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MASTER'S THESIS

# Design, Construction and Validation of an articulated solar panel for CubeSats

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# Abstract

The aim of the project was an attempt to design a solar panel for CubeSats to address the increasing power requirements. Therefore solution options for the realization of the various subsystems – mechanisms, solar cells and materials – were collected and analyzed. This included mechanisms for actuation, guidance, damping, release and control aspects. In order to maximize the power output from a specific solar cell, simulations about the influence of the sun-incident angle were performed. The difference in energy generation between body-fixed panels and articulated panels in one degree of freedom is in the range of 2 to 3. However, the improvements by articulating in two degrees of freedom did not show a big increase in generated power for the designated orbit in 400 kilometers altitude and 40 degrees of inclination.

The proposed design is based on a small stepper motor incorporated with a planetary gear-head. The selected material for most of the components was aluminum to reduce the mass of the system. Afterward, the system was validated by vibrational and thermal computational analyses. The analysis showed that some of the components, in particular the attachments of the mechanism at the satellite, are suggested to be redesigned with steel instead of the earlier selected aluminum. For future work, the results from the analyses will be validated by the tests described.

## Acknowledgments

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## List of Abbreviations

| | |
|---|---|
| AOCS | **A**ttitude and **O**rbit **C**ontrol **S**ystem |
| AM0 | **A**ir **M**ass **0** (space solar spectrum) |
| ASD | **A**cceleration **S**pectral **D**ensity |
| BOL | **B**eginning **O**f **L**ife |
| Cm | **C**enti**m**eters |
| Cnes | **C**entre **n**ational d’**é**tudes **s**patiales (Space Agency of the French Republic) |
| COTS | **C**omponents **O**f **T**he **S**helve (commercially available components) |
| CubeSat | Nano-satellite complying to CubeSat Specification |
| CUTE-1 | **Cu**bical **T**ITech **E**ngineering Satellite 1 |
| CUTE-1.7+APD | **Cu**bical **T**ITech **E**ngineering Satellite 1.7 + **A**valanche **P**hoto **D**iode |
| DLR | **D**eutsches Zentrum für **L**uft- und **R**aumfahrt (German Aerospace Center, Space Agency of the Federal Republic of Germany) |
| EOL | **E**nd **O**f **L**ife |
| EP | **E**uropean **P**atent |
| ESA | **E**uropean **S**pace **A**gency |
| GEVS | **G**eneral **E**nvironmental **V**erification **S**pecification |
| HOP Actuators | **H**igh **O**utput **P**araffin Thermal Actuators |
| MeV | **M**ega **e**lectron **V**olts |
| MOVE | **M**unich **O**rbital **V**erification **E**xperiment (CubeSat of the Technical University of Munich) |
| NASA | **N**ation **A**eronautics and **S**pace **A**gency (Space Agency of the United States of America) |
| Ncm | **N**ewton **c**enti**m**eter |
| Nm | **N**ewton **m**eter |
| P-POD | **P**oly - **P**icosatellite **O**rbital **D**eployer |
| PCB | **P**rinted **C**ircuit **B**oard |
| Rpm | **R**evolutions **P**er **M**inute |
| SMA | **S**hape **M**emory **A**lloys |
| SPSPAD | **S**mart, **P**assive **S**olar **P**anel **A**rray **D**rive |
| STS | **S**pace **T**ransport **S**ystem (usually used together with flight number) |
| TITech | **T**okyo **I**nstitute of **Tech**nology |
| US | **U**nited **S**tates |
| UV | **U**ltra **V**iolet (radiation) |

# 1 Introduction

CubeSats have become a low-cost and fast alternative to bigger satellites in the recent years. For space limited cubesat operations many components were successfully miniaturized. The stabilization types changed from simple spin stabilization and passive stabilization using permanent magnets to fully three-axis stabilized spacecraft. Some recent missions also validated propulsion systems for CubeSats. Despite this significient progress, two problems remain unsolved due to the small surface area of CubeSats. The commonly used body fixed panels produce insuffiecient energy and similarly provide too little surface area for adequate energy dissipation. This thesis will adress the first one. One of the possible solutions is the use of deployable structures to increase the available surface area.

The developed design is based on a generic CubeSat mission and an orbit with an altitude of 400 kilometers and an inclination of 40 degrees during the year 2011. The satellite is assumed to be three-axis stabilized. In order to validate the survivability of the mechanism for launch, vibration analyses and tests have to be performed. The panels are usually in stowed position to avoid damage during the lauch phase and are deployed later on when the satellite reaches its desired orbit.

In general, mechanisms on board of CubeSats are limited to small dimensions and are required to be extremely light weight by the CubeSat launch containers. Further details can be found in the CubeSat specification. [1] Working in an environment with no possibility of later corrections or modifications requires a high functional reliability and repeatability. The two major impacts on the satellite are the compatibility of the thermal heat expansion ratios and the large occurring temperature changes. These result in thermally induced stresses which might cause cracks in components or delamination of glued components like solar cells. This can be prevented by the use of materials with a similar coefficient of thermal expansion and larger tolerances.

Beside the constraints discussed earlier, solar cells degrade during their lifetime. Therefore it is common practice to design solar panels with a higher energy output at the beginning of the mission to meet the requirements at the end of the mission.

Another critical issue, which will be dealt in this report, is the electric connection of the solar panel to the satellite bus. The most common solutions in this field are cables and slip ring devices.

This report focuses on the use of deployed or articulated solar panels to generate the required energy during the whole mission. Hence, it evaluates several options for the design of the subsystems of a deployable or articulated solar panel for CubeSats. Afterward the final design is described and validated by the use of computational analyses and practical testing.

# 2 Previous Work

This chapter covers the literature review of solar arrays used in space applications. The first section gives a brief overview of the principle solution options. Afterward currently used techniques are evaluated to determine the most valuable direction of development. This chapter is based on a similar chapter in the thesis [2].

## 2.1 Overview of the solution options

For a systematic review of existing solar array systems, the complete system of a deployable solar array was split into several subsystems:

- Actuation mechanism for deployment (rotating and linear)
- Guiding mechanism for deployment
- Damping mechanism for deployment
- Initial release mechanism
- Actuation mechanism for articulating
- Control mechanism for articulating
- Solar cell technologies
- Solar panel materials

Solution options were generated by analysis of current solar panel systems and research in scientific journals, patent databases and books. The options originate from satellites ranging from CubeSats to very large satellites, like the ISS or the Hubble Space Telescope. An overview of all found and evaluated possibilities is given in the table at the following page.

| Sub-Mechanism | Solution options | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Actuation mechanisms for deployment rotating | Coil spring | By flexible joints | By shape memory alloys | Torsion spring in hinge | Spiral spring in hinge | Electric motor in hinge | Torsion bar spring in hinge | Spin of satellite | | |
| Actuation mechanisms for deployment linear | Deployable boom | Inflatable boom / structures | Lanyard Deployment with rotational damper | Canister Deployment | | | | | | |
| Guiding mechanisms for deployment | Rotational deployment | Telescopic cylinder | Mechanical guiding | Tether | Scissors shaped booms | Synchronized by rope mechanisms | Flexible joints | None | | |
| Damping mechanisms for deployment | Counter-force by spiral spring | Rotation damper | Electric motor | External friction | Eccentric bolt | Electric damping by Electro-rheologic / magneto-rheologic fluids | Friction in joints | Counter-force by Belleville springs | Rubber damper at desired position | Latch at desired position | Torsion spring in hinge |
| Initial release mechanisms | Thermal loosening of interference fit | Heat wire | Phase changes (HOP actuators) | Shape memory alloys | Electric motor with rod mechanism | Release from P-POD | Decompression | Pyrotechnic cutter | Mechanical by releasing key | Magnetic | Cone movement by magnetic pusher |
| Actuating mechanism for articulating | Flat electric motor | Piezoelectric motors | HOP motor with spiral cam | Shape memory alloys | Torsion spring in hinge | Spiral spring in hinge | Bi-metal strips | Torsion bar spring in hinge | By linear displacement | Electric motor in hinge | None |
| Control mechanism for articulating | Electronic controller | Changing shadowing mechanically | Clamping by electro-rheologic / magneto-rheological fluids | Photo-chromatic lens | External friction | Photo-diodes with shield for damping | None | | | | |

## *2.2 Evaluation of Solution options*

This section is structured into four different groups, mechanisms for deployment, release mechanisms, mechanisms for articulation and types of solar cells.

Inside the mechanisms for deployment, the actuating mechanisms were split into two different groups, rotating and linear. Unlike in the rotating type the linear one utilizes a main deploying movement that is translating instead of rotating. Linear mechanisms are not considered for articulating, as their use is very complicated compared to rotational ones. The actuation mechanisms require an extremely high reliability, as they are first and most important single point of failure in the complete deployment process. Therefore mechanisms shown in this chapter would provide redundancy in the real design.  Other mechanisms in this group include guidance and damping mechanisms for the deployment process.

For articulation mechanisms, these are divided in control mechanisms and actuation mechanisms. Both have a large impact on the reliability of the complete system. Therefore they would also include redundancy in the real design.

# 2.2.1 Actuation mechanisms for deployment - rotating

### *2.2.1.1 Coil spring*

Small springs are widely used in CubeSat applications due to volume constraints. Coil springs were, for example, used for the satellites CUTE-1 and CUTE-1.7+APD for the deployment of solar panels. After release the expanding spring provides an initial velocity. Afterward, the movement of the panel is uncontrolled, as damping at final position of the deployable solar panel cannot be achieved by the sole use of a coil spring. The other option of using coil springs is a conversion from the linear to the rotational movement, like a scram or winding. CUTE-1 is shown in its deployed state in Figure 1. An axial application is shown in the chapter about **H**igh **O**utput **P**araffin (HOP) actuators (chapter 2.2.6.3).

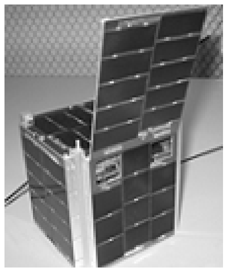

*Figure 1: CUTE-1 with deployed solar panel (source: [3])*

**Advantages**

- Usable in axial and radial directions
- Applied torque just restricted by the lever arm
- Flight approved mechanism
- Reusable when panel retracted
- Can partially placed inside of the satellite
- Can be easily combined with other methods
- Can be incorporated with **S**hape **M**emory **A**lloys (SMA)

**Disadvantages**

- Force applied rapidly just at the beginning
- For radial case large volume requirements
- Needs guiding when reused (otherwise prone to buckling)
- Doesn't lock panel in end position
- Limited to rigid solar panels
- When incorporated with SMA constantly power required

**Conclusion:**

Coil springs are promising due to their large space heritage. Itself used in radial direction are not sufficient for the current application, as they only provide an unchangeable initial speed. However, they can be valuable as an addition to another solution option for actuation.

For the use in axial like direction they are a good approach, because they can be easily actuated and locked by the incorporation of SMA materials and require little volume.

#### 2.2.1.2 Flexible joints (includes flexible struts)

Flexible joints are widely used in space systems for deployment and locking. One example is the CubeSat of the Technical University of München MOVE, which includes two deployable solar panels attached by flexible joints which consist of four crossed flexible straps. (see Figure 2) These provide guidance and actuation energy for the deployment process in a volume-efficient way. After reaching the final position the movement is damped solely by friction inside the flexible joints. The estimated minimum bending radius is 4 millimeters, as the CubeSat specification (see [1]) gives a maximum height of 6.5 millimeters above the upper panel minus 1 millimeter for the panel and minus 1 millimeter for the screws to attach the stripes at the satellite bus.

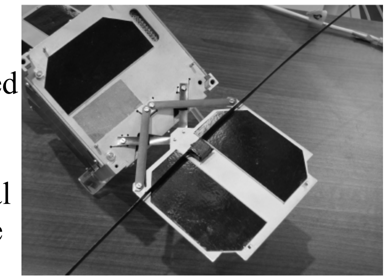

*Figure 2: model of MOVE with deployed solar panel*

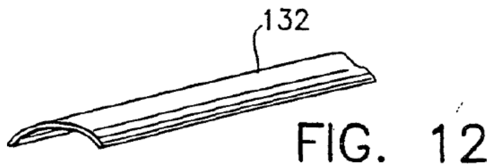


*Figure 3: longitudinal bent strap (Source: EP-0754625-A1)*

In order to improve the performance of the straps, it is suggested in patent EP-0754625-A1 (see [4]) to bend the straps in longitudinal direction, as shown in Figure 3. The earlier mentioned problem of a weak damping can be improved by the application of viscous-elastic material to both sides. (see [5]). Another type is described in the patent US3,386,128, where three strips are used, while one is bent in the opposite direction of the two others.(see [6])

Band springs are also used in the frictionless hinges ADELE from Thales Alenia Space (see [7]).

The second type in this section, flexible struts, is used in the Spartan lite mission. (see [8]) These act as actuation mechanism after the solar panels were already partially deployed to an angle of 45 degrees. They also lock the panel in the final position, as shown in Figure .

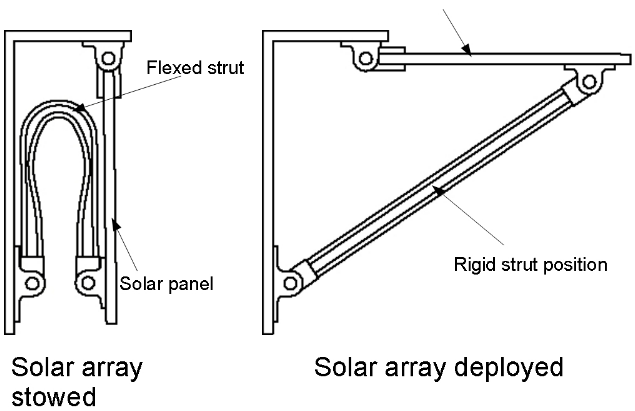


*figure 4: Flexible struts*

**Advantages**

- Locks panel in final position
- Small required volume (as actuation device)
- Also acts as hinge (multifunctional)
- Simple harnessing
- High reliability (small number of mechanical parts)
- Small deployment torque (→ relatively low deployment speeds, see page 4 in [9])
- Utilization of bi-metallic bands enables articulation (see chapter 2.3.7.7)

**Disadvantages**

- Difficult to retract (locking)
- Angle just adjustable by rotation of band
- Difficult to damp at end position
- Limited to rigid solar panels

**Conclusion:**

Flexible joints are widely used and offer promising opportunities for the use in articulation mechanisms by the incorporation of SMA or bi-metallic bands. Furthermore the volume consumption is very small. Therefore they will be considered for further research. In order to prevent damage from the instruments, the mentioned vibrations at the end of the deployment process should be more effectively damped.

#### *2.2.1.3 Shape Memory Alloys (SMA)*

Mechanisms based on SMA alloys are used in various branches, like aerospace industry or medicine. Shape Memory Alloys make use of the so-called memory effect. This effect can be divided into two different types, one-way and two-way shape-memory effect. While the one-way effect offers the possibility for only one actuation, the two-way effect can be used for cyclic actuation. The achieved deformations are typically one or more orders of magnitude higher than the deformation resulting from conventional material behavior such as thermal expansion. SMA undergo phase transformations which enable them to memorize a particular shape. The first phase transformation converts austenite, which has a cubic crystal model, in the temperature range between the start martensitic temperature and the finish martensitic temperature to martensite, which has a tetragonal crystal model. This happens while cooling down the austenite. In the absence of loads the resulting martensite is twinned, i. e. no changes in shape occurs. Otherwise the martensite is detwinned. When the material is heated up again above the austenitic start temperature the back transformation starts. It finishes when reaching the finish austenitic temperature. In this state the original geometric shape will be recovered unless a load is still applied. Otherwise the shape will partially recover.

A similar effect occurs when the component temperature is above the austenite finish temperature and a load is applied. There are also comparable stress levels to temperatures, like austenite start stress. This effect is called pseudo-elastic effect.

The two-way shape memory effect results from specific training of a material along a repeated stress-strain-temperature path. This leads to a changed hysteretic response of the material. The training has to be continued until the hysteresis fits the desired one.

Depending on the size of the deformation, i. e. whether it stays within the elastic region, the fatigue life can reach up to $10^7$ cycles. Otherwise the number of cycles might decrease to several thousands. (see [9])

Shape Memory alloys can be incorporated with four different kinds of actuation mechanisms:

- Coil spring
- Torsion spring
- Flexible joints
- Spiral spring
- Torsion bar spring

As the major advantages and disadvantages are discussed in the specific sections, the mentioned pros and cons are specifically for mechanisms based on shape memory alloys.

**Advantages**

- Can be used for retracting (coil spring just axial case)
- High work per volume ratio
- Existing small mechanisms in other fields available (partially)
- Ability of articulation

**Disadvantages**

- Training for retracting required
- Perhaps external trigger required
- Just two positions depending on the possible actuation frequency
- Risk of forgetfulness when stowed in different position for long time (training)
- complicated design process

**Conclusion:**

Shape memory based mechanisms offer a very good volume and mass to energy ratio. As they can also utilized for articulating purposes they will be considered in the further research.

### *2.2.1.4 Torsion springs*

Torsion springs are typical component for hinges. They were also considered as deployment mechanism for the proposed Netlander mission of CNES and ESA.

Another specific mechanism utilizing torsion springs is described in the book [10]. The movement induced by the spring is damped by a counter-acting pack of Belleville springs.

In the US Patent 5,720,452 the damping is, however, realized by a conventional rotation damper.

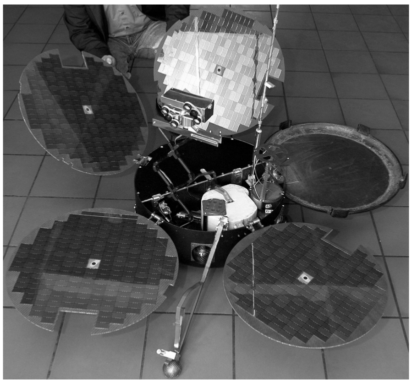

*Figure 5: model of Netlander (Courtesy of University of Münster)*

**Advantages**

- Can be incorporated with SMA
- Can be easily incorporated with damping mechanisms
- Large space heritage
- Direction torque transfer
- Small radial size
- Deceleration close to final position
- Linear characteristic

**Disadvantages**

- Too low mechanical strength to act as hinge
- Small torques possible
- Small force remaining at end of deployment
- Undefined final position

**Conclusion:**

When combined with hinges, torsion springs offer a reliable and volume-efficient deployment mechanism. As they can also be used for articulation they are considered in the further research.

