripper shall cause no harm to other subsystems and the satellite during all stages of the mission.

Quality assurance requirements for the gripper shall be defined.

6.8 Configuration requirements

The gripper shall consist of 3 parts: the controller, the base structure and 4 arms of DEA.

The arms shall be stored in rolls before the beginning of the mission.

6.9 Design requirements

The controller shall operate with TBD V input on-board voltage. This will require converter providing output voltage $\sim 2\text{kV}$.

The arms shall have protection layer to prevent short circuits between electrodes on DEA and a conductive surfaces.

6.10 Verification requirements

The gripper shall be tested in artificial zero-gravity environment before the mission.

7 Actuators

7.1 Dielectric elastomer actuators (DEA)

DEA is a type of actuators based on elastomers. They provide relatively large displacement $>100\%$ and have small mass. Actuation principle is shown in Figure 19. Actuator consists of thin elastomer membrane coated on both sides with compliant electrodes. High voltage applied to the electrodes causes electrostatic pressure. Due to the mechanical compression the elastomer film contracts in the thickness direction and expands in the plane directions. The elastomer moves back to its original position when voltage is turned off.

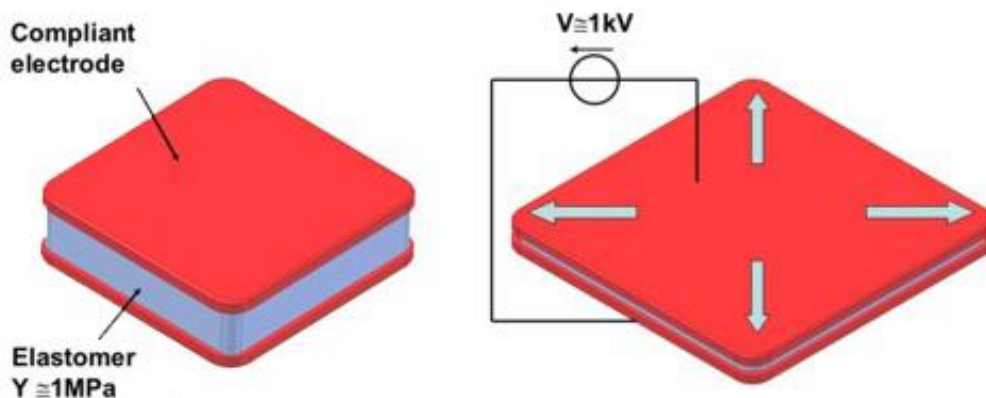


Figure 19 – DEA principle

7.2 Actuator materials

Electroactive polymers (EAP) are the key materials for actuators. They are distinguished by large actuation stroke and lightweight. EAPs can be divided into two main categories based on their method of actuation - ionic and field-actuated. Further subdivision based on their actuation mechanism and the type of material is also possible.

EAPs have different range of possible actuation stroke, respond time and required actuation field. Comparison of EAPs and its efficiency are presented in Table 14.

Table 14 – Comparison of EAP materials

	Strain, %	Activation field, V/ μm	Maximum pressure, MPa	Elastic energy density, J/ cm^3	Specific density	Coupling efficiency, %	Response time	Suitability
Ionic Gel	>40	-	0.3	0.06	1	-	Fast	
Dielectric EAP (silicone) ⁽³⁾	32	235	1.36	0.2	1	54	Fast	
Dielectric EAP (pre-stretched silicone)	100	100	3	0.75	1	63	Fast	
Dielectric EAP (pre-stretched acrylic)	380	100	7.02	3.4	1	85	Medium	
Ferroelectric Polymers ⁽⁴⁾	10	150	45	0.9	1.96	10-40	Fast	
Electrostrictive Polymers	4	150 ⁽²⁾	43	0.92	1.8		Fast	
Liquid Crystal Elastomers (Thermally activated)	400	-	0.27 ⁽⁴⁾	0.056			Medium/ Slow	
Liquid Crystal Elastomers (Electrically activated)	10	250		0.02			Fast	
Piezoelectric Ceramic	0.2	4 ⁽³⁾	110	0.1	7.7	52	Fast	
Piezoelectric Polymer	100	30 ⁽³⁾	4	0.0024	1.8	7	Fast	
Shape Memory Alloys ⁽³⁾	>5	-	>200	>100	6.5	5	Slow	
Shape Memory Polymers ⁽³⁾	100	-	4	2	1	-	Slow	

Good	Normal	Insufficient
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For the gripper application strain, response time and elastic energy density is very important. Elastic energy density defines amount of energy per EAP volume and consequently maximum possible blocking force. The gripper shall have fast response to be possible to grab the target in right moment. Strain provides available range of actuation angle that shall be large enough to embrace the target.

Comparison shows that dielectric EAPs (DEAP) with pre-stretch are more convenient for current use than others. Two DEAP types are taken into account for the comparison – silicone and acrylic. Acrylic EAP has better strain and elastic energy, but acrylic materials have viscoelastic nature as well, that change acrylic DEA characteristics in time. It is not efficient for use in the gripper, because the gripper arms shall be stored in rolls for a long time and keep their geometry and physical properties steady after release. Silicone EAP doesn't have viscous properties and can be applied for the gripper structure.

7.3 DEMES

Dielectric elastomer minimum energy structure (DEMES) is subtype of DEA suitable for use in highly-deformable soft robots. DEMES consists of pre-stretched DEA attached to rigid frame and can demonstrate areal strain greater than 380% and energy density as high as 3.4 MJ/m³.

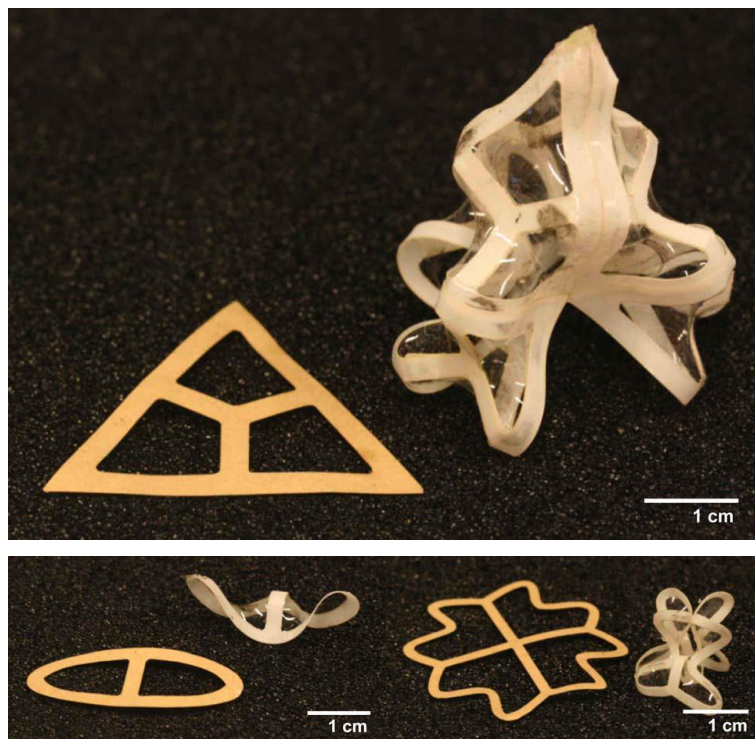


Figure 20 – Various DEMES, original planar frame and 3D structures with adhered pre-stretched elastomer film [5]

8 DEMES fabrication process

8.1 Materials

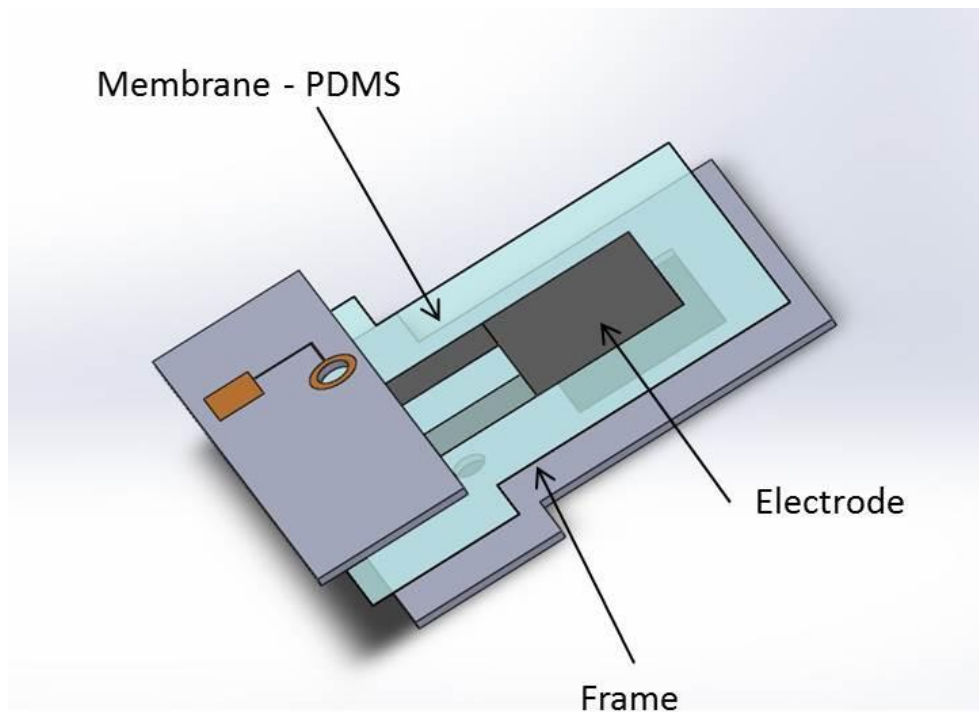


Figure 21 – DEMES composition

Various materials were used for DEMES to find most efficient combination.

Frame:

- Kapton flexible PCB 50 μ m;
- PI film 50 μ m;
- Folex 50 μ m.

Elastomer membrane:

- PDMS SYLGARD DC 136 – silicone elastomer

Electrode:

- Carbon black mixed silicone

Adhesive:

- Silicone R32;
- Double-sided Kapton tape.

8.2 Equipment

8.2.1 Membrane fabrication

Silicone elastomer is stored not mixed and shall be prepared according to the recipe. Teflon film is used as substrate for casting membrane. The applicator (Figure 22) helps to smooth the substrate and coats it with constant thickness silicone layer.

Process:

- Prepare silicone mix;
- Mount glass plate on the applicator;
- Fix substrate film on the glass plate;
- Clean the substrate with solvent;
- Smooth the substrate using the applicator (applicator gap equals substrate thickness minus $5\mu\text{m}$);
- Change the gap and the speed of the applicator to required value (calculated according to desired membrane thickness);
- Bring a small quantity of silicone mix on working area of applicator;
- Coat the substrate with silicone;
- Cure 90 min @80°C.



Figure 22 – Film applicator

8.2.2 Frame fabrication

Laser cutting is optimal way to fabricate flexible frame. Laser (Figure 23) provides fast cutting and accuracy of cut shape. In case of using double-sided Kapton tape instead of adhesive the frame shall be cut after bonding tape to the flexible film.



Figure 23 – Trotec Speedy 300 Laser

8.2.3 Pad-printing

The pad-printer allows coating membrane with very thin compliant electrode. The main parts of the pad-printer are shown in Figure 24.

Process:

- Equip the pad-printer;
- Fix the holder with pre-stretched membrane on the stage of the pad-printer;
- Put the mask on the membrane;
- Print;
- Remove the mask;
- Cure 60-90 min @90°C.

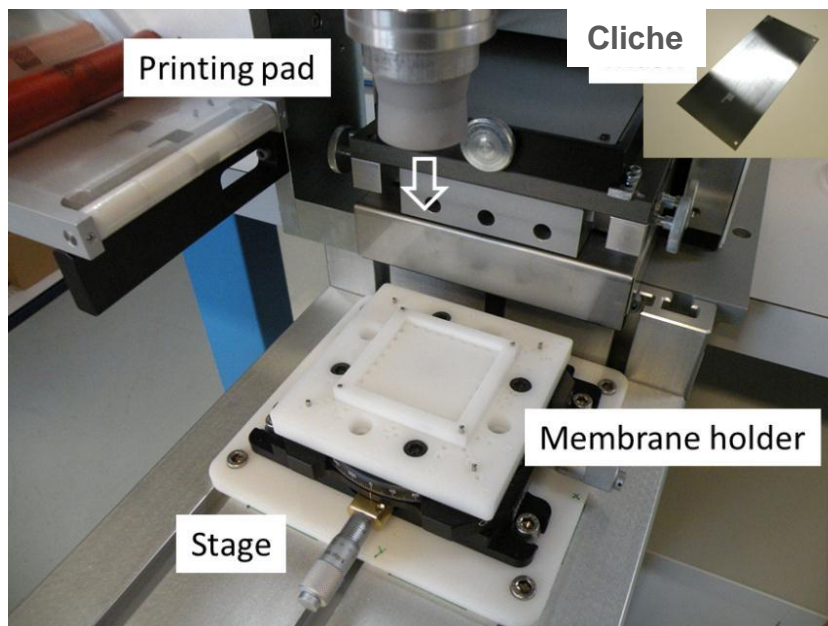


Figure 24 – Pad-printer

8.3 Standard DEMES fabrication method

1. Stretch membrane and fix it the holder



2. Print electrode on one side of the membrane and cure in the oven 60min@90°C



3. Print electrode on other side of the other side of the membrane and cure in the oven 60min@90°C



4. Coat adhesive, attach flexible frame and cure in the oven 60min@90°C



5. Drop silver epoxy to make contact with copper track and air-cure 40 min



6. Cut membrane and release DEMES



All fabrication process takes 8h 40 min.

8.4 Gripper DEMES requirements

DEMES shall have multisegment structure of required length.

All segments shall be electrically connected in parallel.

DEMES stiffness in active zones (Figure 25) shall be equal.

Passive zones shall be minimized.

All structure shall be mechanically and electrically robust.

Possibility to replace membrane in case of damage during fabrication shall be provided.