#### *2.2.1.5 Spiral Spring*

Spiral springs were proposed for driving the solar panel deployment in many patents, like DE-3215431-C2, as shown in Figure 6.

In other applications, like in the Netlander mission, they were proposed as backup mechanism for electric motors to open the outer shell of the spacecraft. Due to their little torque they would not have been able to open the shell in an upside-down position, i. e. in an unexpected landing situation. [10]

Another patent, DE-3240327-C2, uses spiral spring shaped wiring as a supporting actuation mechanisms. Moreover, this approach reduces the stress induced in the cables.

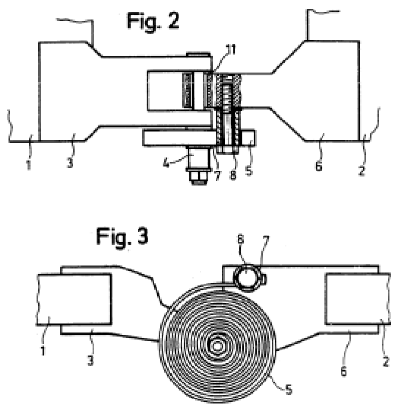


*Figure 6: deployment mechanism incorporating a spiral spring (Source: DE-3215431-C2)*

**Advantages**

- Can be incorporated with SMA
- Can be incorporated with bi-metallic band
- Provides torque directly
- Decelerates close to final position
- Can be easily incorporated with damping mechanisms
- Linear characteristic

**Disadvantages**

- Too weak to act as hinge
- Small torques possible
- Large volume required (due to radial winding)
- Undefined final position without additional latch mechanism
- Difficult to mount at panel

**Conclusion:**

Despite the fact the advantages of the system, the volume consumption is too high to consider this option for an application on CubeSats.

### 2.2.1.6 Electric motor

Rotational electric motors are used when a deployment requires high torques, high precision or highly flexible deployment schemes. The first case, however, requires the use of a gearing to transform the usually high revolutions per minute to the desired torque. This could be done space-efficient either by a planetary gearing or a rope based gearing. [10] Linear motors, like the squiggle motor, can on the other hand offer some of the mentioned features also within a very small volume.

**Advantages**

- Retractable
- Complex deployment schemes possible (also articulating)
- High precision
- Can be locked in position by detent torque
- No release mechanism required
- Large torques achievable

**Disadvantages**

- Additional energy required
- Requires additional control circuit
- Requires large volume
- Likely to require gears (rotational type only)
- Requires additional transmission to rotational movement (linear type only)
- Difficult to mount at panel (linear type only)

**Conclusion:**

Most rotational electric motors are too big for an application on board of CubeSats. The linear type fits the required dimensions, but will not be considered here, as it is difficult to mount at the panel.

### 2.2.1.7 Torsion bar spring

Torsion bar springs are a volume-efficient mechanism which can be incorporated with shape memory alloys. One example for this combination is given in the patent EP-0817744-B1 (see [11]). While one of the ends is attached to the panel, the other one is fixed at the satellite body. The shape memory material described uses the two-way memory effect. In order to achieve a directional response, the Sun radiation is blocked from an angle larger than $\alpha_{max}$ . Thus, the torsion bar spring cools down and returns to the cold state. Within the interval between $\alpha_{min}$ and $\alpha_{max}$ the torsion bar spring is heated up and changes to the hot state.

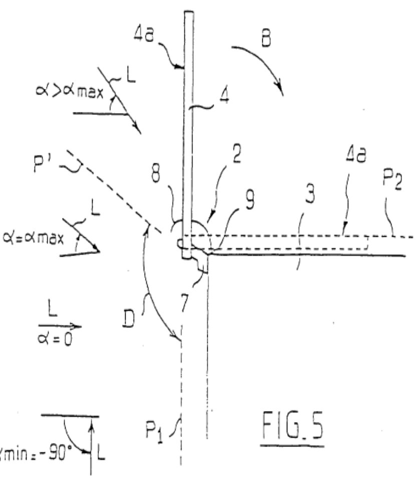


*Figure 7: directional response with two way shape memory alloys (Source: EP0817744A1)*

**Advantages**

- Can be incorporated with SMA
- Very volume efficient
- Can be used for articulating
- Provides torque directly

**Disadvantages**

- Small force remaining at end of deployment
- Undefined final position
- High manufacturing efforts
- Limited capability for shear forces
- High stresses in material
- Suitable for rigid arrays only

**Conclusion:**

As torsion bar springs are very volume-efficient and can be used together with SMA, they will be considered in the further research.

### *2.2.1.8 Spin of Satellite*

The use of the spin of the satellite for the deployment of solar arrays was suggested in [12]. (see Figure 8) As many satellites are spin-stabilized during the deployment from the launch vehicle, this type of deploying solar arrays can be used to reduce the spinning rate. Investigations in the same paper showed that the ideal deploying rotational speed is 20 rpm for deployment and 5 rpm for stiffening the solar panel. In order to shift to a non-spinning state later additional measures have to be taken to introduce stiffness to the deployed thin film solar array.

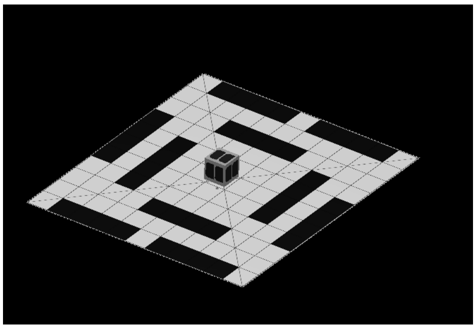

*Figure 8: CubeSat with deployed Solar array*

Another interesting application of this type can be found in the patent US-2009/0283132-A1. This type is rather intended for large satellites or space stations. Figure 9 shows its usage at a space station. The depicted cylinders represent the modules. In operating state the wind-mill shaped solar array is kept in a continuous rotation.

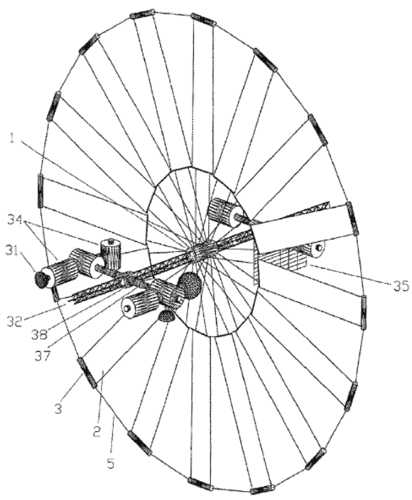


*Figure 9: Space station powered by a wind-mill shaped solar array (Source: US-2009/0283132-A1)*

| Advantages | Disadvantages |
|---|---|
| • Large area arrays possible | • Spin stabilized satellite required |
| • Can be used for de-spinning of satellite | • Suitable for thin film solar cells only |
| • No external energy required | • No control of orientation of array after deployment |
| | • Unknown impact on AOCS subsystem |
| | • No space heritage |

**Conclusion:**

As the proposed mission on which this work is based on is nadir pointing this mechanism cannot be used.

## 2.2.2 Actuation mechanisms for deployment – linear

### *2.2.2.1 Deployable boom*

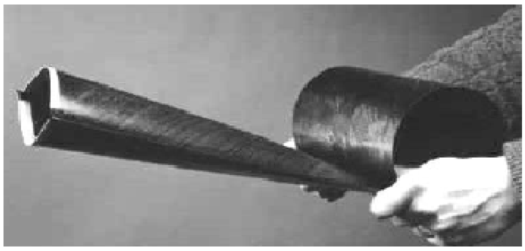

*Figure 10: deployable boom of first described type (Courtesy of DLR)*

Mechanisms similar to this have a long space heritage. They were already used during the later Apollo missions 15 and 16. Deployable booms can be classified into two different categories, pre-assembled and on-orbit-assembled. The first one was described in the paper [13] by the German Aerospace Center (DLR) for the deployment of a large solar sail. In this case the deployable boom is manufactured in two parts, which are attached to each other. The whole boom is wound on rolls in order to save volume. On orbit it is unreeled again and regains its structural stiffness. The principle is shown in Figure 10.

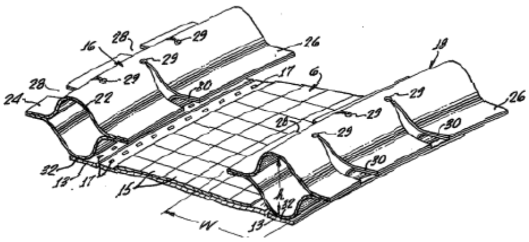

*Figure 11: cracked boom for weight reduction (Source: [15])*

The second type was, for example, used for the first solar array of the Hubble Space Telescope. It stored the two halves of the boom on separate rolls and glued them together while deploying. A similar mechanism is depicted in Figure 12. It differs by the power source of the unfolding process. While in the earlier one the rolls are directly driven by electric motors, in the later one the movement is transferred by a gearing like edge of the deployable boom. (see [14] and Figure 12) The second approach prevents the creation of cracks which can occur during the folding of booms of the first type. Parts of the boom are removed in order to save weight. (see [15] and Figure 11)

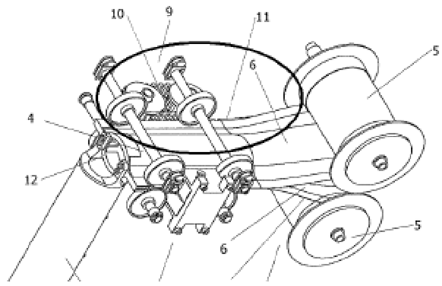

*Figure 12: deployable boom of second described type (source:* DE-102004021569-A1)

**Advantages**

- Suitable for large solar arrays
- Large space heritage
- Volume efficient in stowed position
- Full stiffness during deployment
- Includes solution for guidance

**Disadvantages**

- Complexity → reliability issues (miniaturization)
- Not retractable (on-orbit assembled type only)
- Additional power required for deployment
- Difficult to use with articulation
- Danger of cracks when wound

**Conclusion:**

The mechanism is very useful for large solar arrays. However, as the solar arrays developed in this work have smaller dimensions, it cannot be used. For future applications in big solar arrays it might become considerable after further miniaturization.

### *2.2.2.2 Inflatable booms*

Inflatable structures are an important issue in future space applications. For example, the Genesis modules of Bigelow Aerospace are launched in a compressed state and inflated when finally reaching their orbital position.

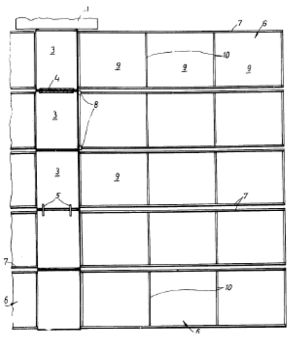

*Figure 13: inflatable booms according to DE1801777*

In particular, inflatable booms are also often suggested for the deployment of solar cells. These are usually manufactured by the thin film technique to minimize volume and mass. One application is described in the patents DE10334352 and DE1801777. Figure 13 shows the mechanism according to the later one. The mechanism combines the usual hinge-spring mechanism for the deployment in the first direction (in the figure top – down) with inflatable booms (7) in the perpendicular direction. In order to make the booms more flexible during the deployment they are soaked with glycol which evaporates later on and stiffens them. A higher stiffness in the perpendicular direction is achieved by additional inflatable sections (10).

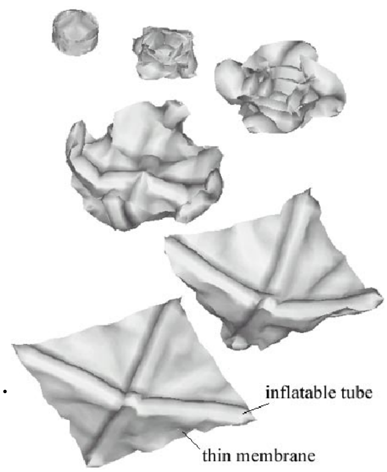


*Figure 14: estimation of deployment process on CubeSat (Nihon University CubeSat program, [16])*

A similar approach without additional stiffening inside the solar panel is suggested in the patent DE-10334352. It is shown in Figure

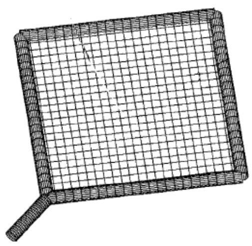

*Figure 15: inflatable solar paddle according to DE-10334352*

Apart from applications in big satellites inflatable structures were also proposed for the use on-board of CubeSats by the Nihon University. (see [16]) However, the first satellite to be flown was destroyed by the disassembling launch vehicle. The second satellite which was actually launched did not include this experiment. The expected deploying process is depicted in [16] and shown in Figure 14.

**Advantages**

- Large solar arrays possible
- Volume-efficient in stowed position
- Small number of mechanical parts

**Disadvantages**

- Gas tank required for deployment
- Difficult to use with articulation
- Suitable for thin film solar arrays only
- No space heritage
- Unpredictable deployment behavior
- Prone to pressure loss by MMOD environment impacts
- May violate CubeSat specification
- For full stiffness after pressure loss rigidifing necessary

#### *2.2.2.3 Lanyard Deployment*

This method uses the deformation work saved during the storage of the boom for its deployment. During the deploying process the outer end of the boom rotates. Unlike other methods, the full stiffness of the boom is not reached until deploying process finishes. Because of this weakness during deploying the mechanism in the current size is only usable for booms with a length of up to 3 meters. The name of the mechanism is derived from the lanyard in the middle of the boom. This rope is used to control the deploying speed by an electric motor or rotation damper. A motor even offers the opportunity to retract the solar array. Compared to the Canister Deployment this method requires less volume while no external energy source is required. Figure Fehler: Referenz nicht gefunden shows a schematic graph of the mechanism. [17] [18]

**Advantages**

- Large solar arrays possible
- Volume efficient in matters of length in stowed position (just 2% of deployed length [19])
- No additional energy required
- Large space heritage
- Includes solution for guidance

**Disadvantages**

- Suitable in current size for small length only (up to 3 m)
- Tip rotates during deployment
- Full stiffness at the end of deployment
- Damping device required to control deployment speed
- No miniaturized types available
- Over-sized for required solar array areas
- Difficult to incorporate with articulation

**Conclusion:**

Despite its advantages the method is not recommended for further research as it is to oversized for the current application and not compatible with simple articulation methods.

### 2.2.2.4 Canister Deployment

In contrast to the last mentioned method the outer end of the boom remains stationary, while the inner end is turned by an electric motor, which also allows retraction of the deployed solar array. The part outside the canister has its full stiffness at any time of the deploying sequence. This is achieved by the use of a transition region in which the boom converts to its final geometry. The Canister Deployment method can be used for the largest structures in space, like the 100 meter long solar arrays of the ISS. [19] When dealing with this large length, thermal expansion puts constraints on the stability of the boom. Therefore it is advisable to deploy in several steps with breaks in between, e. g. like done during the installation of a solar array on the ISS in the STS-117 mission. [20]

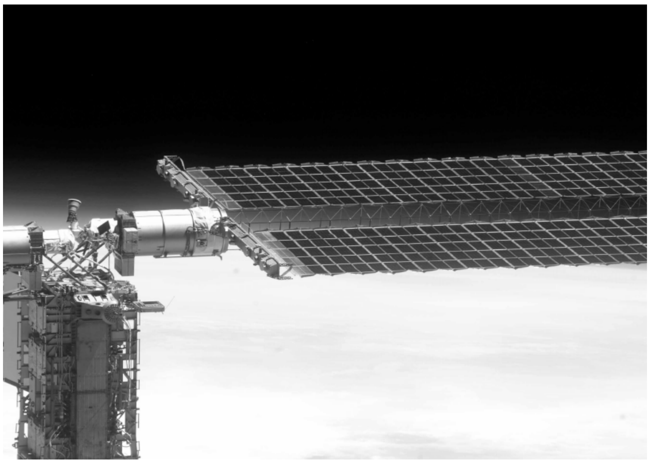

*Figure 16: deployed solar array at ISS (Source: NASA)*

**Advantages**

- Large solar arrays possible
- Large space heritage
- Full stiffness any time during deploying process
- Tip fixed during deployment process
- Good control of deployment process by electric motor
- Includes solution for guidance

- Large in matters of length in stowed position (6 % of final length [19])
- Actuator required
- No miniaturized types available
- Oversize for required solar array areas

**Conclusion:**

Despite its advantages the method is not recommended for further research as it is to oversized for the current application and not compatible with simple articulation methods.Guiding mechanisms for deployment

## 2.2.3 Guiding mechanisms for deployment

### 2.2.3.1 Rotating deployment

The rotating deployment as covered in this section was part of the Space Technology 8 program of NASA. It was also proposed for the Orion spacecraft. The deploying sequence will be explained in the following paragraph. After the launch tie-down is released the package of solar cells flaps 90 degrees away from the spacecraft. The array is then deployed by a motor driven lanyard which is attached to the pivot panel and reeled onto the motor pulley. This is continued until the pivot panel reaches close to its final position at 360 degrees. Then a spring preloaded system tightens the solar array and latches it in the desired position. [22]

**Advantages**

- Low volume requirements in stowed position
- High power per mass ratio
- Can be used for articulation
- Suitable for rigid and thin film solar cells

**Disadvantages**

- Complex deployment process
- Electric motor required
- Introduction of additional torques to spacecraft
- High absolute volume requirements

**Conclusion:**

Even though the technique offers a very high power to mass ratio and can be articulated, it would consume too much volume and introduces unknown torques to a CubeSat with limited attitude control abilities. Therefore it is not considered in this work any longer.