Fabrication method shall be independent of number of the segments.

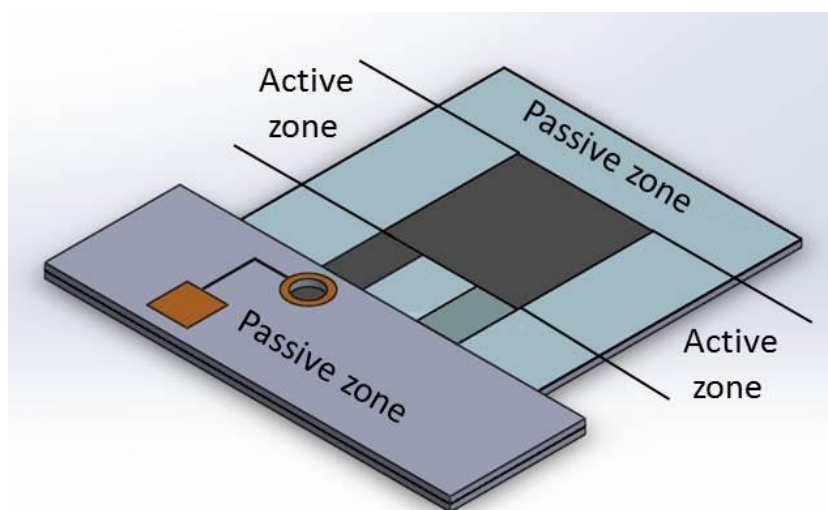


Figure 25 – Unisegment DEMES

8.5 Multisegment DEMES design

8.5.1 General

Standard fabrication process doesn't meet DEMES requirements, because it provides only unisegment DEMES as result. This process can be basis for new fabrication, but DEMES design has to be improved according to requirements.

8.5.2 Proposition 1

First proposition of new DEMES based on standard one with minimum of changes (Figure 26). Important part of pad-printing is cliché, which provides certain design of the stamp. Improved fabrication process doesn't need any change in cliché design as well as in frame design. Generally, suggested DEMES is a chain of connected unisegment DEMES. But thin strips and wires cannot provide fail-safe connection between segments. As well this design has large passive zone. Those disadvantages make proposition not efficient for defined goals.

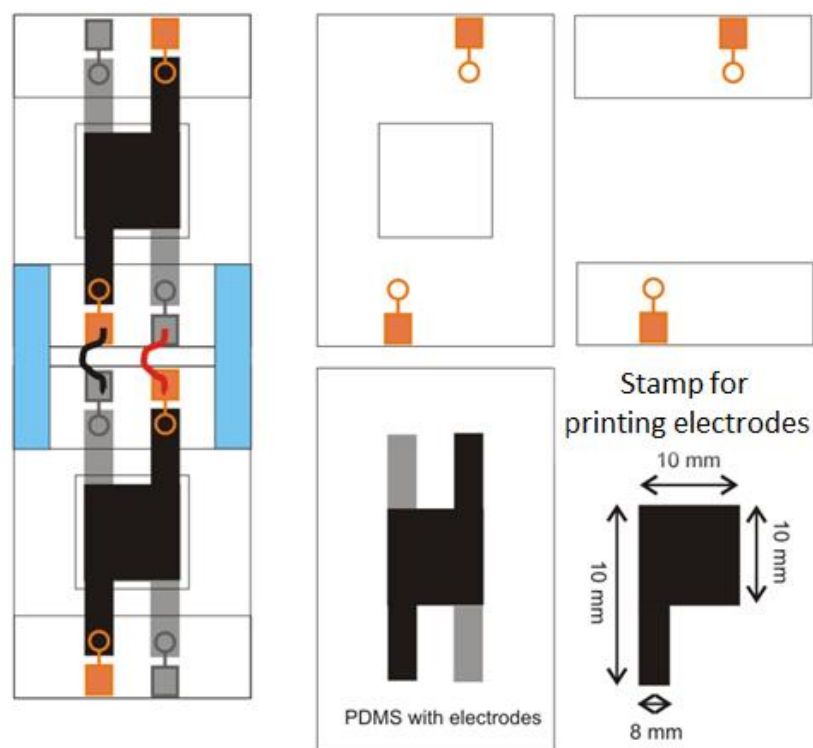


Figure 26 – 1st proposal of improved fabrication process

8.5.3 Proposition 2

Another design is presented in Figure 27. DEMES consists of whole frame on one side of elastomer and thin strip on other side. Advantages of this design are whole structure and short passive zones. Electrical connection between electrodes and frames is located in active zones of DEMES that increases the risk of silver epoxy damage when DEMES activates and increases frame stiffness in active zone. Thin stripe increases structure stiffness as well, but only on one side that possibly causes spiral DEMES bending.

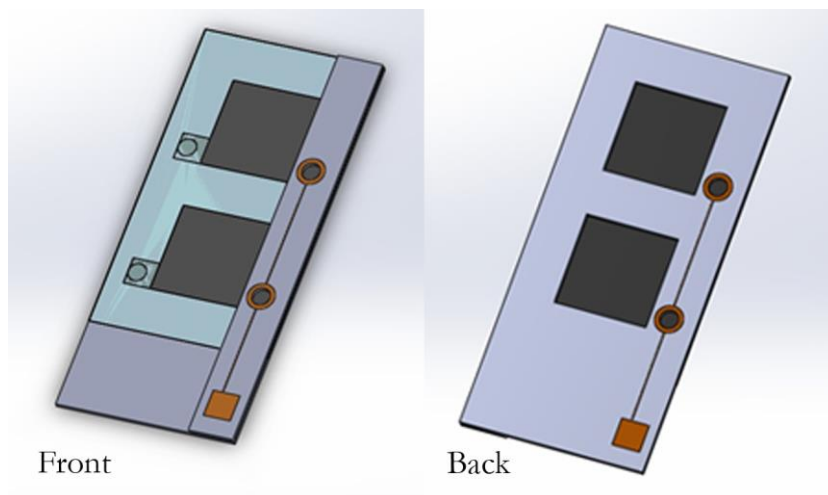


Figure 27 – 2nd proposal of improved fabrication process

8.5.4 Proposition 3

The more efficient design is presented in Figure 28.

Advantages of this design:

- One frame (made of two parts) for one actuator;
- Same frame design for both sides;
- Points for connection electrodes and copper tracks in passive zones of the frame;
- Fabrication method doesn't depend on length of the actuator;
- Same stiffness for all active zones.

This DEMES has some disadvantages as well:

- Fabrication problems to bond a few membranes on one frame;
- Frame bending during fabrication;
- Relatively large passive zone.