#### *2.2.3.2 Telescopic Cylinder*

This method was applied during a tethered-satellite experiment during the Space Shuttle mission STS 46. [23] During this test the satellite was deployed to a distance of 256 meters. It utilized a telescopic cylinder consisting of seven different single cylinders with a diameter between 50 and 120 millimeters and a length of 400 millimeters. The deployment of all cylinders was performed simultaneously. While the largest one was moved by an electric powered spindle drive, the smaller ones were pulled by a rope mechanism. [24] A simplified version taken from [25] is shown in Figure 17.

Another possible actuating mechanism is the usage of a wound band. This is also driven by a motor and pushes the different cylinders in their desired position. (see [26] and Figure 18)

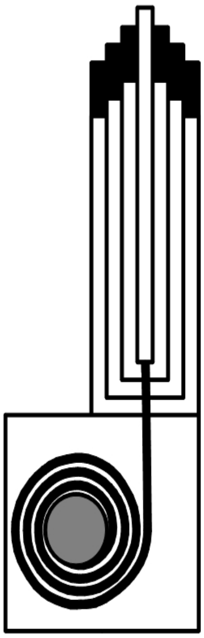

*Figure 18: second describe telescopic cylinder mechanism*

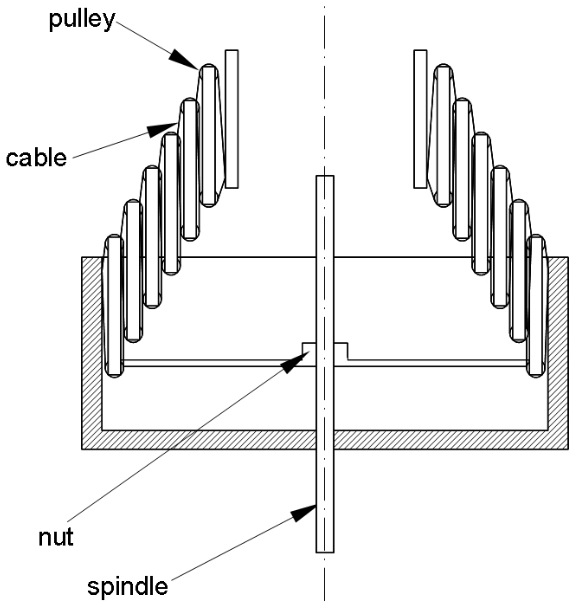


*Figure 17: schematic sketch of the telescopic cylinder used at STS-46*

**Advantages**

- Good and precise guidance of deploying process
- Can be also used as actuating mechanism
- Retractable
- Suitable for rigid and thin film solar cells

**Disadvantages**

- Too large volume requirements in axial direction for CubeSats
- Difficult to combine with articulation

**Conclusion:**

The advantages mentioned in this section are not important in CubeSat applications. As this method is also difficult to combine with an articulating mechanism, it is not further considered.

#### 2.2.3.3 Mechanical Guiding

Mechanical guiding is widely used in terrestrial applications. Figure 19 shows a mechanism planned for BREM-SAT-2 for deploying the heat shield of the re-entry capsule. [27] It uses a spindle drive to rotate the intermediate part. With some modifications it can be also used for deploying solar panels. Furthermore it can stop the deployment mechanism at any time, i. e. it can be also used for articulation. The deployment sequence is shown in Figure 19.

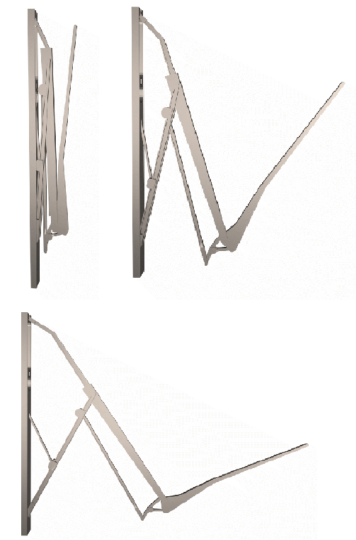

*Figure 19: deployment sequence of the hear shield for BREM-SAT-2 (Source: Matthias Wiegand, [27])*

**Advantages**

- Good precise guidance
- Includes damping at the end of deployment process
- Retractable
- Includes articulation mechanism
- Process very predictable

**Disadvantages**

- Many components required
- Suitable for one panel only
- Lubrication difficult
- Danger of cold welding
- Suitable for rigid solar cells only

**Conclusion:**

Even though the mechanism is very compact, it would be difficult to fit within six millimeters. At the current state the increase of area is not important enough to justify the high complexity of the mechanism. In case of insufficient solar array area in the design phase it should be considered again.

### 2.2.3.4 Tether

The CubeSat CUTE-1.7+APD of the Tokyo Institute of Technology used a 0.1 millimeter thick and 10 meters long wire to control the ejection of a solar panel. This was however not meant for energy production but an increase of the atmospheric friction of the satellite to increase its orbital descend rate. The panel was accelerated by the coil springs at the bottom of the satellite. Due to the low speed of 30 centimeters per second the damping could be neglected. [28] Figure 20 taken from [28] shows the solar panel in the deployed state.

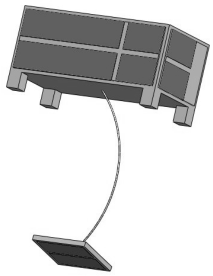

*Figure 20: Line guided solar panel in CUTE-1.7+APD mission*

Another application were the already mentioned tether satellite experiments during the Space Shuttle missions STS-46 and STS-75. The aim of these experiments was basic research on tethered satellites. In case of a sufficiently long wire it could be also used as an additional energy source. A voltage is induced in the cable, as the orbital movement is a movement relative to the magnetic field of the Earth. [29] [30] However, the author does not know of any successful test in orbit.

Tether based mechanism are also used in other mechanisms like the earlier described lanyard deployment mechanism.

**Advantages**

- Volume and mass efficient solution
- Large distances from satellite possible
- Use as additional power source possible

**Disadvantages**

- Inaccurate guidance
- No damping possible
- Prone to shear forces
- No articulation possible
- Enhances atmospheric friction
- Suitable for rigid solar cells only

**Conclusion:**

As the panel and its attitude cannot be controlled after deployment this mechanism is not useful in this project. However, it would be interesting to test tether generated power supply.

### 2.2.3.5 Scissors shaped booms

The mechanism discussed in this section is considering initially just thin film solar panels. The mechanism from patent DE-102005004922-A1 is similar to devices used for the deployment of blinds. In the current example, a rope is attached to the bar furthermost from the satellite. This is lead via rolls which are fixed at the joints. An electric motor at the satellite drives a roll to reel up the rope. This is done symmetrically at both edges of the solar panel.

With some modifications the described mechanism could be also used for rigid solar panels.

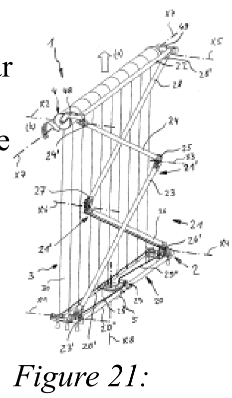

*Figure 21: mechanism described in DE-102005004922-A1*

**Advantages**

- Simple harnessing

**Disadvantages**

- Only suitable for thin film solar cells
- Maximum distance limited to the length of the booms (rather short)
- No retraction possible
- Not suitable for articulation
- Large volume and mass requirements

**Conclusion:**

As the mechanism requires too much volume, it is not considered for this project.

### *2.2.3.6 Synchronization by rope mechanisms*

Patent DE-19610297-C1 describes a mechanism that utilizes a traction drive. This is disconnected at the end of the deployment process. The orientation of the solar panel can then be adjusted by a motor attached to the shaft of the hinge. Attitude adjustments can also be transferred to other panels using the traction drive. The final position can be arbitrary defined by the position of the groove. The complete deployment process is depicted in Figure 22 and described in the next paragraph.

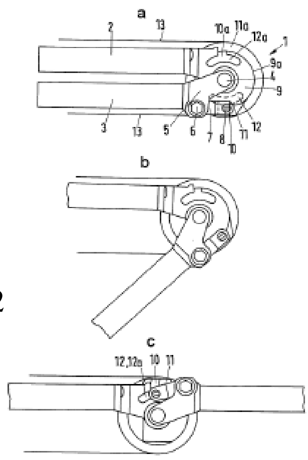


*Figure 22: Sketch of the synchronization by ropes described in DE-19610297-C1*

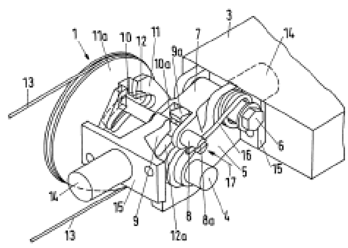

*Figure 23: 3-dimensional View of the mechanism described in DE-19610297-C1*

In the original position (see Figure 22a) the bolt (8) is pressed by a not shown torsion spring attached to the bolt (6) to the surface of the cam disc (9a). As the bolt is within the dashed drawn groove, it is deployed by the roll (11a) via the rope (13). (see Figure 22b) When reaching the final position the bolt is pressed through the slit (10a) into the groove (12a). This has the same dimension as groove (12). As the bolt (8) is not lead by the roll (11a) any more, the hinge is decoupled from the traction drive. In this condition orientation of the hinge can be adjusted by a motor within the limits given by the groove (12a). A 3-dimensional sketch of the mechanism is shown in Figure 23.

**Advantages**

- Can be incorporated with mechanism for articulation
- Useful for large solar arrays
- Locked in final position
- Good guidance of deployment process

**Disadvantages**

- Many components required
- Large volume requirements
- Tautness changes with temperature
- Cannot be retracted
- Articulation angle limited

**Conclusion:**

The mechanism is useful for large solar arrays. As this project, however, is aimed on very small satellites, CubeSats, it is not considered any further.

#### *2.2.3.7 Flexible Joints*

Flexible joints offer actuation energy, as well guiding during deployment. Also in case of guiding they are a very volume-efficient method. Further discussion can be found in chapter 2.2.1.2.

**Advantages**

- Small volume requirements
- Includes actuator
- Locks in 180 degrees position
- Articulation by incorporation of bi-metals or SMA possible

**Disadvantages**

- Difficult to retract (locking)
- Angle just adjustable by rotation of band
- Difficult to damp at end position
- Limited to rigid solar panels

**Conclusion:**

Flexible joints are widely used and offer promising opportunities for the use in articulation mechanisms by the incorporation of SMA or bi-metallic bands. Furthermore the volume consumption for this function is very small. Therefore they will be considered for further research. In order to prevent damage from the instruments, the mentioned vibrations at the end of the deployment process should be more effectively damped.

### 2.2.4 Damping mechanisms for deployment

#### *2.2.4.1 Spiral Spring*

The patent DE-3240327-C2 describes a device which is similar to a spiral spring, as already mentioned in chapter 2.2.1.5. In addition to the discussed additional actuation energy, it is suggested to use the spring to decelerate the panel at the end of the movement. This can reduce the vibrations when reaching the final position. However, the damping is just a minor side effect named in the patent. The major advantage is to reduce the stress due to thermal expansion put onto the supply lines of the solar panels.

**Advantages**

- Smooth damping by continuously increasing deceleration
- Final position defined by design of spring
- No external energy required
- Better fatigue behavior of the supply lines

**Disadvantages**

- Large volume consumption
- Difficult to mount at panel
- Rather deceleration than damping
- Suitable for low speed due to low achievable torques only

**Conclusion:**

As the design developed in this thesis might put many cycles at the supply lines, this mechanism should be considered to reduce the risk of breaking the wiring. The side effect may also help for the use of articulation.

### 2.2.4.2 Rotation damper

The only rotation dampers appropriate for space are according to an inquiry to ACE Stoßdämpfer GmbH those one based on friction. In the US patent 5,720,452 (see Figure 29), however, dampers utilizing viscous fluids are suggested. The basic principle for damping is to press the damping liquid through a throttle by turning the damper. By adjusting the viscosity of the liquid and the size of the throttle the damping torque can be varied in an interval between 0.05 Ncm and 40 Nm. The damper can be either attached directly, as shown in Figure 24, or via a gear wheel. [31] A special type of damping liquid is described in section
.

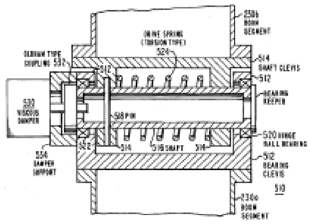

*Figure 24: mechanism described in US5,720,452*

As already mentioned earlier rotation dampers are also used to control the deployment speed of the lanyard based boom mechanisms.

| Advantages | Disadvantages |
|---|---|
| • Simple design process | • Danger of leakages in vacuum |
| • Damping widely controllable | • Large volume consumption |
| • No external energy required | |
| • COTS possible | |

**Conclusion:**

Current rotation dampers are too big for the use in CubeSats. As they also interfere with the aim of articulated panels, they are excluded from the further research.

### 2.2.4.3 Electric Motor

The patent EP-0754625-A1describes the use of electric motors for the deceleration of spring actuated and rope synchronized deployment mechanisms. It is also depicted in Figure 25. In this process the panels 56 and 44 are attached by a traction drive to the electric motor. This can influence the deployment velocity by changing the applied torque.

Another possible application is the earlier mentioned lanyard based mechanism where the electric motor can be also used to change the deployment speed.

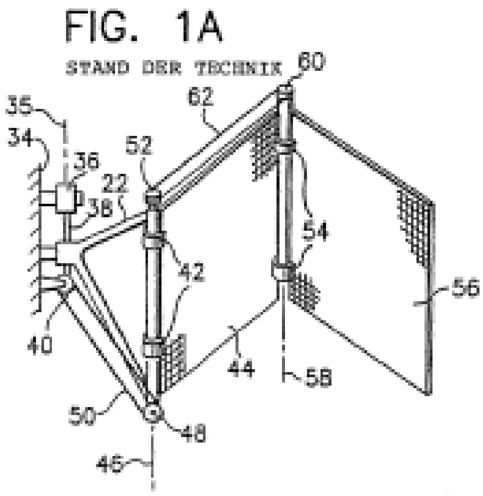


*Figure 25: mechanism using electric motor for breaking, as described in EP-0754625-A1*

**Advantages**

- Very good control
- High deployment process flexibility

**Disadvantages**

- Additional power consumption
- Mechanism requires large volume
- Heat expansion problems when used with rope mechanisms
- Requires additional control circuit
- Likely to require gears (rotational type only)

**Conclusion:**

The suggested mechanisms based on electric motors are too big for an application on board of CubeSats. Therefore they are excluded from the further research.

#### *2.2.4.4 External Friction*

This method uses friction at the outer faces of the hinge to damp the deploying movement. The rate and the start of the damping can be arbitrary adjusted by using a specific profile for the outer faces. With a known friction coefficient the final angle can be defined by changing the force normal to the surface of the hinge. A design based on this principle was described in [2]. Despite the simplicity of the solution it inherits a high risk of failure as the prediction of friction relies on experiments and the friction coefficients might change with time due to degradation in orbit. In the mentioned paper, however, it was still feasible, as the deployment was planned to be in a very early mission phase.

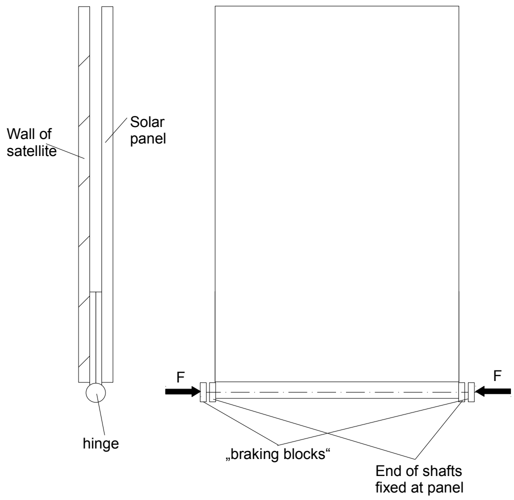

*Figure 26: damping by external controlled friction*

**Advantages**

- Final position adjustable after manufacturing
- Small volume required

**Disadvantages**

- High risk for mission success
- Danger of cold welding
- Friction difficult to predict

**Conclusion:**

Due to the functional risk which is even increased for an articulated design the solution option is not considered in this project.

#### *2.2.4.5 Eccentric bolt*

The idea behind this mechanism is to modify the outer end of the shaft to rub against a plain surface at the satellite bus. As a side effect the end might get stuck and slightly locks the panel in its final position. Different decelerations and final positions can be obtained by adjusting the shape of the eccentric bolt.

**Advantages**

- Small volume required
- High reliability
- Locking in final position possible

**Disadvantages**

- No space heritage
- Eccentric bolt prone to breaking
- Final position inaccurately defined
- Difficult to unlock

**Conclusion:**

As this option is a one-shot mechanism it cannot be used in this project which requires the hinge not to lock permanently in a final position at all.

#### *2.2.4.6 Electric damping by electro-rheologic / magneto-rheologic fluids*

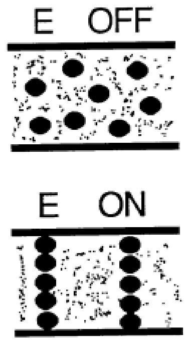

*Figure 27: schematic view of active liquid at different field strength (Source: NASA)*

Dynamic perturbations of any kind can be damped by the use of active materials, like electro-rheologic or magneto-rheologic fluids. The damping coefficient can be adjusted by changing the electric or magnet field strength between the base viscosity of the liquid and an almost fixed connection. An increase in field strength will result in a higher damping rate. In case of a deployable or articulable solar panel this gives the chance for arbitrary deployment and articulation processes. Figure 27 taken from [32] shows a schematic view of the liquid at different electric field strengths.