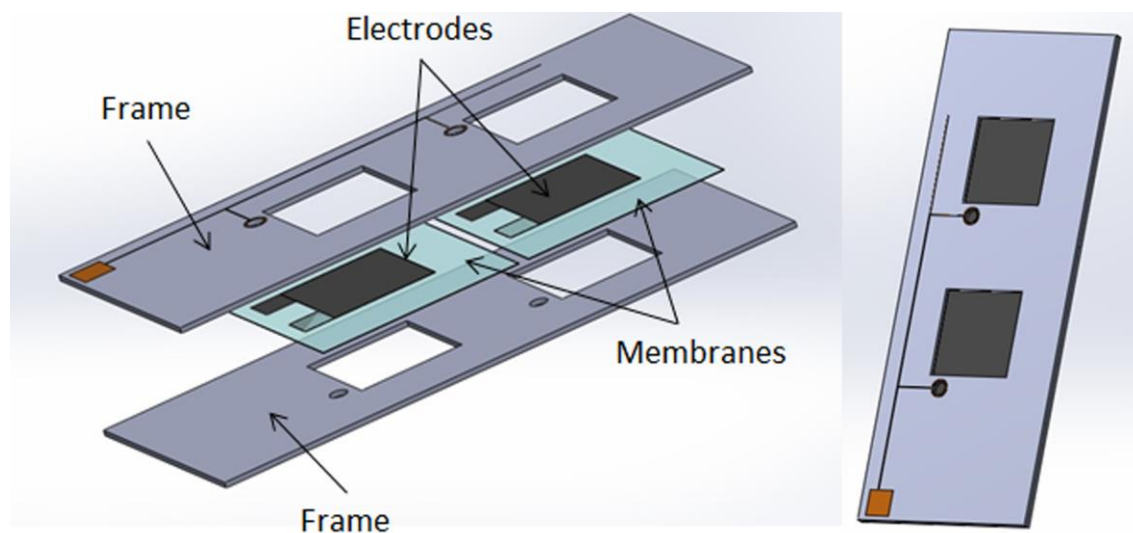


Figure 28 – 3rd proposal of improved fabrication process

8.6 Experimental methodology

8.6.1 DEMES fabrication problems

First attempt of multisegment DEMES fabrication with 3rd proposed design have shown some problems in the method:

1. When many membranes are used for one DEMES fabrication, membrane shall be cut before the next one will be attached to the frame. The membrane cause frame bending and complicates forward fabrication steps - Figure 29.

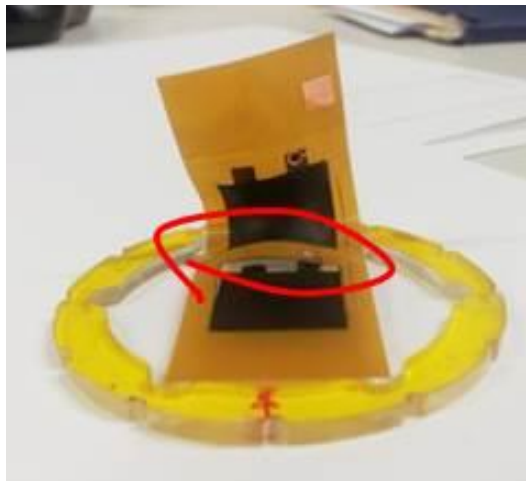


Figure 29 – Frame bending cause fabrication problems

2. Membrane tears when actuator cured in the oven - Figure 30.

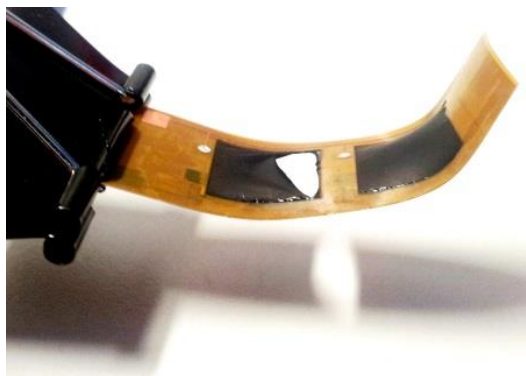


Figure 30 – Broken membrane

3. Quite often actuation causes short circuits on the edges of the electrodes.
4. Small stroke

Safe segment of DEMES was tested with applied voltage up to 2.3kV and it shows maximum blocking force – 3.2mN and maximum angle change – 2.3°.

Appeared problems of the fabrication process shall be solved to provide robust fabrication results.

8.6.2 Monomembrane method

The main problem of fabrication is using several membranes for one DEMES. It causes fabrication difficulties and explains other problems indicated above. Single membrane can be used to improve existent method - Figure 31.

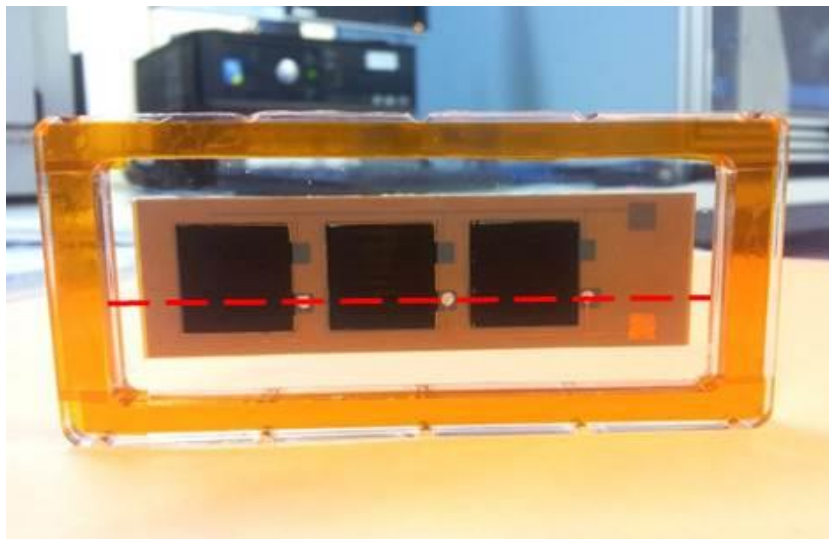


Figure 31 – DEMES made of single membrane with shown cross section plane

1. Print all electrodes on one side of pre-stretched PDMS and cure in the oven 60min@90°C



2. Print all electrodes on other side and cure in the oven 60min@90°C



3. Coat adhesive, attach frames on both sides and cure in the oven 60min@90°C



4. Drop silver epoxy on both sides to make contact and air-cure 40 min



5. Release DEMES



Monomembrane approach makes fabrication process shorter and more safety for DEMES. But in case of damage one or few segments during fabrication change of broken membrane becomes impossible for this approach.

8.6.3 Improvements

Test DEMES with use of monomembrane approach was made – Figure 32.



Figure 32 – DEMES made of single membrane

Use of monomembrane approach decreased fabrication time but didn't solve all problems. Membrane break and short circuits still appear. Blocking force, equilibrium and actuation angles still don't meet requirements. This indicates necessity of changes in DEMES design. Some recommendations on new design were made:

- Round corners of the frame to prevent membrane break;
- Gap between the frame edges and the electrodes to prevent short circuit;
- One frame instead of two with different thickness, because thickness difference of available materials are not enough for sizeable equilibrium and actuation angles;
- Other materials for membrane and frame to increase blocking force.

New design is shown in Figure 33 and Figure 34.