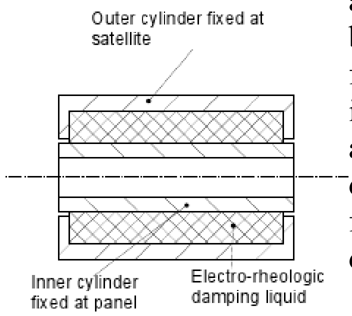

*Figure 28: schematic view of damper based on active liquids*

A device based on this technique might consist of two unconnected co-axial cylinders. The gap in between is filled by the electro-rheologic / magneto-rheologic fluid. (see Figure 28)

**Advantages**

- Damping rate flexible adjustable
- Small volume required
- Can be locked in final position

**Disadvantages**

- Function endangered by leakages
- Additional electric energy required
- Strong electric fields required
- Danger for electronic components inside satellite
- Perturbations of electric or magnetic field sensors

**Conclusion:**

As the system adds large perturbations on the electronics on board of CubeSats and the risk of leakage the mechanism is not considered any further.

#### *2.2.4.7 Friction in joints*

This solution relies on the damping created by friction at the contacts between the hinges, the bearings and the used actuation mechanism. As this effect is very small compared to other damping solutions the vibrations transferred from the solar panel to the satellite bus are comparably large. This can be only ignored in missions where no sensitive instruments prone to vibrations are on board of the spacecraft. One example for the application of this method is the proposed MOVE mission of the Technical University München.

**Advantages**

- No additional components necessary
- No additional energy required

**Disadvantages**

- Unpredictable
- Small damping efficiency
- Still strong oscillations at end of deployment (→ another damping mechanism required)

**Conclusion:**

The solar array to be designed should be suitable for a wide range of mission profiles. As this is impossible to achieve with large vibrations at the end of a deployment process, this solution option is not considered any further.

#### *2.2.4.8 Counter-force by Belleville springs*

The solution described in [10] uses Belleville springs to damp the deployment movement. These are located around the shaft in the middle of the joint. While turning the hinge the pack of Belleville springs is compressed. Therefore the panel is decelerated at the end of the deployment.

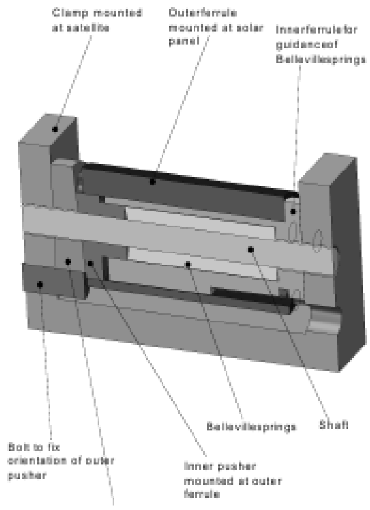

*Figure 29: Schematic sketch of the mechanism using Belleville springs*

**Advantages**

- Proved mechanism
- Small volume required
- Continuous deceleration
- Final position roughly defined

**Disadvantages**

- Too large volume for application in CubeSats
- Many components involved
- Complex mechanism (→ higher risk)
- Risk of cold welding
- Uncertainties due to friction between outer and inner ferrule

**Conclusion:**

As the mechanism cannot be adjusted during usage, it is not suitable for articulating solar arrays. Therefore it is not considered any further.

#### *2.2.4.9 Rubber damper at desired position*

In combination with an actuator which can still apply torques at the end of the deployment process a rubber plate can damp the vibrations in a simple and fast way. However, the author does not know of any space heritage of the method.

**Advantages**

- Simple to implement
- Small volume required
- Final position determined by position of damper

**Disadvantages**

- No space heritage
- No locking in final position
- Danger of outgasing
- Short way of deceleration

**Conclusion:**

As the mechanism can be only designed for a fixed final position, it is not suitable for articulated solar panel and will be excluded from the further research.

### *2.2.4.10 Latch at desired position*

US patent 5,400,987 describes a latching mechanism for deployable solar arrays on board of spacecrafts. When locking in the final position the panel can only move in a small range decreasing the amplitude of the occurring oscillations. A further reduction could be achieved by coating the impacting surfaces with an elastic material. By adjusting the size of the part 16 in Figure 30 the final angle can be varied in a range between 80 and 100 degrees.

FIG. 5.

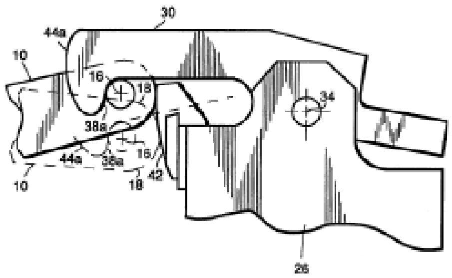

*Figure 30: latch in final position (Source: US-5,400,987)*

**Advantages**

- Final position defined
- Locking in final positions
- Can be unlocked

**Disadvantages**

- Difficult to unlock
- Puts constraints on articulation
- Many components
- Large volume required

**Conclusion:**

As the deployment angle is predefined and the angular range is too small, articulating solar arrays would be very difficult to realize with this solution. Therefore it is not considered any further within this paper.

### *2.2.4.11 Torsion spring in hinge*

Similar to the damping by a spiral spring, as discussed in section 2.2.4.1, torsion springs could be also used for the deceleration of deploying solar panels. However, they offer the same function in a comparable small volume. A more detailed description about the use of torsion springs in hinges can be found in chapter 2.2.1.4.

| Advantages | Disadvantages |
|---|---|
| • Smooth deceleration<br>• Final position determined by design of spring<br>• Little volume required<br>• Simple to mount<br>• Linear characteristic<br>• Can be incorporated with SMA | • Small damping torques possible<br>• Does not lock in final position |

**Conclusion:**

Torsion springs might be useful for damping an actuation driven by shape memory alloys. However, as they cannot be adjusted to different distinct angles they are not considered any further within this

project.

### 2.2.5 Initial Release Mechanism

Due to limited space in launch vehicle, large structures in space systems can not be launched in their deployed state. As these are locked in their stowed position and oftenmission critical it is necessary to release them very reliably and at a specific time. The following chapter describes solution options shown in chapter 2.1.

#### *2.2.5.1 Thermal Methods*

Thermal methods utilize environmentally or by actuators changed temperatures for the release of the deployable solar panels.
The following section describes the methods evaluated in this thesis.

##### 2.2.5.1.1 Thermal loosening of interference fit

The mechanism described in this section consists of a pin and a corresponding ferrule. This is shrunk on the pin. Afterward both are mounted with the satellite bus and the deployable solar panel respectively. Due to different coefficients of thermal expansion of the materials the temperature change resulting from the space environment causes the original press fit to get loosen. As the process depends on the surrounding conditions the time of deployment can be only roughly estimated. A possible material pairing could be steel for the ferrule and aluminum for the bolt. This assumes that the mechanism will be cooled down after entering the desired orbit.

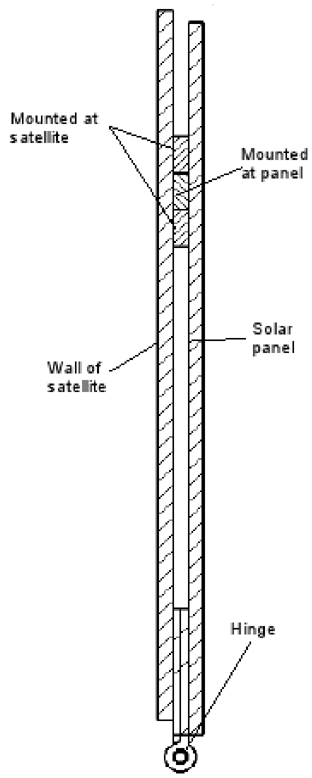

*Figure 31: Schematic sketch of the release by thermal loosening*

**Advantages**

- Reusable
- Passive method
- Small number of components
- Volume efficient

**Disadvantages**

- Time of deployment not exactly defined
- Risk of unexpected temperature changes
- No space heritage

**Conclusion:**

As this mechanism cannot offer a predefined deployment time and the reuse requires high efforts, it is not considered further for this project.

#### 2.2.5.1.2 Heat wire

The mechanism is based on the fact that the tensile strength of a wire decreases when heated up until it melts. When the deployment force reaches the ultimate strength of the wire it is ruptured by the force resulting from the deployment mechanism.

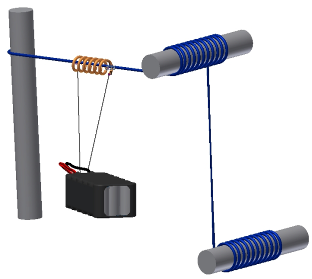

*Figure 32: schematic sketch of release by heat wire*

The CubeSat CUTE-1 of the Tokyo Institute of Technology utilized a simple wire which was melted via a heat winding. Afterward the antennas of the satellite were deployed. [3] Figure 32 shows a schematic sketch of the release process.

Another application mentioned in the patent DE-3215432-C2, however, is more complicated. In this solution the panels are held by spring driven hook (8). This is fixed by the wire (10). After cutting this the hook is released and starts the deployment sequence.

**Advantages**

- Very large space heritage
- Simple mechanism
- Suitable for more than one deployable
- Time of deployment good controllable
- High reliability
- Little vibrations created

**Disadvantages**

- Danger of contamination
- Danger of creation of space debris
- Additional energy required

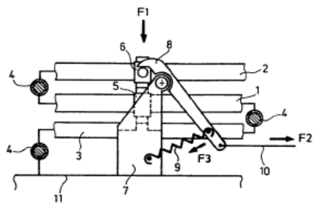


*Figure 33: release mechanism described in the patent DE-3215432-C2*

**Conclusion:**

As this method is very simple and reliable, it is considered for further investigation within this project.

### 2.2.5.1.3 Phase Changes (HOP actuators)

This mechanism utilizes the big volume changes during phase changes of materials. Figure 34 shows a pin puller based on this principle. In the original state the two chambers of the cylinder are filled by solid paraffin and the counteracting spring. By heating up the paraffin above its melting temperature, its volume increases and moves the piston. The mechanism can be reused after the solidification of the paraffin. Similar to other thermal methods, the time period between command and release is rather large. [10]

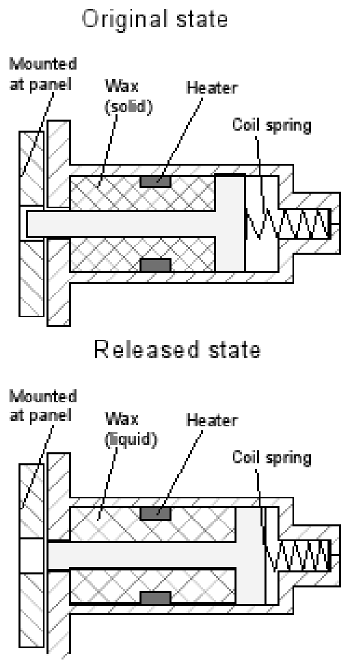


*Figure 34: schematic sketch of a HOP pin pusher*

**Advantages**

- Little vibrations created
- High cutting force available
- Large space heritage
- Reusable
- Hardware can be handled easily

**Disadvantages**

- High energy consumption [21]
- Large volume required
- Large mass required

**Conclusion:**

Even though a pin is a very reliable and reusable device, it is not considered for the project as its power and volume consumption is too high.

### 2.2.5.1.4 Shape memory alloys devices

Release mechanisms based on SMA are widely proposed, such as in [33] or [34]. This section will focus on the most promising solution from the later one. (see Figure 35) It consists of three strips made of SMA which lock the release plunger in the initial position. These change their shape when heated up and release the plunger. The heating can be achieved either by external resistive heaters or direct heating while the latter one offers a shorter release time. In case of installing both solutions the mechanism is very reliable as it has a mechanical and electrical redundancy. The mechanical redundancy is given by the fact that it is sufficient for release to achieve a shape change at only two of the three stripes.

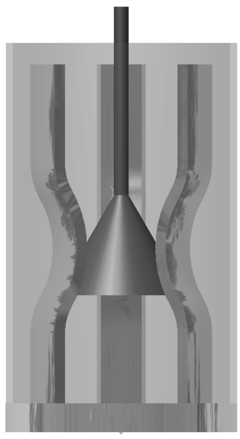

*Figure 35: release mechanism based on shape memory alloys*

**Advantages**

- Very easy reusable
- High reliability
- Simple mechanism
- Time of release good controllable

**Disadvantages**

- Additional energy required
- Danger of too early release by strong vibrations

**Conclusion:**

Even though the solution option is not as simple as the heat wire, it should be considered as a backup solution for cases where heat wires cannot be applied.

### *2.2.5.2 Mechanical solutions*

#### 2.2.5.2.1 Electric motor with rod mechanism

In this in patent EP-0754625-A1 described mechanism the brace (150) locking the panel is kept by a rope (156) in the stowed position. In order to release the solar panel a stepper motor (136) turns the cable winch. Thus, the rope slips of the open roll (154). This releases the brace which unblocks the solar panel for deployment by the mentioned springs (152).

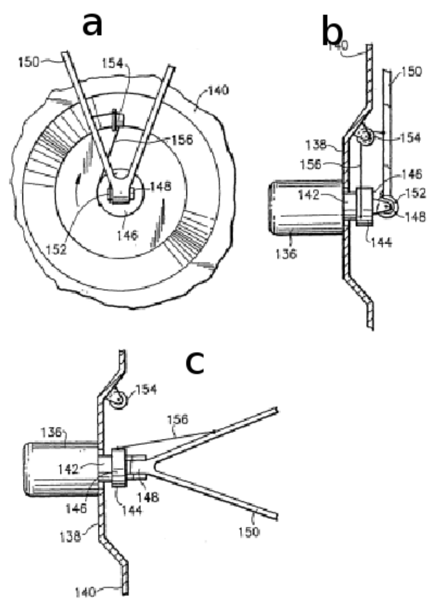

*Figure 36: sketch of mechanism described in EP-0754625-A1*

**Advantages**

- High reliability
- Good control of release process

**Disadvantages**

- Additional energy required
- High mass
- Large volume required
- Many components involved

**Conclusion:**

As the mechanism is not suitable for the small available volume on board of CubeSats it is not considered in further research.

#### 2.2.5.2.2 Release from P-POD

This method is characterized by the fact that it does not require any further components. As nothing except the P-POD is locking the deployable solar panels in their stowed position they are deployed during the ejection from the P-POD. However, when the CubeSat is launched together with other satellite or depending on the launch vehicle this approach could cause harm to those. Moreover, required by the CubeSat specification (see requirement 2.4.2 in [1]) deployable mechanisms are permitted to be activated as early as 30 minutes after the deployment of the satellite and not allowed to be constrained by the P-POD only (see requirement 2.2.8 in [1])

However, this method is planned for the ParkinsonSAT mission of the US Naval Academy Satellite Lab. (see page 26 in [35])

**Advantages**

- No additional components required
- High reliability
- High volume and mass efficiency
- Simple mechanism

**Disadvantages**

- Incompatible with CubeSat specification
- Endangering neighboring components / satellites
- Possible impact on deployment from P-POD

**Conclusion:**

As the method has a very simple approach and a high reliability, it would be interesting to use within this project. However, the issue about the violation of the specification must be negotiated with the launch provider.

### 2.2.5.2.3 Decompression

This proposed mechanism utilizes the vacuum in space to actuate a pin-puller. In the stowed position the pressure in both chambers of the cylinder as at an equal level, while the upper one in the figure is separated from the vacuum by a membrane. The release actuation can be triggered by the material degradation of the membrane or its intentional destruction by an addition mechanism. In order to adjust the actuation speed the diameter of the hole in the cylinder or another throttle could be used. A breaking membrane, as shown in Figure 37, could be the simplest option for a time delayed blow-off valve.

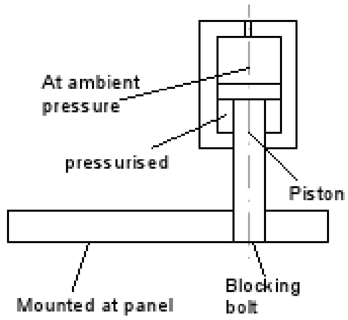

*Figure 37: schematic sketch of proposed release by decompression*

In addition to the mentioned applications the pressure inside the chambers could be increased in order to use the mechanism as cutting mechanism.

**Advantages**

- No additional energy required
- No external trigger required

**Disadvantages**

- Time of release roughly defined
- Production of space debris
- No space heritage
- Functional risk due to uncertainties in material
- Danger of leakages before release
- Large thickness of wall required
- High volume consumption

**Conclusion:**

The thickness of the membrane for the survival against a pressure difference similar to the pressure at sea level, the thickness would be too large for practical applications in CubeSats. However, future materials might resolve this issue.

### 2.2.5.2.4 Pyrotechnical cutter

Pyrotechnics are widely used for release mechanisms in many different space systems, e. g. for stage separation of multistage rockets. In applications for solar panel deployment they are mostly used as cutting device. The principle structure is very similar to the earlier described HOP actuators. However, pyrotechnical cutters replace the solid paraffin by an explosive mixture. As the detonation creates a high pressure, the performance increase is very high compared to HOP actuators enabling pyrotechnical cutters to release bolts of bigger diameter. Due to the simplicity of the mechanism it is very reliable. [10]

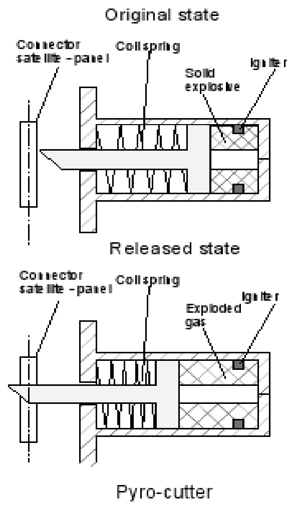


*Figure 38: schematic sketch of a pyrotechnical cutter*

**Advantages**

- Large space heritage and widely used mechanism
- High volume efficiency
- High mass efficiency
- High forces achievable
- No danger of leakages

**Disadvantages**

- Introduction of vibrations to structure
- Endangering other components or satellites in P-POD
- Prohibited by CubeSat specification

**Conclusion:**

As pyrotechnic mechanisms are prohibited by the CubeSat specification they are not considered within this project.