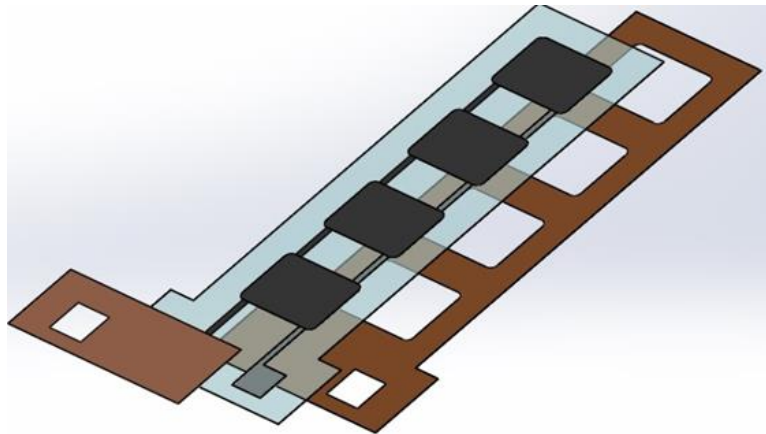


Figure 33 – Improved DEMES design

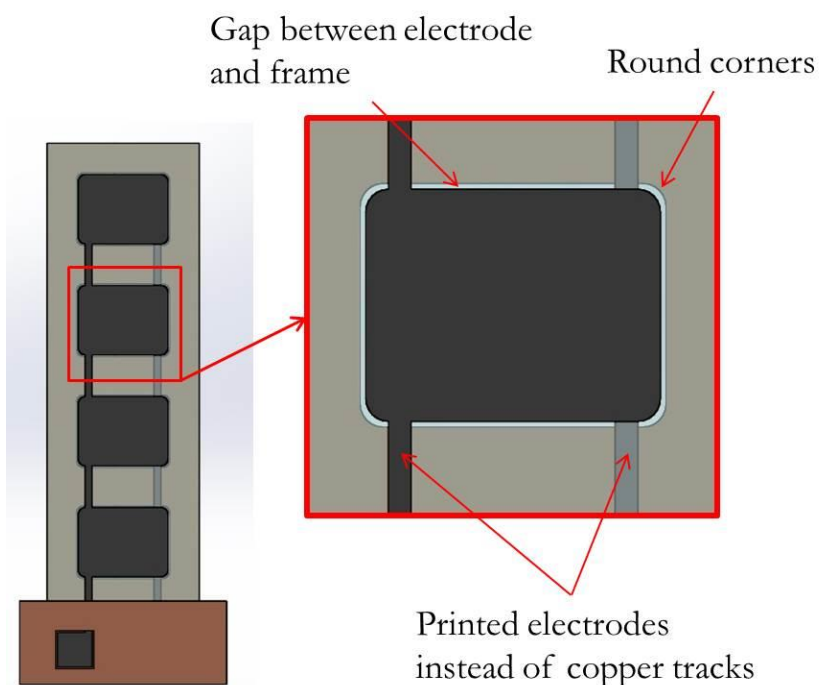


Figure 34 – Improved DEMES design

The new DEMES design has one full frame and short one on other side of the membrane only for enforcement of the base.

The important improvements of this design are refusing of cured adhesive. The frame consists of PI film and double-sided Kapton tape that adheres to elastomer membrane. This changes fabrication and reduces required time.

Experimental fabrication methodology:

1. Print all electrodes on one side of pre-stretched PDMS and cure in the oven 60min@90°C



2. Print all electrodes on other side and cure in the oven 60min@90°C



3. Attach frames with Kapton tape on both sides



4. Release DEMES



This approach gives constant thickness of adhesive layer and constant stiffness of the frame because of electrode tracks. Those issues provide more isotropic structure.

Unfortunately Kapton tape has viscoplasticity that changes DEMES properties in time.

DEMES made with this fabrication approach is presented in Figure 35.



Figure 35 – DEMES made with single membrane and Kapton tape adhesive layer

8.6.4 Advantages

Improvements in the fabrication process and design resulted in decreased fabrication time and new approach to DEMES fabrication. The time comparison is shown in Figure 36. Fabrication time shortened from 8h 40min to 3h 55min. The design became more simple and reliable. Improved DEMES achieves quite large equilibrium and actuation angle. The disadvantage of new fabrication – viscoplasticity of the adhesive layer – can be solved with use of the other material with same adhesive properties, such as M3 laminating adhesives or ARClear adhesives.

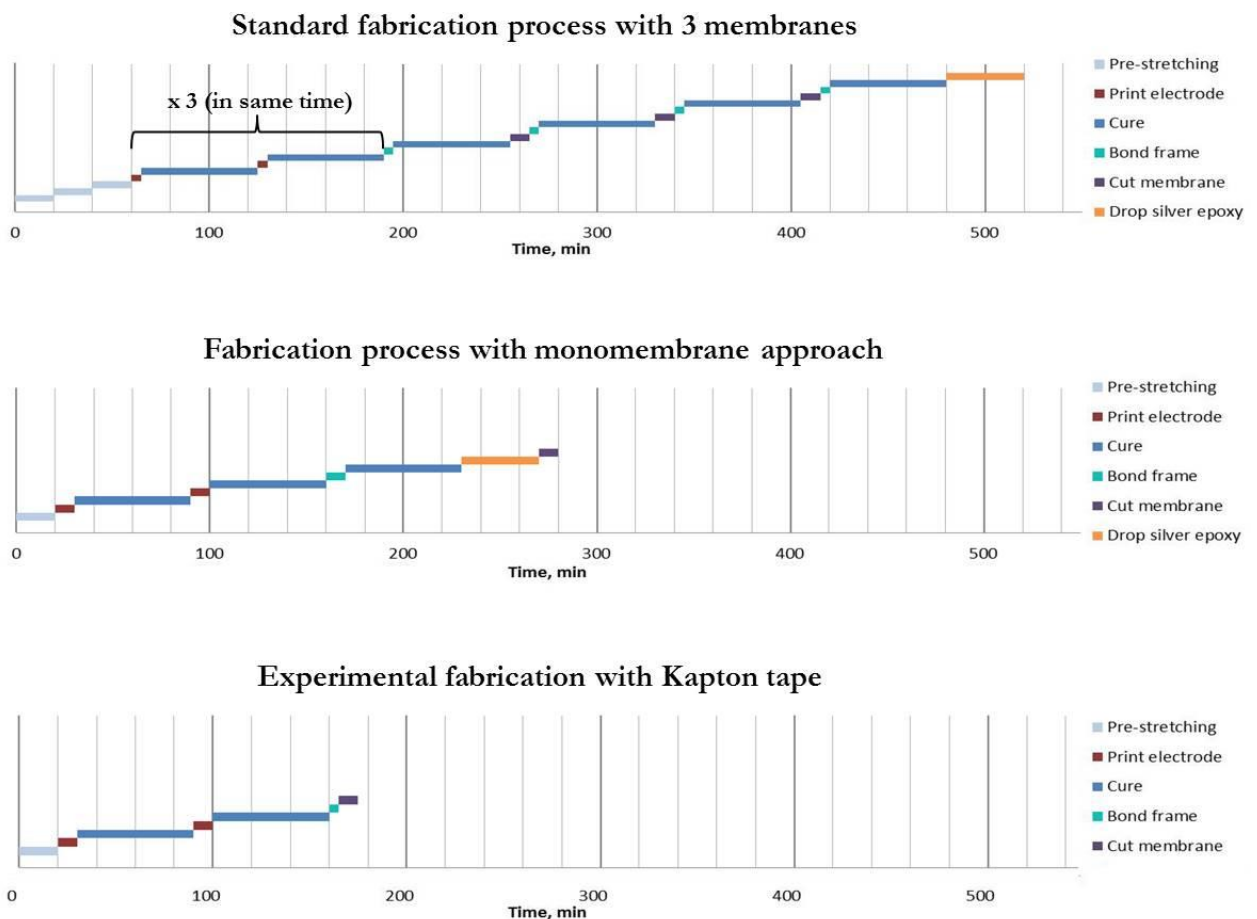


Figure 36 – Time comparison of different fabrication processes

9 Actuator tests and results

9.1 Geometry optimisation

Many DEMES parameters can be modified to achieve required properties. There are types of materials used for frame and membrane, number of elastomer layers, electrode area, elastomer thickness and frame thickness, elastomer pre-stretch ration and direction, number of segments and frame geometry. For first iteration of optimisation only two parameters were varied. Materials, thicknesses and pre-stretch are similar for every of experimental samples to permit to compare results.

Five DEMES samples were fabricated of 45-50 μ m PDMS with quasi pure share pre-stretch 1.25:1 and 50 μ m PI frame with 50 μ m Kapton adhesive tape. DEMES geometry is varied according to Table 15 and Figure 37.

Table 15 – DEMES geometry variations

Sample	a, mm	b, mm	c, mm	d, mm
#1	10	10	4.5	5
#2	10	10	6	5
#3	10	10	3	5
#4	13	10	4.5	5
#5	10	13	4.5	5

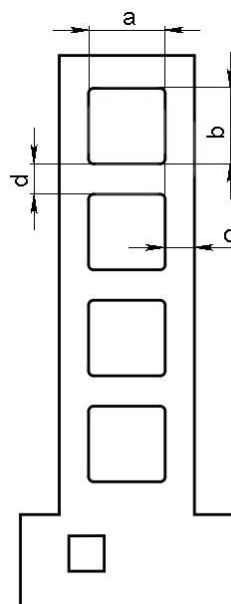


Figure 37 – DEMES geometry variations

9.2 Angle and force measurements

DEMES samples were characterise in terms of blocking force and angle change. The measuring setup presented in Figure 38 and consists of the fixing stage, the load cell and the camera.

- Camera FMVU-13S2C 1328x1048
- Load cell FUTEK LRF400: capacity 0.1N; resolution 0.00196 mN

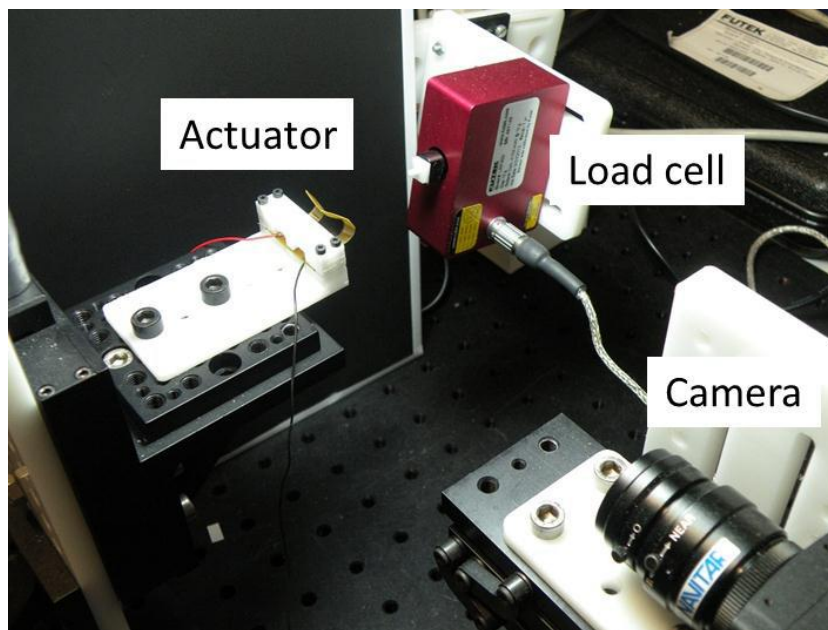


Figure 38 – Measuring setup

Force measurements are made with 100V step in range of 0-3000V. The received data provide good accuracy and allow feather interpolation.

The camera gives images of actuated DEMES in front projection view; those images were manually postprocessed as shown in Figure 39. Manual processing cannot give very accurate results, as well complex 3D shape of DEMES makes angle measuring difficult and less precise. Though the results allow understanding how angle and forces change depending on applied voltage.

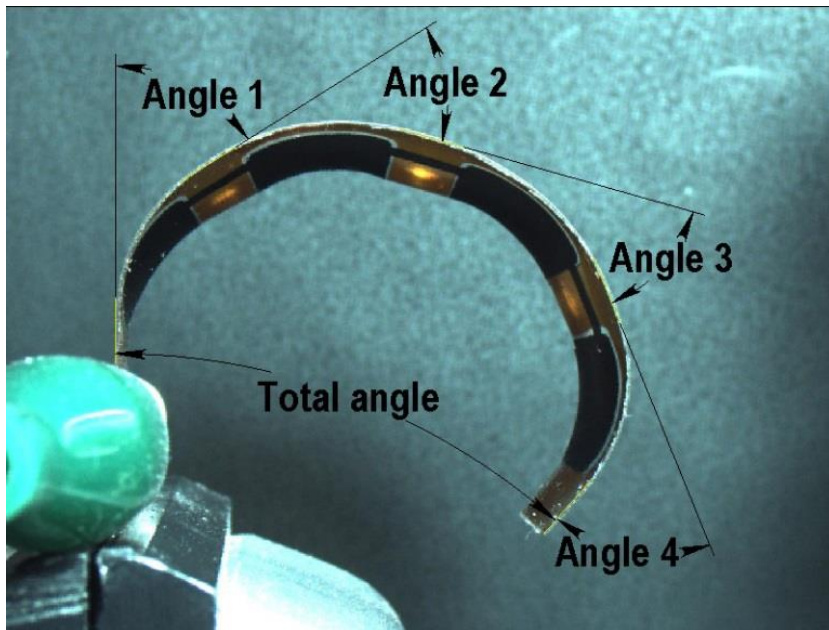


Figure 39 – Angle measuring

9.3 Results

The DEMES #3 with most thin frame got buckling after fabrication. This let us suppose, that thin frame and PDMS pre-stretch shall relate according to certain ratio to prevent buckling.

Other samples got expected shape and were tested on measuring equipment. Measurement results are presented in Figure 40 and Figure 41.