### 2.2.5.2.5 Mechanical by releasing key

This volume-consuming but reliable method was selected by the Tokyo Institute of Technology for its first CubeSat CUTE-1. It is based on a plunger which is connected to the deployable panel. The plunger is locked by a rail. This driven by an electric motor via a small gearing. The stopper is released after a rotation of the rail by an angle of 270 degrees. Despite the large consumed volume the solution was chosen to decouple the risk of failure of the solar array and the antenna deployment. [3] [36]

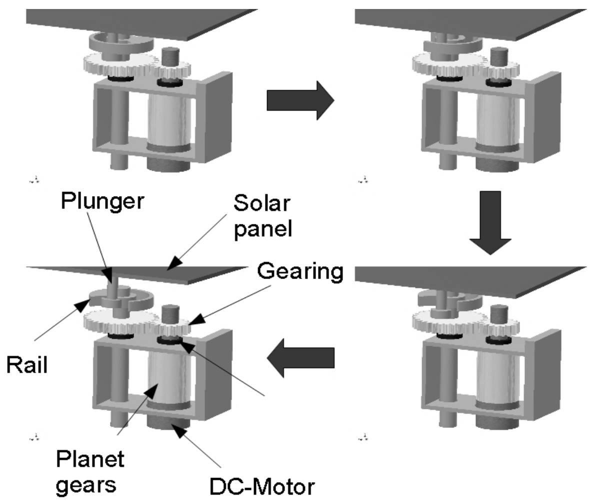


*Figure 39: release sequence at the CUTE-1 mission*

**Advantages**

- Space heritage
- High reliability
- Reusable

**Disadvantages**

- Large volume required
- Large mass consumption
- External energy required
- Demanding lubrication
- Many components
- Complex mechanism

**Conclusion:**

As the volume consumption is very high for this mechanism, it is not considered any further within this project.

### *2.2.5.3 Magnetic solutions*

#### 2.2.5.3.1 Weakening magnet field by spool

This method utilizes strong magnets for locking the solar panel in the stowed position. In order to release a second magnetic field is produced by a coil to counteract the magnet force of the permanent magnet which should consist of an alloy similar to Neodymium-iron-Boron to maximize the clamping force during launch. In order to decrease the required power for the coil it should be placed further away from the rotational axis compared to permanent magnet.

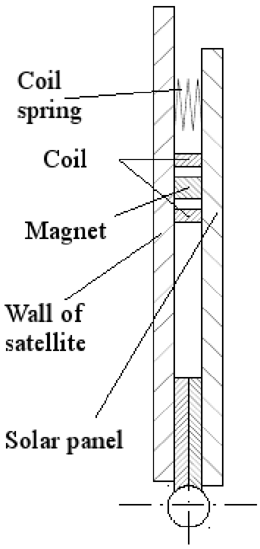


*Figure 40: schematic sketch of a magnet release mechanism*

**Advantages**

- Simple mechanism
- High clamping forces achievable
- Little volume required

**Disadvantages**

- High mass required due to ferromagnetic materials
- Disturbance of on-board instruments and components
- Specific material for panel required
- Danger of cold-welding
- High stress on panel
- No space heritage

**Conclusion:**

As the magnets interfere with the on-board magnetometers this method can only be used for mission not requiring magnetic field measurements. For the scope of this project this is unacceptable, as it should work for generic space missions.

### 2.2.5.3.2 Cone movement by pusher

The application of magnet pushers is described in this section uses a cone to maximize the clamping force. At release time the pin moves the cone away from the blocking position freeing the solar panel to deploy. However, as the cone and the spring form an oscillator the natural frequencies of the systems have to be investigated thoroughly.

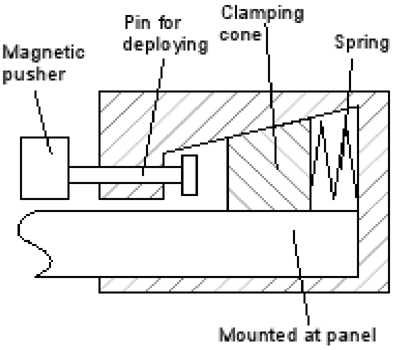


*Figure 41: cone based release mechanism*

**Advantages**

- High clamping forces
- Force amplification by cone
- Reusable
- Use of COTS

**Disadvantages**

- Cone-spring form oscillator
- Additional energy required
- Danger of cold-welding between cone, housing and panel
- No space heritage

**Conclusion:**

As the mechanism consumes a considerable volume it is not considered for further research.

## 2.2.6 Actuating mechanism for articulation

As most of the mechanisms in this section were already discussed in the section about actuation mechanisms for deployment, only differences to that section are discussed in this chapter.

### *2.2.6.1 Flat electric motor*

In [37] the Moog Inc. proposed a compact motor for pointing purposes. Unlike common mechanisms this device can handle tilting in two degrees of freedom at the same time. The main part of the motor is a gimbal with attached magnets. These magnets are oriented by adjusting the magnetic field induced from the coils in Figure 42. For the use for articulating a solar array in this project, however, the mechanism is not suitable as the motor is limited to an angle range of 90 degrees. The design described in [46] has still dimensions of 6 times 6 times 4 centimeters. The website of the manufacturer does not give any more recent information.

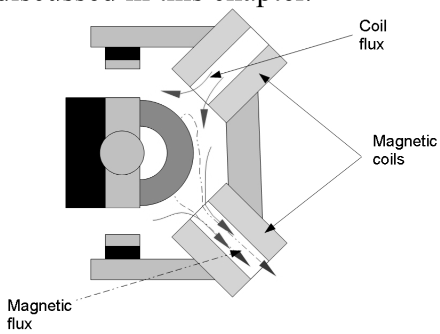


*Figure 42: electric motor described in [37]*

| Advantages | Disadvantages |
|---|---|
| • Compact design (flat, compared to common electric motors)<br>• Arbitrary articulating angles at any time possible<br>• Useful after further miniaturization | • High additional energy required for actuation<br>• Additional energy constantly required for locking<br>• Strong magnetic field causes disturbances in instruments<br>• Large volume required<br>• Large mass consumption<br>• Limited angle range |

**Conclusion:**

As the mechanism is still to large for the use in CubeSats, it is not considered for this project any more. After further miniaturization in future, it might become useful for CubeSat missions.

#### *2.2.6.2 Piezoelectric motors*

Piezoelectric motors, like the Squiggle motor SQL-RV-1-8, are actuators of very small size, e. g. 2.8 x 2.8 x 6 mm. As they are linear motors it is necessary to include a converter from a linear to a rotating movement. This can be done by cams, windings or by a direct connection to the solar panel. The maximum power consumption is 1.8 watts. A motor driver is needed for the operation of the motor. In order to meet the space requirements this has to be implemented on a custom PCB. [38]

| Advantages | Disadvantages |
|---|---|
| • High volume efficiency<br>• No power required for locking<br>• High mass efficiency<br>• High positing precision | • Require linear to rotation conversion (like cam, windings or crankshafts)<br>• Additional driver required<br>• Driver has to be self integrated to meet space requirements<br>• No space heritage<br>• Insufficient temperature range (-30 – 80 ° C) |

**Conclusion:**

When kept within the temperature range, the mechanism offers a good control of the articulation angle. Therefore it is considered for further research.

### 2.2.6.3 High Output Paraffin (HOP) motor with cam

Mechanisms based on HOP motors are similar to the ones with squiggle motors, as both are linear actuators. The mechanism described in has a diameter of 2.58 centimeters and a length of 15 centimeters. The coil spring keeps the solar panel in the stowed position. This system measures the Sun incident angle by an electronic Sun sensor. The control system then adjusts the orientation of the solar panel by switching on and off the HOP actuator. Power required by the system is generated by the system itself. [39] Figure 43 shows the complete mechanism.

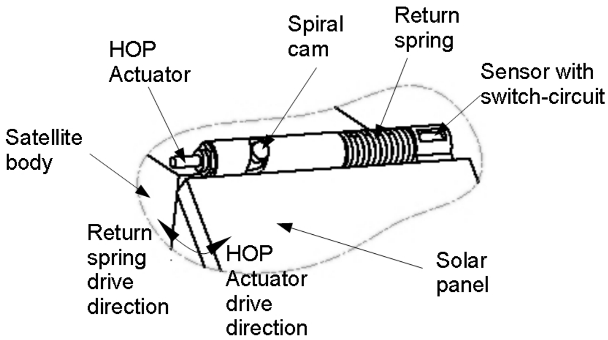


*Figure 43: SPSPAD system from Starsys Research Corp.*

**Advantages**

- High reliability
- No shock operation
- Reusable
- High mass efficiency compared to force

**Disadvantages**

- Danger of cold-welding
- High power consumption
- Large volume required (2.58 x 15 cm)

**Conclusion:**

As the system is too big to fit in the space required for the mission, it will not be considered any further in the scope of this project.

### 2.2.6.4 Shape memory alloys

The system is essentially the same as described in section 2.2.1.3.

**Advantages**

- Passive mode possible
- Active mode possible
- High volume efficiency (passive mode)
- High mass efficiency (passive mode)

**Disadvantages**

- Limited to two final positions (two-way memory effect)
- Damping mechanism required for more positions
- Material training required
- Possibly protected by patents (DE-69604165-T2, EP0817744B1, US6062511A)

**Conclusion:**

As SMA are a promising mechanism with a high work to mass ratio they are considered as a possible mechanism in this project.

### 2.2.6.5 *Torsion spring in hinge*

The system is essentially the same as described in section 2.2.1.4. However, as in both types, with and without SMA, the final deployment angle is predefined, another mechanism has to be used to clamp the solar panel at positions in between. This could be for example done by the use of electro- / magneto-rheologic liquids.

| **Advantages** | **Disadvantages** |
|---|---|
| • High volume efficiency | • Damping mechanism required |
| • High mass efficiency | • Small torques available |
| | • Predefined characteristics |

**Conclusion:**

The use of a clamping mechanism could spoil the memorization abilities of the material. As an alternative the actuation frequency of the SMA material should be reduced to sufficiently low rates.

### 2.2.6.6 *Spiral Spring*

The system is essentially the same as described in section 2.2.1.5. However, as in both types with and without SMA the final deployment angle is predefined, another mechanism has to be used to clamp the solar panel at positions in between. This could be realized by the use of electro- / magneto-rheologic liquids.

| **Advantages** | **Disadvantages** |
|---|---|
| • Direct torque transfer | • Damping mechanism required |
| • Linear characteristic | • Small torques available |
| | • Predefined characteristics |
| | • Difficult to mount at panel |

**Conclusion:**

As the size of the solution is too big compared to alternatives it is dropped for this project.

### 2.2.6.7 *Bi-metal strips*

Bi-metal strips generate their actuation movement from different thermal expansion ratios of materials bonded together. As the change in length and therefore the achieved angle is directly proportional to the temperature of the mechanism it offers the ability for arbitrary actuation processes when using an applied heater.

An application of this type of mechanisms is described in the US-patent 3,311,322. (see Figure 44) As Sun light is shining on the strip (28) it starts expanding, thus, changing the sun incident angle of the solar panel. In order to control the movement of the solar panel another metal sheet (32) is used to shadow parts of the strip.

A mechanism which automatically adjusts its orientation according to its temperature was also claimed in the patents EP-0817744-B1 and US-6062511-A. However, these patents are already lapsed.

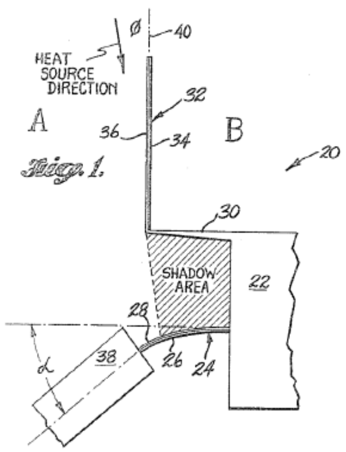


*Figure 44: mechanism based on bi-metal strips (Source: US-3,311,322)*

**Advantages**

- Active mode possible
- Passive mode possible
- Arbitrary positions defined by temperature
- High mass efficiency
- High volume efficiency

**Disadvantages**

- Materials limited to space qualified only
- Possibly protected by patents in Europe (DE-69604165-T2, EP0817744B1, US6062511A)

**Conclusion:**

As the mechanism offers a good control of the articulated angle and has a redundant functionality it should be further considered within this project. In order to decrease the size of the bi-metallic strips even further they could be combined with a hinge leaving just the actuation to them.

#### *2.2.6.8 Torsion bar spring in hinge*

The system is essentially the same as described in section 2.2.1.7.

**Advantages**

- High volume efficiency
- High mass efficiency
- Provides torque directly

**Disadvantages**

- Damping mechanism required
- Limited to combination without torsion bar spring as actuating mechanism for deployment
- Limited capability for shear forces

**Conclusion:**

As torsion bar springs are very volume-efficient and can be incorparated with SMA, they will be considered in the further research.

#### *2.2.6.9 By linear displacement*

This technique is based on the latch mechanism described in section 2.2.4.10. It articulates when the motor with gear-head (50) drives the spindle drive consisting of a screw (52) and the corresponding slider (54). The slider (58) moves then within the groove in (56) causing the panel to articulate. Guidance for the rotational movement of the panel is provided by part (60). Apart from the selected rotational motor HOP actuators or Squiggle motors could be also used to avoid a volume consuming rotational to linear conversion. [40]

FIG. 6b.

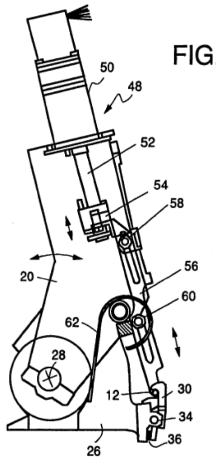


*Figure 45: mechanism using linear displacement for articulation (Source: [40])*

**Advantages**

- Can be incorporated with hop actuators or piezoelectric motors
- Precise articulation
- Provides locking

**Disadvantages**

- Limited angle range
- Large volume required
- Complex mechanism
- Large mass required
- Additional actuator required

**Conclusion:**

As the mechanism consumes a large volume, it is not considered any further within this project.

#### *2.2.6.10 Stepper Motor*

Stepper motors offer a high flexibility and precision for the articulation process. The accuracy and the torque can be further improved by the use of a gearing. This could be volume-efficient either done by a planetary gearing or rope based gearing. Another advantage of stepper motors is their good controllability.

**Advantages**

- Retractable
- High precision
- Can be locked in position by detent torque
- No release mechanism required
- Large torques achievable

**Disadvantages**

- Additional energy required
- Requires additional control circuit

**Conclusion:**

Because of the good control of stepper motors and their high precision stepper motors are considered an option within this project. The additional required energy can be minimized by small duty cycles.

### 2.2.7 Control mechanism for articulating

#### *2.2.7.1 Electronic controller*

Electronic controllers are widely used in any field of engineering. For the articulation of solar arrays their usage is limited to the actively controlled mechanisms. In order to generate an accurate actuation signal they need sensors to determine the Sun incident angle on the solar panels. Alternatively they can be recalibrated by the detection of the angle with the highest power output. The controller could also be included in the general flight avionics to save volume.

**Advantages**

- Use of COTS
- Large space heritage
- High flexibility regarding control

**Disadvantages**

- Requires additional sensors
- Requires additional energy
- Requires additional circuits

**Conclusion:**

As electronic controllers require additional mechanisms and energy, they should be avoided in the design of this project unless the complexity of the system would increase too much.

#### *2.2.7.2 Changing shadowing mechanically*

This method was already briefly described in section 2.2.1.7. It is included in this chapter to show the full scope of possibilities.

**Advantages**

- Passive system
- High volume efficiency
- High mass efficiency

**Disadvantages**

- Likely to be protected by patents
- Limited to two different states
- Limited to predefined direction shadows

**Conclusion:**

As the orientation of the shield is fixed during the whole mission time it is difficult to adjust solar panel to changing solar incident angles during a complete year. This could be overcome by a change the transparency of the shield along its angular range.

#### *2.2.7.3 Clamping by electro-rheologic / magneto-rheologic fluids*

As many articulation mechanisms are designed for a fixed deployment angle clamping mechanisms based on electro-rheologic or magneto-rheologic fluids could be used to stop the solar panel at the desired angles. Background information about this mechanism can be found in the chapter about damping deployment mechanisms. (see section 2.2.4.6)

**Advantages**

- Can be incorporated with any spring actuating mechanisms
- Clamping at arbitrary dynamically chosen position
- Also suitable for damping

**Disadvantages**

- High electric / magnetic field strength required
- Danger for other components
- Disturbances to instruments
- Current drawn during clamping

**Conclusion:**

As the systems adds large perturbations on the electronics on board of CubeSats and the risk of leakage the mechanism is not considered any further.

### 2.2.7.4 *Photo-chromatic lens*

Another possible solution to create a time depended incident solar radiation can be achieved by photo-chromatic lenses. The base material used is Silver-bromide or Silver-chloride. Under incident UV-radiation these substances decompose changing themselves from transparent to opaque. This could be utilized for creating a specific temperature profile with heating and cooling during the daylight part of the orbit.

**Advantages**

- Passive mechanism
- High reliability

**Disadvantages**

- High complexity
- Danger of leakages
- Suitable for bi-metallic and shape memory alloys based solutions only
- No space heritage
- Low cycle number (usually below $10^4$ [42])

**Conclusion:**

As the technique is not space-proven, it should be avoided if possible.

### 2.2.7.5 *External friction*

The mechanism of external friction (see section 2.2.4.4) can be also applied for clamping the solar panel in desired positions. It is also similar to the clamping by electro-rheologic / magneto-rheologic fluids.

**Advantages**

- High reliability (clamping)

**Disadvantages**

- Danger of cold welding
- Large mass required
- Large volume required
- No space heritage

**Conclusion:**

As the mechanism is not space-proven and has also a high risk of cold welding it is not considered further within the scope of this project.

### *2.2.7.6 Photo-diodes with shield for damping*

The US-patent US-20090314279-A1 (see Figure ) describes an arrangement of photo diodes which is also shadowed similar to the mechanism described in the section about changing shadowing mechanically. However, the shadow region, the ideal range, is used in this device to separate the forward and backward sensing range from each other.

Current produced by the photo-diodes can be used to drive an electric motor via a relay to orient the solar panel to towards the ideal range.