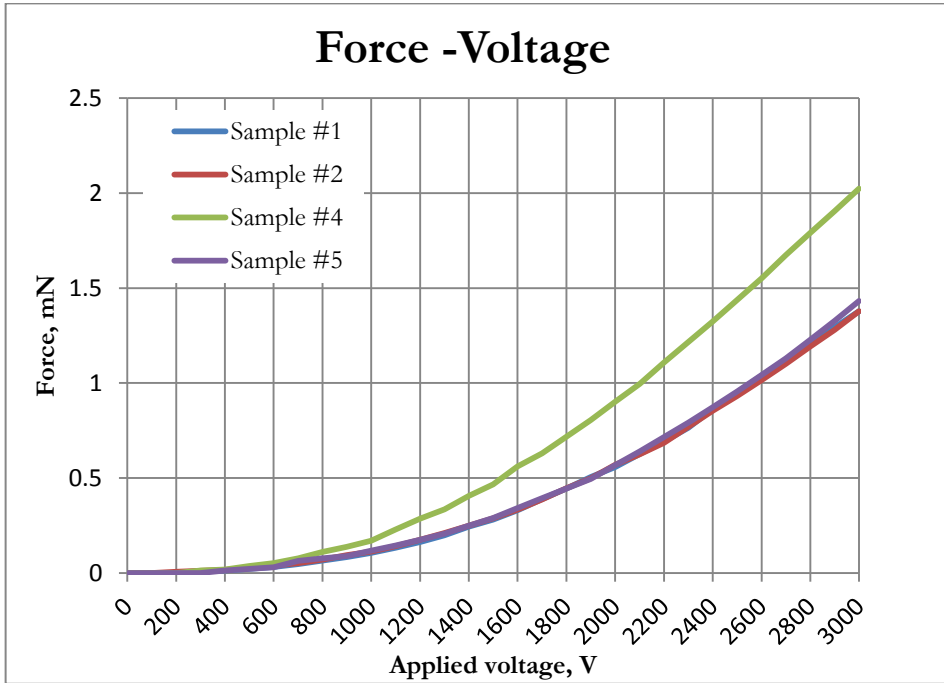


Figure 40 – Blocking force

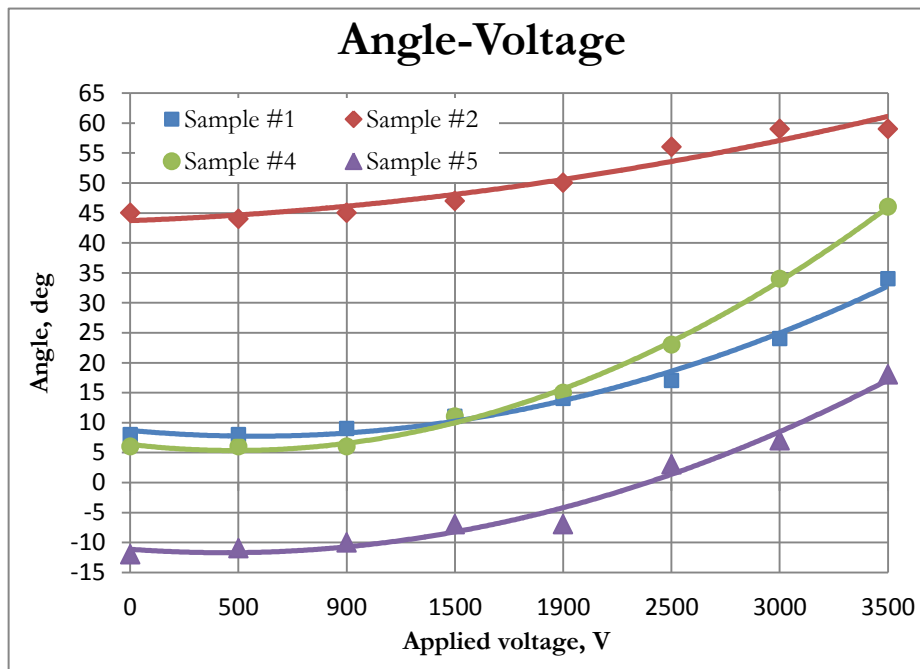


Figure 41 – Angle change

As easy to see on the Figure 40 and Figure 41 the DEMES # 4 has biggest blocking force (around 2mN at 3kV) and its angle change in the largest range – around 40deg at 3.5kV (Figure 42).



Figure 42 – DEMES #4

The DEMES #5 has same electrode area and frame width in active zone (consequently, same stiffness) as sample #4, but its blocking force and angle change are smaller. This can be explained with different electrode size in stretch direction. DEMES #4 has same electrode area but long electrode side is along the inactivated pre-stretch direction, where PDMS has smaller pre-stretch. The less pre-stretch ratio the more actuator can expand this direction, but the less PDMS energy. So DEMES #4 get enough energy due to pre-stretch in actuation direction, but has more possibility to expend.

The geometry of the sample #4 was taken for fabrication gripper DEMES.

10 Gripper prototype

10.1 Design

The gripper prototype (Figure 44) consists of four 6-segment DEMESes. The DEMES has sizes 22mm x 106mm. Optimised geometry allows required angle change (Figure 43). The gripper is able to grab the object of random shape. Figure 45 shows how the gripper grasps the SwissCube model scaled down with factor 3.

Internal surfaces of the gripper arms are coated with 5-10 μ m silicone layer to prevent short-circuit between them and grabbed object.