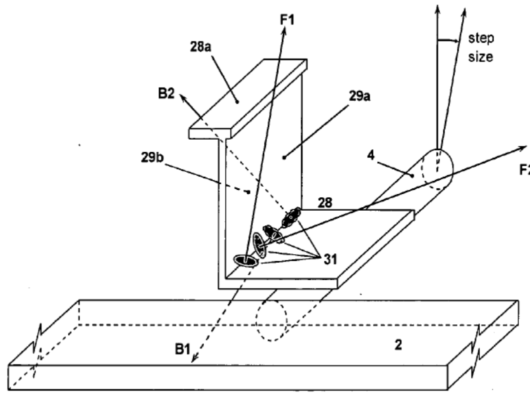


*Figure 46: photo-diodes with shield to create forward (right part), backward and ideal ranges*

**Advantages**

- Range of 180° for controlling
- Range without control

**Disadvantages**

- Large volume required
- Large mass required
- Needs additional controller

**Conclusion:**

As the shield needs a sufficiently high distance between sensors and itself the mechanism requires too much volume to be used within the scope of this project.

## 2.2.8 Types of Solar Cells

Solar cells are the most used energy source for Earth orbiting satellites since the beginning of the space age. Since then, beginning from rigid silicon solar cells more advanced technologies like thin film solar cells were developed. In order to increase the efficiency further other materials, like Gallium-Arsenide, and more layers for different spectral bands were introduced.

The complete power system of a spacecraft consists of the energy source, – in this section solar cells – batteries, a power control system and the wiring. In order to generate the required electric currents and voltages solar cells are connected in series and in parallel. Voltage requirements are met by series connections, while current requirements make use of parallel circuits.

Solar cells experience degradation during their lifetime. Cover-glass that protects the active material of the cells changes its translucency due to solar UV radiation. [41] Another notable degradation source is particle radiation.

### *2.2.8.1 Silicon solar cells*

Rigid solar cells are the type with the longest space heritage. They have a good radiation resistance and can be produced very low costs. The first use was on board of the Vanguard 1 satellite. In order to improve the energy to weight ratio modern solar cells are manufactured using the thin layer technology. Thin film solar cells were first used for the first solar panel of the Hubble Space Telescope. [42] This also improves the radiation resistance even further. Current solar cells provide a conversation efficiency of 14.8 percent and experience a degradation of 15 percent by 1 MeV electrons in 10 years. [43] Silicon solar cells are used as primary energy source on board of the International Space Station (ISS). [41]

**Advantages**

- Cheap and unlimited raw-material
- Well matured processing technologies
- Full knowledge of all material properties
- Small density of material
- Large space heritage

**Disadvantages**

- Larger area required (→ higher mass and volume compared to GaAs based)
- More prone to radiation damage
- Lower efficiency

**Conclusion:**

Even though silicon solar cells are very cheap and very mature, they will not be used within this project as most CubeSats already use more efficient solar cells.

#### *2.2.8.2 Rigid Gallium-Arsenide solar cells*

Rigid Gallium-Arsenide solar cells were the next step in the development of solar cells. They feature improvements in efficiency and radiation resistance. Current solar cells provide a conversation efficiency of 18.5 percent and experience a degradation of 15 percent by 1 MeV electrons in 33 years. [43] However, compared to silicon based solar cells they are more expensive and have a higher mass.

**Advantages**

- Higher efficiency
- Widely used in newer satellites
- Good radiation resistance

**Disadvantages**

- Higher density of material
- High cost

**Conclusion:**

Despite the advantages over silicon based solar cells, Gallium-Arsenide solar cells are not considered within this project, as one of the aims of the project is the highest economic possible power output.

#### *2.2.8.3 Triple-Junction Solar cells*

While the earlier discussed solar cells use just one n-p junction, triple junction solar cells combine three material pairs to cover a larger part of the spectrum of the electromagnetic radiation. A possible combination is the three junctions are Gallium-Indium-Phosphorus, Gallium-Indium-Arsenide and Germanium. Current solar cells provide a conversation efficiency of 28.3 percent [44] and experience a degradation of 15 percent by 1 MeV in 33 years.[43]

**Advantages**

- Highest efficiency
- Good radiation resistance

**Disadvantages**

- High cost
- Complex mechanism

**Conclusion:**

Triple-Junction solar cells offer the highest conversation rate and a good radiation resistance. This enables this project of reaching the optimum power output from the solar cells. Therefore triple-Junction solar cells will be used within this project.

## *2.3 Thermal Issues*

Space systems undergo large temperature variations of up to 200 K during an orbit. These cause thermally induced stresses between attached parts and can lead to fatigue of the material. In order to minimize this effect materials with a similar coefficient of thermal expansion should be used in any possible situation. Another possibility to reach this goal partially is the utilization of larger tolerances that allow the expansion to occur. Thus the resulting stress level is also lower compared to the restricted case.

## *2.4 Vibration testing*

Vibrations during launch can cause severe damages on satellites sent to space. These might be caused by the loosening of parts or impacts. Therefore it is important to perform vibrational analyses and testing during the design process of any component for launch qualification. Such tests commonly involve sine survey, random vibration and shock tests. The first one is used to investigate the modes of the oscillation for the components. Using the results requirements demanding a minimum natural frequency can be verified. Random vibration tests evaluate the influence of random oscillations during launch. The last ones are important for the understanding of the vibrations during separation maneuvers.

Computational simulations are usually based on finite element models. The sine survey is commonly named as modal analysis and also the first step for a random vibration analysis. In the second step the actual analysis is performed resulting in displacements and stresses. Random vibration simulations use spectral densities (see chapter 7.1.1) as input for the excitation of the assembly. These can be retrieved for the specific launch vehicle. CubeSat missions use a generic acceleration spectral density which should represent all major launch vehicles. [45]

Practical tests can be performed by the utilization of shaker tables, loud speakers or hammers as excitation sources. This report will focus on the use of shaker tables.

## *2.5 Materials*

Materials are very important to ensure that mechanical components work in the expected way. This section gives an overview of the materials considered for the design of the mechanical mechanism and structure.

### 2.5.1 Steel

Austenitic steels are used for propulsion systems due to their toughness also at low temperatures and their good resistance against aggressive fuels. [46] Other steel alloys are utilized for optical and high precision assemblies, as their coefficient of thermal expansion can be adjusted as required. Components including the processing with galvanization might experience a higher brittleness because of diffusing hydrogen. However, this can be resolved by appropriate counter-measures.

Another kind of steel used in space technology are Invar alloys. These offer a good stiffness in the temperature range between -200 and 100 °C. [47] Invar steels are alloys with 35 percent nickel and face-centered cubic crystal models. The extraordinary property of this kind of steels is the very small coefficient of thermal expansion below the Curie – temperature. Above this temperature the material is behaving as other common materials. A further discussion for this behavior can be found in [2].

Ferromagnetism of some steel alloys might be also an issue when using magnetometers on board of the satellite. [48]

In general, steel alloys are resistant against the environmental conditions in space, i. e. radiation, atomic oxygen and vacuum. [46]

**Advantages**

- Easy machinable
- High yield strength
- Good resistivity against space environment
- Low cost

**Disadvantages**

- High density
- Danger of hydrogen embrittlement
- Danger of ferromagnetism
- Additional wiring outside panel required
- Additional isolation layer required

**Conclusion**:

Due to its high weight, steel should be just used in areas where the high stiffness is required.

### 2.5.2 Aluminum

Aluminum alloys are characterized by their good stiffness to mass ratio, good machinability and low magnetism. However, the yield strength is comparable low. In order to prevent problems by the assembly of components of different materials, the high coefficient of thermal expansion must be taken into account. Even though aluminum has a small specific heat capacity, it is a very good thermal conductor. Use under space conditions requires a protective layer against corrosion. [32]

Apart from the danger of cold-welding aluminum is not affected by the conditions in space. [46]

When using aluminum as substrate for the solar cells, an additional layer has to be applied to assure the insulation of the panel and cells.

**Advantages**

- Good stiffness-mass ratio
- Good heat conduction
- Good resistivity against space environment
- Good machinable
- Low density
- Low costs

**Disadvantages**

- High coefficient of thermal expansion
- Protective layer against corrosion required
- Danger of cold-welding between different parts
- Small structures difficult to manufacture
- Small yield strength
- Additional wiring required

**Conclusion**:

As Aluminum has a very low density it should be used in as many structural components as possible.

### 2.5.3 PCB

The panel itself could be also manufactured as a PCB. This would simplify the electric design significantly, as the complete harnessing can be done within the panel. Compared to the materials mentioned above its material – FR-2 – comes with a smaller coefficient of thermal expansion and a lower density. Solar cells can be attached to a panel manufactured as PCB without any additional isolation layer.

**Advantages**

- Simple harnessing
- Common practice
- Small density
- Coefficient of thermal expansion similar to range of aluminum and steel

**Disadvantages**

- Danger of outgasing
- Sensitive to UV radiation
- Sensitive to particle radiation
- Sensitive to atomic oxygen
- Inserts for attachment required

**Conclusion**:

As the material simplifies the harnessing and can be adjusted to fit with the coefficient of thermal expansion, a PCB used will be used for the solar panel within the scope of this report.

### 2.5.4 Titanium

Titanium has beside a weaker magnetism a significantly higher yield strength as compared to aluminum. As it features a substantial lower density – between 3.37 and 4.85 g/cm$^3$ compared to 7.85 g/cm$^3$ – as steel at a similar yield strength, its specific stiffness is very high. Moreover, it has in the unalloyed state a very high corrosion resistance. Using alloys it also offers a durability at low temperatures. Thermal properties are a small thermal conductance, a small specific thermal capacity and a small coefficient of thermal expansion. Therefore thermal induced stresses are very small. The good damping properties of titanium make also suitable for applications with shock loads. Despite all this advantages, the materials is very expensive and requires comparable large efforts for the manufacturing of components. Furthermore, it requires a protective layer against corrosion. [32] [49]

**Advantages**

- High specific stiffness
- Good resistance against corrosion
- Small coefficient of thermal expansion
- Good damping properties

**Disadvantages**

- Bad thermal conductivity
- Protective layer against corrosion required
- High costs
- Difficult to manufacture
- Additional wiring required

**Conclusion**:

Titanium could be considered in applications where its yield strength is sufficient in order to save mass compared to a solution with steel. However, the machine workshop must be able to meet the requirements for the use of titanium.

## 2.6 Solar Panels

The maximum size of the solar panels with in this project is defined by the CubeSat specification. [1] Other constraints are induced by the layout of the solar cells. Usually the shape of the solar cells cannot be changed. This limits the area of the solar panel covered by solar panels. By optimization of the pattern of the solar cells 3U CubeSats can usually put up to 8 solar cells on a side facing panel. [50] Every solar panel is estimated to generate around 1 Watt on orbit average. This can be improved by articulation, as discussed in chapter 6.2.

## 2.7 Summary and Conclusion

The most promising actuation mechanisms for deployment and articulation are springs based on SMA, bi-metal strips, squiggle motors and stepper motors. For guiding no guiding, flexible joints or hinges should be considered. In order to reduce the stress on connection lines these can be formed similar to a spiral spring. Passive controllers which change the intensity of the incident sun light should be preferred against electronic controllers. The considered mechanisms are given in the following list:

- Actuation for deployment
  - Flexible joints
  - Shape memory alloys
  - Torsion spring in hinge
  - Torsion bar spring in hinge
  - Coil Spring
- Guidance
  - Flexible joints
  - Mechanical guidance
- Damping
  - Counter-force by spiral spring
- Actuation for articulation
  - Bi-metal strips
  - Piezoelectric motors
  - Torsion spring in hinge
  - Torsion bar spring in hinge
  - Electric motors
- Damping
  - Changing shadow mechanically
  - Electronic controller
  - Photo-chromatic lens
- Solar cells

    - Triple-junction solar cells
- Materials
    - Steel
    - Aluminum
    - PCB

# 3 Thesis Statement

The generated electric energy on orbit average can be increased by at minimum $P_O = 12\,Wh$ at AM0 by the use of articulated solar panels within the constraints mentioned below:

- Output voltage between 16 and 20 volts
- Embedded torque coil including interface
- Temperature sensor at back side of panel
- Possibility to print antenna circuit on or with in the array substrate without degradation of array performance
- Electrical interface for antenna, torque coil, power and temperature sensor
- Size:
  - 10x30x0.6 cm (placed completely outside of spacecraft) for deployed solar array
  - 10x30x1.6 cm for articulating solar array
- Mass:
  - 182.5 gram
- Compliance to the launch loads specified in NASA GEVS
- Compatibility with on orbit temperatures
- Compatibility of thermal expansion / contracting of all used materials

# 4 Plan and approach

## *4.1 Approach*

Chapter 2 concluded that two options for the implementation of an articulated solar panel should be considered, one based on shape memory alloys or bi-metal and the other based on electric stepper motors. In the scope of this thesis the second option is used in the final design due to the decreased complexity of the design. An overview of how good the suggested mechanisms from chapter 2.2 meet the requirements is given in the following section.

# 4.2 Decision Table

| Actuation mechanism - deployment | Size requirements | Mass requirements | Launch loads | On orbit temperatures | Reliability |
|---|---|---|---|---|---|
| Coil spring | | | | | |
| Flexible joints | | | | | |
| Shape memory alloys | | | | | |
| Torsion spring | | | | | |
| Spiral spring | | | | | |
| Electric motor | | | | | |
| Torsion bar spring | | | | | |
| Spin of satellite | | | | | |
| Deployable boom | | | | | |
| Inflatable boom | | | | | |
| Lanyard deployment | | | | | |
| Canister deployment | | | | | |

| Guiding mechanism - deployment | Size requirements | Mass requirements | Launch loads | On orbit temperatures | Reliability |
|---|---|---|---|---|---|
| Rotational deployment | | | | | |
| Telescopic cylinder | | | | | |
| Tether | | | | | |
| Scissors shaped booms | | | | | |
| Synchronization by rope mechanisms | | | | | |
| Flexible joints | | | | | |

| Damping mechanism - deployment | Size requirements | Mass requirements | Launch loads | On orbit temperatures | Reliability |
|---|---|---|---|---|---|
| Spiral spring | | | | | |
| Rotation damper | | | | | |
| Electric motor | | | | | |
| External Friction | | | | | |
| Eccentric bolt | | | | | |
| Electric damping | | | | | |
| Friction in joints | | | | | |
| Belleville springs | | | | | |
| Rubber damper | | | | | |
| Latch | | | | | |
| Torsion spring | | | | | |

| Initial release mechanism | Size requirements | Mass requirements | Launch loads | On orbit temperatures | Reliability |
|---|---|---|---|---|---|
| Thermal loosening | | | | | |
| Heat wire | | | | | |
| Phase changes | | | | | |
| Shape memory alloys | | | | | |
| Electric motor | | | | | |
| P-POD | | | | | |
| Decompression | | | | | |
| Pyrotechnical cutter | | | | | |
| Release key | | | | | |
| Weakening magnetic field | | | | | |
| Pusher | | | | | |
| **Actuation mechanism - articulation** | **Size requirements** | **Mass requirements** | **Launch loads** | **On orbit temperatures** | **Reliability** |
| Flat electric motor | | | | | |
| Piezoelectric motor | | | | | |
| HOP motor | | | | | |
| Shape memory alloys | | | | | |
| Torsion spring | | | | | |
| Spiral spring | | | | | |
| Bi-metal strips | | | | | |
| Torsion bar spring | | | | | |
| Linear displacement | | | | | |
| Stepper motor | | | | | |
| **Control mechanism - articulation** | **Size requirements** | **Mass requirements** | **Launch loads** | **On orbit temperatures** | **Reliability** |
| Electronic controller | | | | | |
| Changing shadowing | | | | | |
| Clamping | | | | | |
| Photo-chromatic lens | | | | | |
| External friction | | | | | |
| Photo-diodes | | | | | |
| **Solar cells** | **Power** | **Mass requirements** | **Launch loads** | **On orbit temperatures** | **Reliability** |
| Silicon solar cells | | | | | |
| Rigid Gallium-Arsenide | | | | | |
| Triple-junction solar cells | | | | | |
| **Materials** | **Embedded torque coil** | **Temperature sensor** | **Printed antenna circuit** | **Outgasing** | **Thermal expansion** |
| Steel | | | | | |
| Aluminum | | | | | |
| PCB | | | | | |
| Titanium | | | | | |

# 5 Solution

Based on the plan from chapter 4 the final design for the panel is described below. The middle part consists of a brush-less electric motor and a corresponding planet gear head, i. e. the ADM 0620 and 06/01 16:1 from Micromo Inc. These provide a precision of 0.6 degrees in half step mode. They are attached by three set screws to the middle connector which in terms is screwed to the satellite body. For articulation the right active part of the hinge is attached by two the set screws to the outgoing shaft of the gear box. The outer parts are completely passive. They consist of the left and right connector, the hinges and shafts which attach the different parts by the utilization of retaining rings. In order to define a proper position of the hinge with respect to the shaft both are connected by set screws similar to the hinge at the opposite side.

In order to meet the requirements for the mechanical envelope, the whole mechanism is mounted at the satellite partially inside of it, i. e. the side face of the satellite is placed above face of the joints. This is depicted in Figure 47.