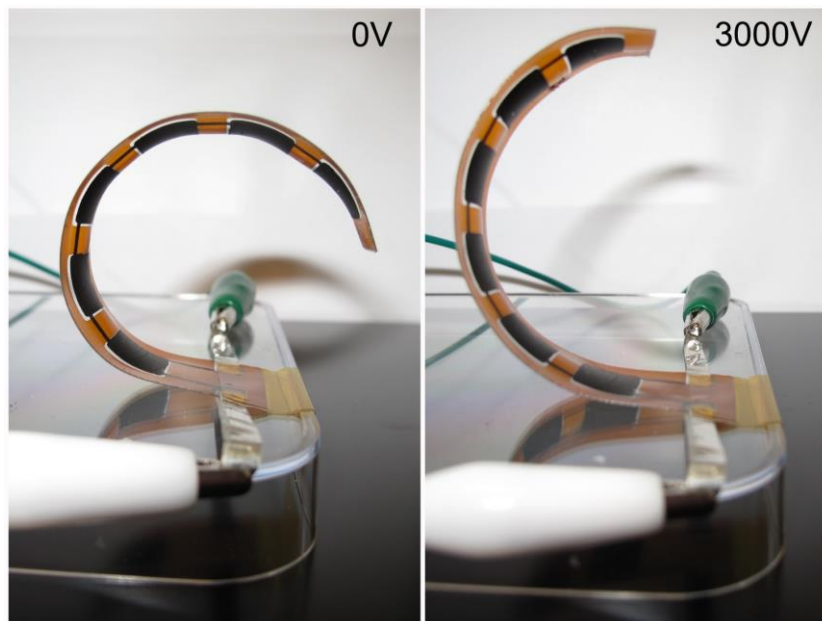


Figure 43 – Gripper DEMES

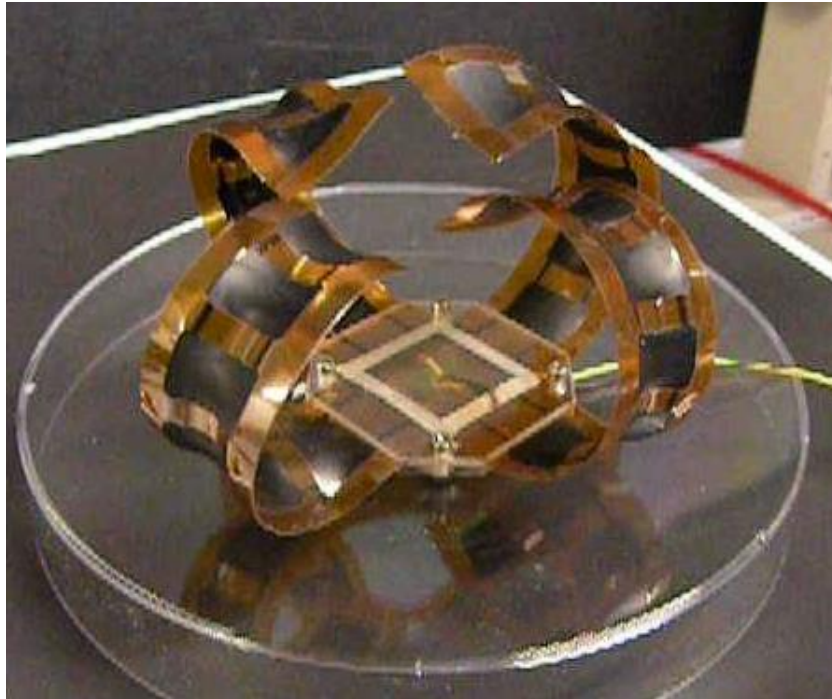


Figure 44 – Gripper prototype

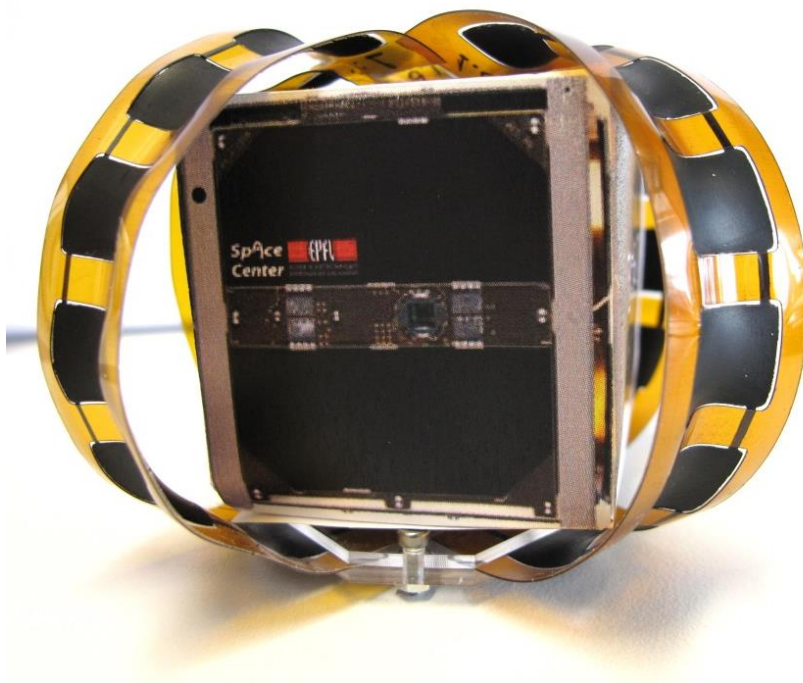


Figure 45 – Gripper prototype with SwissCube model on a scale 1:3

10.2 Robustness

Some tests were made to prove the gripper robustness.

The gripper shall be actuated after it stored in rolls for a long-time. One 6-segment DEMES actuator was tested to show its functionality and rolled after that. After 24 hours the DEMES was released and tested again. It shows full functionality, but initial and actuated angles increased due to viscosity of materials that has to be taken into account for next prototypes.

Test shown in Figure 46 proves the gripper operability after mechanical impact. The DEMES was successfully actuated after contact with sharp corner and large membrane deformation.

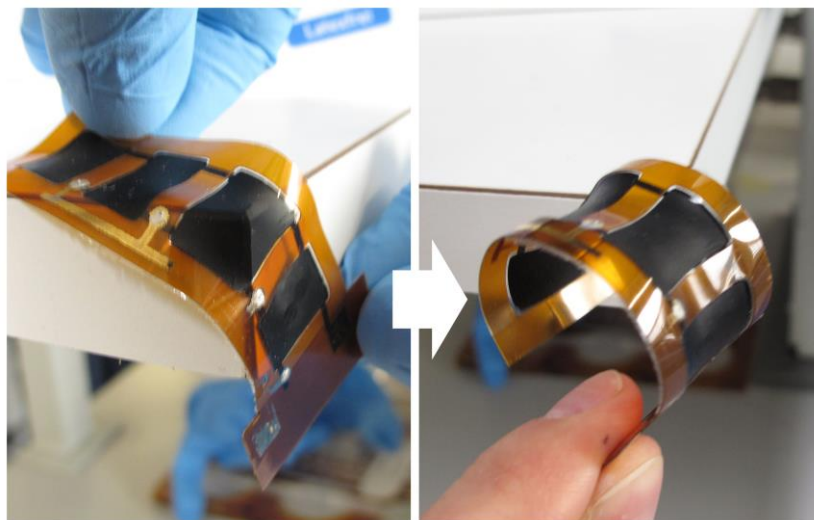


Figure 46 – Robustness test

11 Conclusion

In this report the possibility of use soft robotics technology for CleanSpace One grasping system. The dynamics analysis was made to define required grasping force in case of compliant gripper. The gripper requirements are defined and possible grasping system design is proposed.

Within the scope of the project practical work and some verification tests were made. The first multisegment DEMES was designed and built with new improved fabrication methodology. After force and angle measurements and data analysis DEMES geometry was optimized to increase blocking force and actuated angle. Results shows, that at the moment good angle change is approached - 40°, this is sufficient for the gripper available to grab real-sized SwissCube. The approached force 2mN is not enough for the mission and this value shall be improved with modifications in applied materials and design.

Finally the first gripper prototype was built and actuated to prove possibility of this DEMES application.

The data resulting this project shows that DEMES approach for compliant gripper is sufficient and promising solution. It has some important advantages – lightweight, small sizes, low power consumption. The DEMES gripper prototype proved its functionality and scalability that make its application suitable for grabbing bigger object, than it was shown in report.

The gripper design and functionality can be improved with changes proposed below:

- Solve problem with viscoplasticity
 - replace Kapton tape with other adhesive material
- Reliable insulation layer on electrode surfaces
- Increase grabbing force
 - multilayer DEA
 - increase membrane thickness and pre-stretch ratio
 - new materials
- Geometry optimization for grabbing object 100x100x100mm

Acknowledgement

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