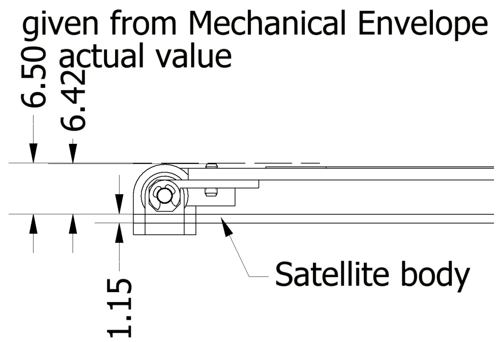


*Figure 47: Compliance to Mechanical Envelope*

Figure 48 depicts the solar panel attached to the mechanism shown in Figure 49. The panel is manufactured as a PCB (see Figure 50) in order to simplify the harnessing (prototype aluminum) and to reduce the mass. It is designed with one internal copper layer for the harnessing and the

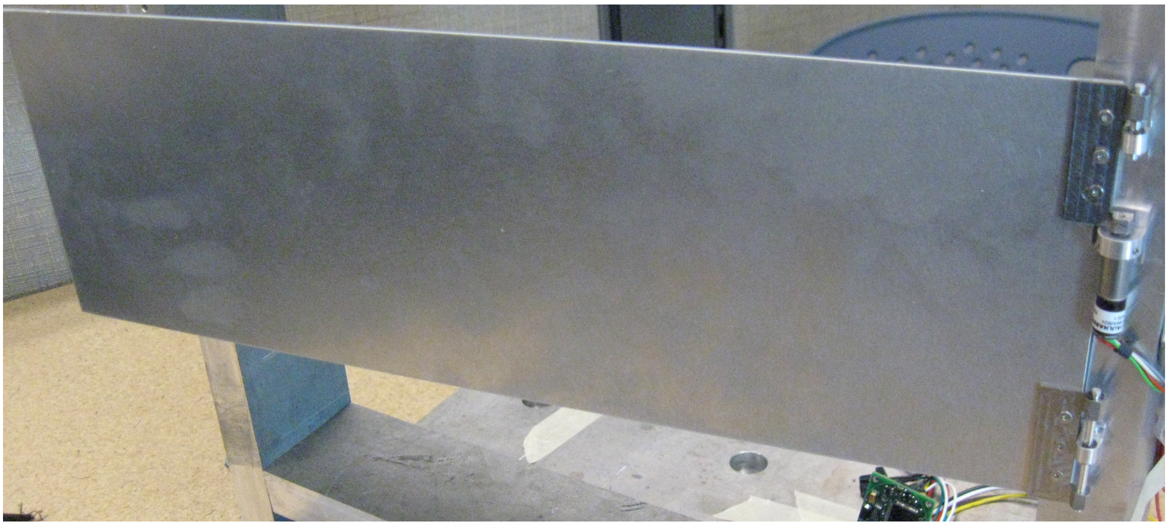

*Figure 48: complete design including attached solar panel*

embedding of torque coils and/or antennas with contacts at the appropriate side of the board.

All solar cells are connected in series. Using the cables soldered to the connector pins at the right, the solar panel is connected to a socket at the top of the satellite. For the use of the proposed socket and plug (DF13-10S-1.25C and DF13-10P-1.25DS from [51]) it might be necessary to place the socket partially inside of the satellite. One temperature sensor, one home switch, one heat winding and three rubber pads, one in a central position and two at the far corners, are attached to the back side. The two later mentioned are used to decrease the response of the panel to launch induced vibrations. Loosening of screws during launch is prevented by the securing them with epoxy.

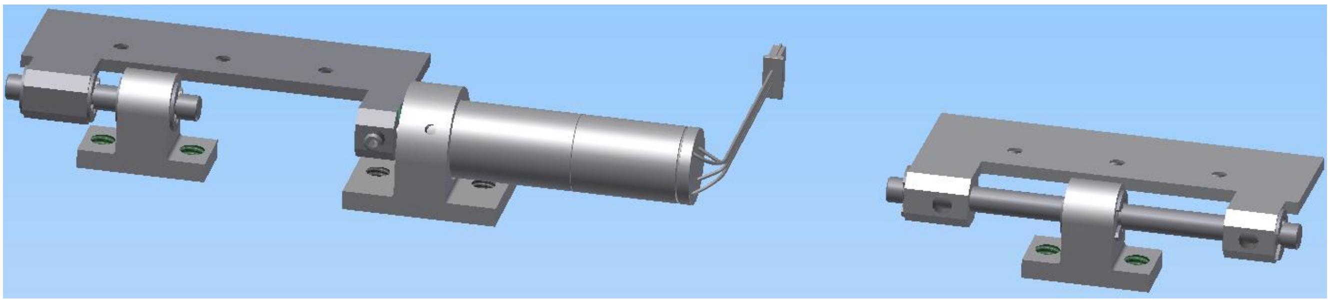

*Figure 49: Overview of complete mechanism without solar panel*

On orbit, the wire pressing the pads to the satellite body will be cut by the heat winding. Afterward the panel can be articulated by the motor and its control electronics, as claimed in the thesis statement. The home switch is used to reset the position pointer to a specific reference position.

Data sheets on all used components can be found in the appendix of this document.

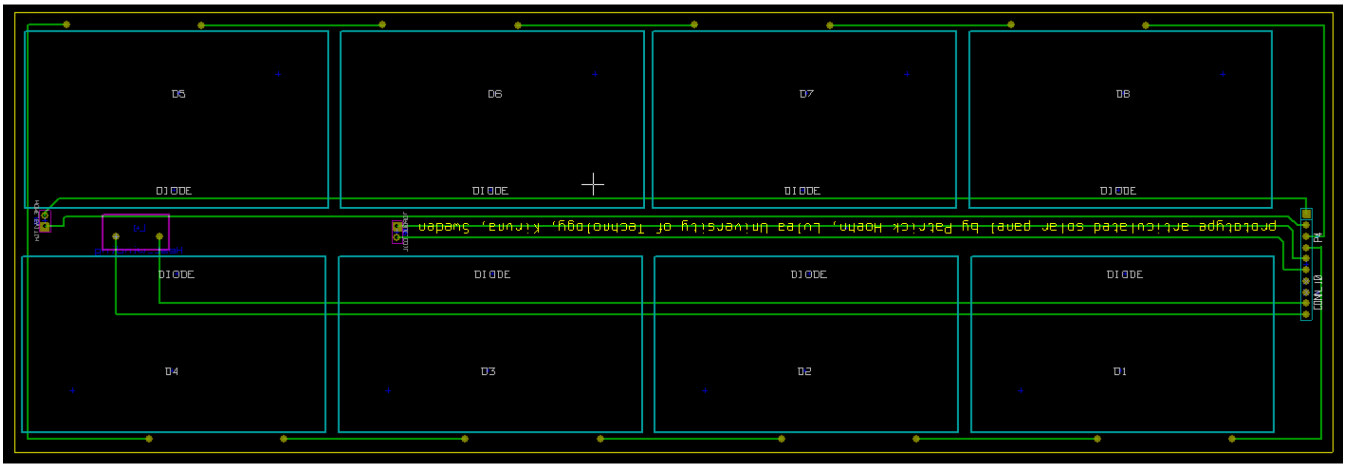


*Figure 50: electrical layout of PCB*

# 6 Design Prototype

Before starting with the design of the actuation devices some of the requirements, in particular regarding temperature and power, need further refinement. This will result in some key parameters, like a specified temperature range or the required area of solar cells. Afterward, the motor is derived from the given parameters.

## 6.1 Revision of Requirements

### 6.1.1 Orbital Temperatures

The influence of the dissipated heat of the satellite on the temperature of the deployed solar panels can be neglected. Thus, the only contribution is the incident IR radiation. The used parameters are summarized in the table below:

| Symbol | Value | Description |
|---|---|---|
| $h$ | $400\,km$ | Orbital Altitude |
| $G_S$ | $1367\,\frac{W}{m^2}$ | Solar constant, average value |
| $\alpha_S$ | 0.92 | Absorptivity of Solar cells, value from [44] |
| $\varepsilon_S$ | 0.85 | Emissivity of Solar cells, value from [44] |
| $\varepsilon_{BS}$ | 0.84 | Emissivity of the back side of the solar panels |
| | (assumed black paint 3M Black Velvet, see [21]) | |
| $i$ | $40\,°$ | Inclination of orbit |
| $a$ | 0.57 | Earth's albedo (see [52]) |
| $R_E$ | $6378\,km$ | Earth's radius |
| $q_{EIR}$ | $257\,\frac{W}{m^2}$ | Earth's emitted black body IR radiation (see [52]) |
| $\sigma$ | $5.67\cdot10^{-8}\,\frac{W}{m^2\cdot K}$ | Stefan-Boltzmann constant |
| $q_{SC}$ | $227\,\frac{W}{m^2}$ | Power converted to electricity (see next section) |

As the solar panels are deployed away from the satellite, the heat influx from the satellite body can be neglected. The remaining incoming heat consists of direct solar flux, albedo and Earth IR. The first can be expressed by the following term:

$$q_{Solar}=G_S\cdot\alpha_S-q_{SC}=1031\,\frac{W}{m^2}$$

Contributions from the albedo are calculated by:

$$q_{albedo}=G_S\cdot\alpha_S\cdot a\cdot K_a\cdot\sin^2\rho \quad ,$$

where

$\sin(\rho)$ angular size of Earth

$K_a$ factor for correction of reflection from the spherical Earth is.

Using the following formula the necessary angular size can be determined:

$$\rho = \arcsin\left(\frac{R_E}{r}\right) = 1.226$$

By using this value the correction factor is:

$$K_a = 0.664 + 0.521 \cdot \rho - 0.203 \cdot \rho^2 = 0.9976 \approx 1$$

Now the heat flux from albedo can be calculated:

$$q_{albedo} = 633.43 \frac{W}{m^2}$$

The remaining heat fraction is the Earth emitted infrared radiation:

$$q_{IR} = q_{EIR} \cdot \varepsilon_S \cdot \sin^2 \rho = 193.49 \frac{W}{m^2}$$

where

$\sin(\rho)$ the angular size of the Earth is.

Therefore the incoming heat flux sums to:

$$q_{\text{in}} = q_{Solar} + q_{albedo} + q_{IR} = (1031 + 633 + 193) \frac{W}{m^2} = 1857 \frac{W}{m^2}$$

The emitted heat energy from the spacecraft is under the assumption of a sun light incident side fully covered by solar cells:

$$q_{out} = (\varepsilon_S + \varepsilon_{BS}) \cdot \sigma \cdot T^4$$

where

T temperature of the corresponding surface

is.

Rearranging the formula leads under the assumption of equilibrium conditions to the temperature of the satellite: $T = \sqrt[4]{\frac{q_{\text{in}}}{(\varepsilon_S + \varepsilon_{BS}) \cdot \sigma}}$

Putting in all known values delivers the surface temperature for the hot case:

$$T = \sqrt[4]{\frac{1857 \frac{W}{m^2}}{(0.85 + 0.84) \cdot 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}}} = 373\,K = 100\,°C$$

The resulting temperature for the cold case is calculated by neglecting the solar and albedo radiation:

$$T = \sqrt[4]{\frac{193 \frac{W}{m^2}}{(0.85 + 0.84) \cdot 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}}} = 212\,K = -61\,°C$$

Remembering the worst-case assumptions, the resulting temperature should be in reality a little bit smaller.

### 6.1.2 Estimation of required solar array area

An important parameter for the evaluation of different solar array techniques is the solar array area required for given power requirement. This will be determined in this section. The required orbit average power of 12 Wh (see chapter 3) gives the power needed from the solar panel. Some of the parameters used in this section are summarized below:

| **Symbol** | **Value** | **Description** |
|---|---|---|
| $h$ | $400\,km$ | Orbital Altitude |
| $i$ | $40\,°$ | Inclination of orbit |
| $R_E$ | $6378\,km$ | Earth's radius |
| $G$ | $6.67\cdot 10^{-11}\frac{N\cdot m^2}{kg^2}$ | Universal gravitational constant |
| $M_E$ | $5.974\cdot 10^{24}\,kg$ | Earth's mass |
| $\eta$ | $28.3\,\%$ | Efficiency of solar cells (see [44]) |
| $P_o$ | $12\,Wh$ | Average orbit power required from solar panel |

Under the assumption of an altitude of 400 kilometers with an inclination of 40 degrees the maximum shadowing orbit fraction can be determined by:

$$\frac{\varphi}{2\cdot\pi}=\frac{1}{\pi}\cdot\arcsin\left(\frac{R_E}{R_E+h}\right)=39\,\%$$

With the orbital period determined by:

$$T=\sqrt{\frac{4\cdot\pi^2\cdot(R_E+h)^3}{G\cdot M_E}}=5553\,s=92.6\,min$$

This leads to an eclipse period of:

$$T_e=T\cdot\frac{\varphi}{2\cdot\pi}=36.1\,min$$

Using all know values and the time in daylight $T_d=T-T_e$, the power provided by the solar array must be at minimum:

$$P_{SA}=\frac{(P_O)}{T_d}=12.7\,W$$

Ultra triple junction solar cells have an efficiency $\eta$ of 28.3 percent at BOL. Using the already known values this gives the maximum deliverable power density at BOL:

$$P_0=\eta\cdot G_S=386\,\frac{W}{m^2}$$

Using an estimated worst-case Sun incident angle $\vartheta$ of 40° and inherent degradation $I_d$ of 0.77 (see [53]) the available power density at BOL results in:

$$P_{BOL}=P_0\cdot I_d\cdot\cos(\vartheta)=227\,\frac{W}{m^2}$$

The lifetime degradation is estimated by:

$$L_d = \left(1 - \frac{degradation}{year}\right)^{satellite\ life}$$

Using the degradation per year of 2.75 percent (see [54] for GaAs solar cells) and an estimated satellite lifetime of one year the degradation becomes:

$$L_d = 0.9725$$

This results in an EOL power density of:

$$P_{EOL} = P_{BOL} \cdot L_d = 220.8 \frac{W}{m^2}$$

Finally, this gives the required solar array area of:

$$A_{SA} = \frac{P_{SA}}{P_{EOL}} = \frac{12.7\,W}{220.8\,\frac{W}{m^2}} = 0.058\,m^2$$

This corresponds to a square of $0.24 \cdot 0.24\,m^2$ .

## 6.2 Improvements by articulating solar panels

The calculation in the previous section assumed the worst case Sun-incident angle of 40 percent. In order to decrease the determined solar array area, this section performs an analysis of the influence of the Sun-incident angle on the power generated. This is done by the use of the program from the Space Dynamics Lab of the Utah State University. Figure 51 shows the satellite in its orbit. One of the simulations is presented in this thesis, covering the improvements for a time step of 15 minutes throughout a complete year for body-fixed panels and panels adjusted in one and two degrees of freedom.

In the body-fixed configuration the additional panel is mounted in parallel to the +x panel. This

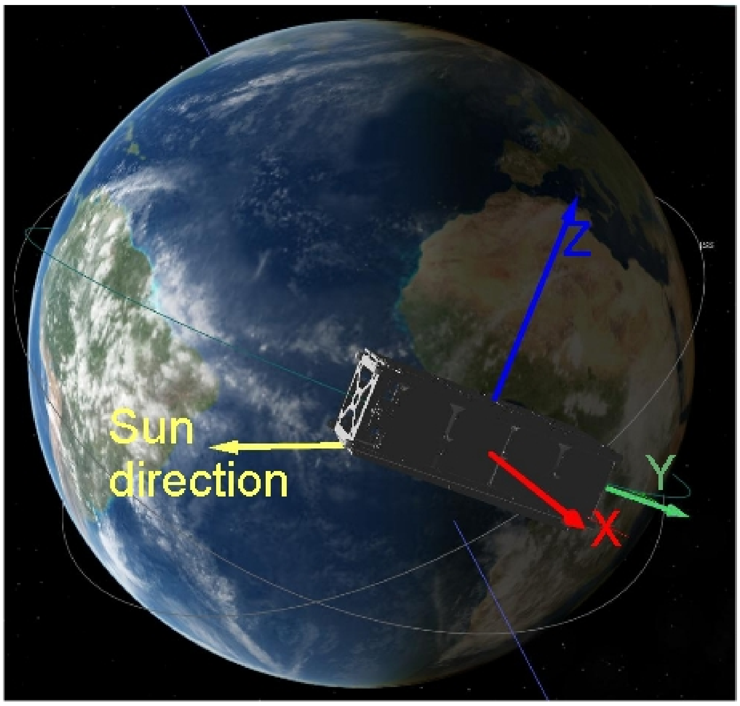


*Figure 51: Attitude of satellite during simulation (generated using Celestia)*

gives an average power density of $286\frac{W}{m^2}$ during one year. By rotation about the y – axis or x – axis this value can be improved up to $817\frac{W}{m^2}$ or $496\frac{W}{m^2}$ respectively. An additional articulation in two degrees of freedom results in a slightly higher power density of $835\frac{W}{m^2}$. Thus, it is most promising to focus on a mechanism with one adjusted degree of freedom around the y-axis.

## 6.3 Assembly of Solar Arrays

Solar arrays are manufactured by interconnecting solar cells. The voltage requirement is met by connecting solar cells in series, the power or current requirement by connecting them in parallel. For generating the power and voltage mentioned in the requirements, the solar array must consist of at least 8 cells in series to produce a voltage at the point of maximum power between 16 and 20 volts. (see section 5 ) The design value is 18.8 volts. In order to generate a power of 12.7 watts (see section 2.1.1) the required current is:

$$I_{mp}=\frac{P}{V_{mp}}=0.68\,A$$

Using the area of each solar cell $A_{SC}$ of $26.62\,cm^2$ and the current density at the point of maximum power $J_{mp}$ of $16.3\frac{mA}{cm^2}$, this results in the number of solar cells strings needed to be in parallel:

$$n=\frac{I_{mp}}{A_{SC}\cdot J_{mp}}=1.6\approx 2$$

Therefore the solar array should consist of at least 2 strings of 8 solar cells, which could be realized with two deployable solar panels.

## 6.4 Design of Panel

The initial design of the panel was using an aluminum substrate in connection with wires for the electrical attachments. However, due to the tight mass budget and for simplification of the harnessing the material was shifted to a PCB. As described in chapter 5, it is still attached by screws to the hinge. Unlike for the aluminum substrate the manufacturing of threads inside plastic materials is very difficult. Therefore the threads are realized by the use of inserts.

After the conduction of computational vibration analysis, it became apparent that the resulting deflections which were in the range of 60 millimeter are unacceptable, as this would cause an impact of the solar panel at both the P-POD and the satellite. This was decreased a lot by the already mentioned rubber pads for the movement away from the satellite and the heat wire for the opposite. The resulting value is around 0.5 millimeters. A more detailed description of the analysis is presented in the next chapter.

## 6.5 Thermal Expansion

This section gives a brief introduction to the design for compatibility of the thermal expansion of all used materials. Three different material groups are used in the scope of this analysis, i. e. Steel (see [55]), Aluminum 6061 (see [56]) and FR-2 (see [57]) for the PCB. One example depicted is the compatibility between the PCB and one of the hinges attached to it. The midpoint distance between the two outer screws is 16 millimeter. Using the corresponding thermal expansion coefficients this delivers a mismatch of:

$$\Delta l = \left| \left( \alpha_{St} - \alpha_{FR-2} \right) \cdot \Delta T \cdot l \right| = 0.02\, mm$$

Even though the dimensions of the model are already pretty small, this mismatch can be neglected, as it is in the range of less than one percent. Due to inaccuracies in the matching of the two hinges the probably occurring mismatch between the two different parts of the hinges is of minor interest.

The second potentially risky mismatch appears at the attachment of the passive hinge to the shaft. In this case the resulting mismatch is:

$$\Delta l = \left| \left( \alpha_{St} - \alpha_{Al6061} \right) \cdot \Delta T \cdot l = \left( 13 - 23.6 \right) \cdot 10^{-6} \frac{1}{K} \cdot 161\, K \cdot 30\, mm \right| = 0.05\, mm$$

This is also still within a range which can be managed by the current design.

## 6.6 Specification of selected electric motor

The data sheet of the motor (see [58]) states an operational temperature range of -35 to 70 °C. As the temperatures determined in section 6.1.1 exceeds this limits, an analysis based the x panel of the satellite was performed with the same parameters as given in section 6.1.2 . This resulted in a temperature range between 16 and 20 °C. Therefore the motor is able to survive under the conditions on orbit.

The torque provided by the motor and gear-head fits the necessary torque easily as the friction is on orbit very small due to the missing gravity which acts as a normal force in an Earth's based environment.

# 7 Evaluation and Testing

The evaluation performed within this thesis, includes random vibration analysis and thermal expansion analysis. While the first one is testing the performance of the mechanism during launch, the later one analyzes the thermal induced deflection and stresses during one complete orbit. Random vibration analyses are based on a power spectrum density which is taken from [45].

## *7.1 Evaluation by computer based simulations*

This computational analysis uses educational version of the program Algor Simulation Professional 2011 from Autodesk Inc.

### 7.1.1 Vibration analysis

The first analysis was performed as a classical random vibration analysis based on a previous model analysis. Figure 52 depicts the shape of the first oscillation mode which has a frequency of around 240 Hertz. The panel is totally fixed its right edge and constrained in the y-direction at the pads at left end and in the center. Table shows the detected fundamental frequencies in the required range between 20 and 2000 Hertz.

*Table 1: fundamental frequencies of the panel with solar cells*

| Mode Number | Frequency |
|---|---|
| 1 | 239.5 Hz |
| 2 | 297.3 Hz |
| 3 | 353.5 Hz |
| 4 | 399.5 Hz |
| 5 | 522.8 Hz |
| 6 | 648.8 Hz |
| 7 | 848.5 Hz |
| 8 | 1041.9 Hz |
| 9 | 1107.4 Hz |
| 10 | 1246.0 Hz |
| 11 | 1304.4 Hz |
| 12 | 1730.4 Hz |
| 13 | 1740.1 Hz |
| 14 | 1886.3 Hz |

Based on the results of the modal analysis a random vibration analysis was performed for a damping rate of 1.5 percent. The results are shown in Figure 53. Despite the two fixing points at the

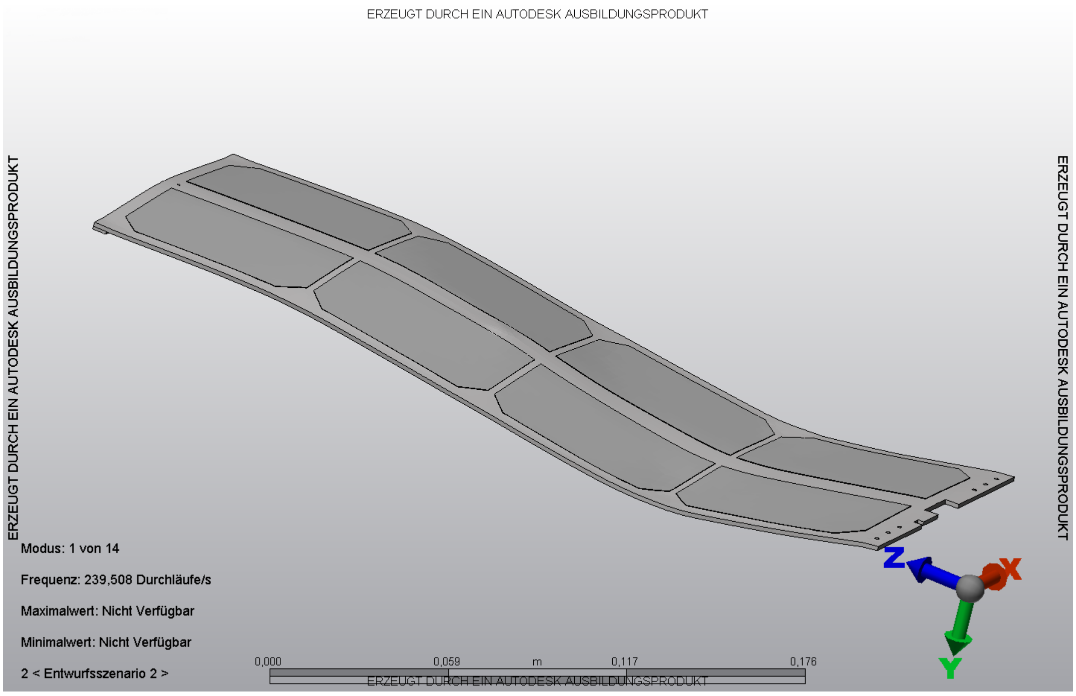


*Figure 52: shape of the first vibration mode*

free end, it seems like that this end undergoes the largest deflections. However, at a closer look this results from the fact that the largest deflection in this analysis appears in x direction and around 0.2 mm. The deflections in the other directions are as expected and one order of magnitude smaller than the ones in x direction.

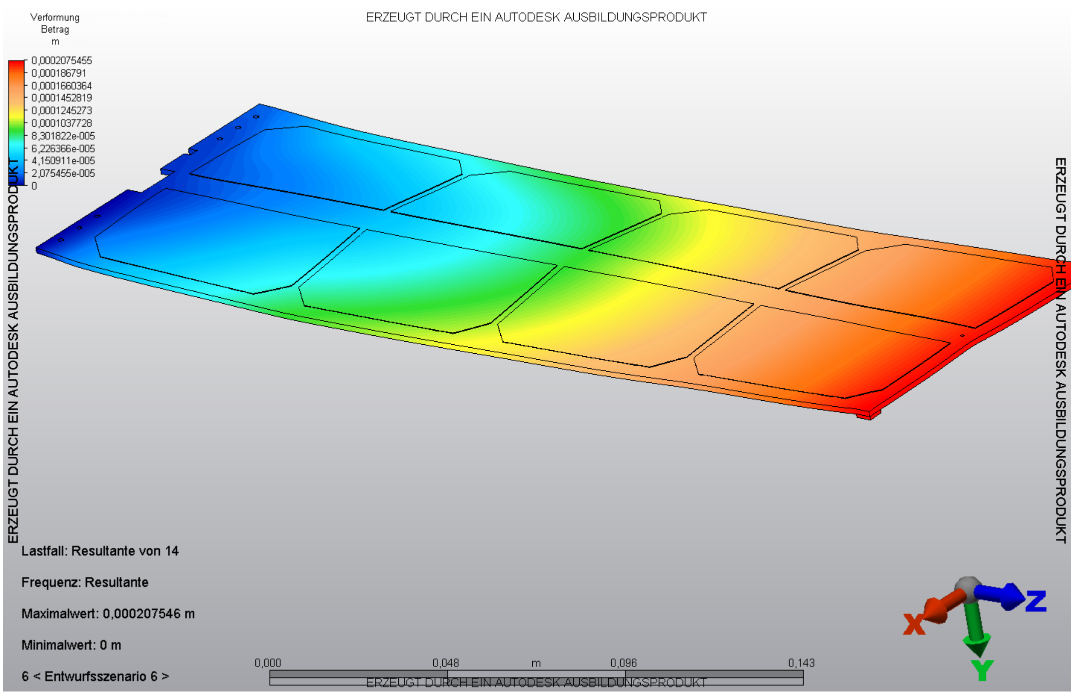


*Figure 53: Absolute Deflection from classical vibration analysis*

In addition to the classical analysis as described before a time depended analysis as described in [59] was performed. The general idea behind is to convert the power spectrum density by approximation of the area below the curve in small slices to an oscillation for the specific frequency. All different oscillations are afterward superimposed at random phase angles. The resulting time series of acceleration amplitudes is then fed into a Mechanical Event Simulation which allows the simulation of a system and a time varying accelerations. The results in terms of deflection and stress are depicted in the Figures 54 and 55. Stress spikes in Figure 54 are calculation artifacts and disappear in a finer mesh.

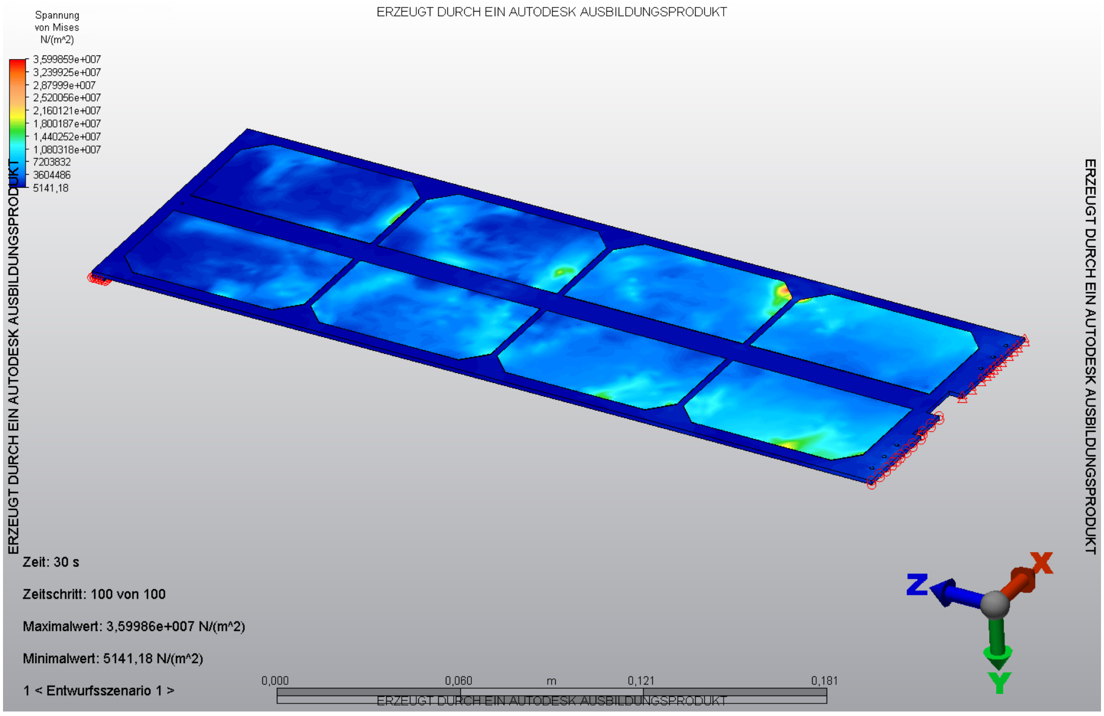


*Figure 54: stress from dynamic vibration study*

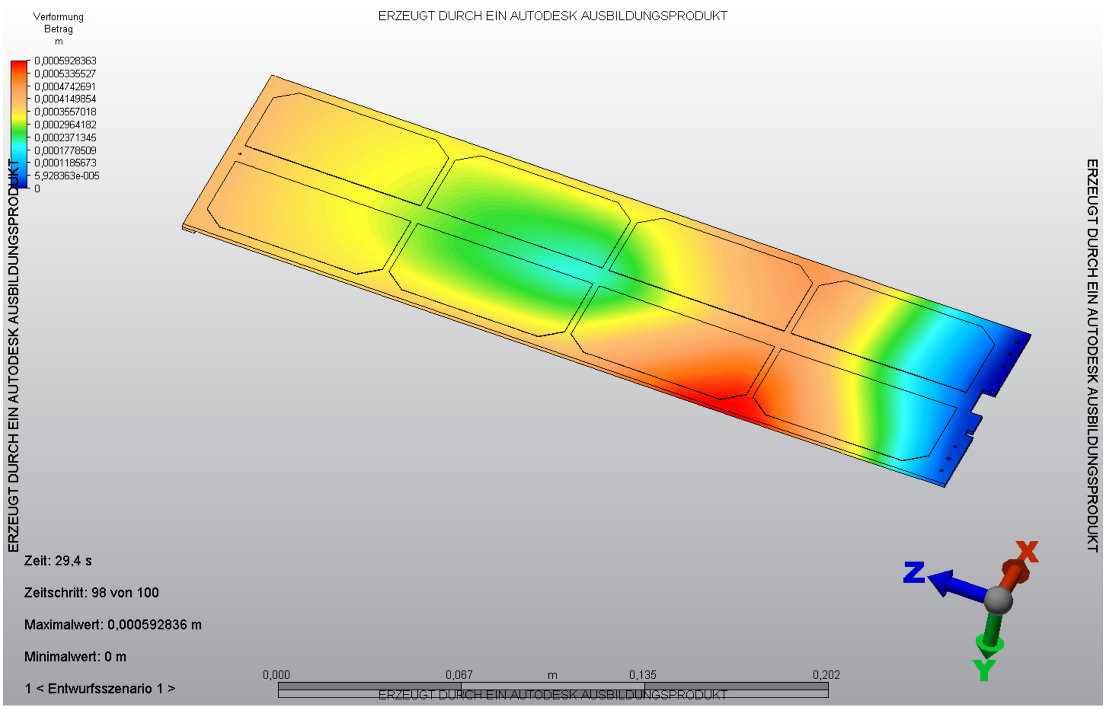


*Figure 55: deflection from dynamic vibration study*

All determined deflections are in a range where no damage to the components is expected. The stresses determined from the analyses, however, might exceed the limits. Therefore a redesign with another material might be necessary.

# 7.2 *Thermal Expansion*

This simulation is performed to verify that the proposed design complies with the requirement of the compatibility of the thermal expansion of all used materials. As the motor and gear-head undergo a much smaller load compared to the loads applied to the hinges it was excluded from the analysis. Temperatures change during the analysis from 0° C to 83 °C for the overall assembly. This interval is similar to the on-orbit environment. Similar to the real attachment on-board of a satellite the solar panel is fixed by four grounded screws. By the application of the above temperature changes the following Figures result:

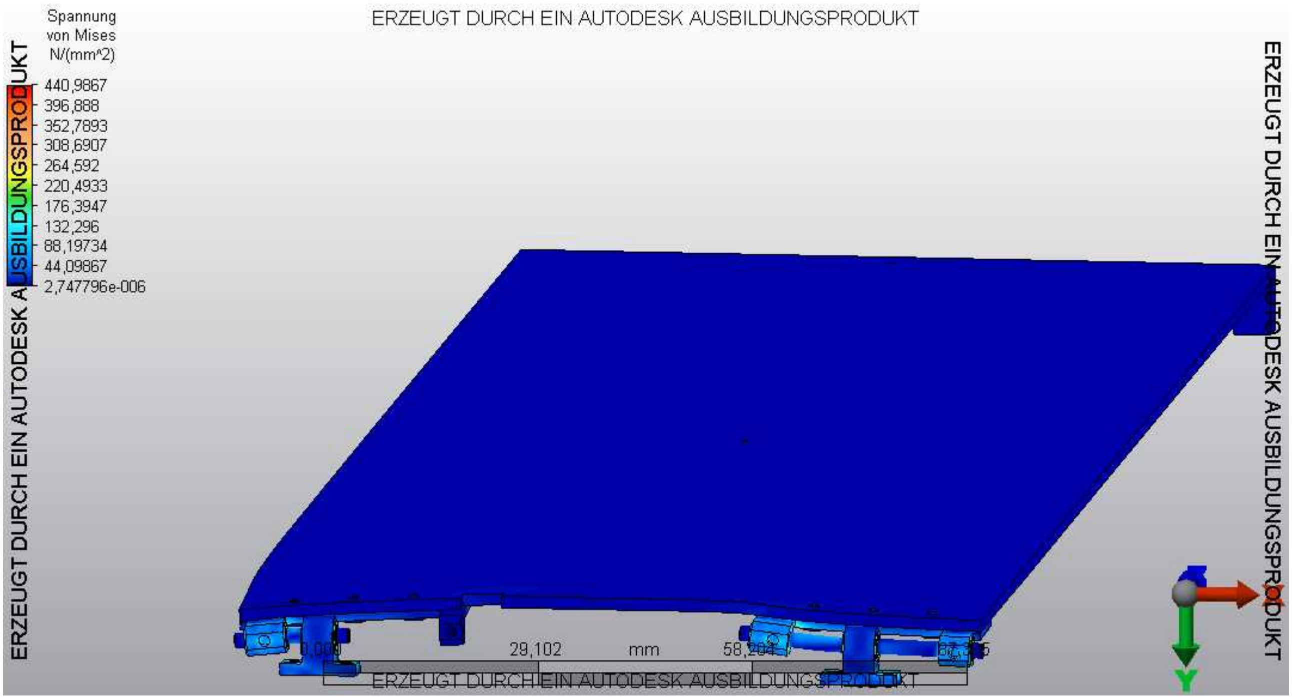


*Figure 56: results from the thermal stress analysis of the solar panel mechanism*

The highest resulting highest stress of $440\frac{N}{mm^2}$ appears within the attachments at the satellite. As this part is made from aluminum, it is likely that the part will fail under the load. Thus, some components need to be changed in material to comply with the requirement of compatibility in the thermal expansion.

# 7.3 *Evaluation by test of prototype model*

The computational analysis gives already a good idea of the possible problems and behavior of the panel. However, every mathematical model has to prove its suitability and accuracy by practical tests. These are described in the following sections.

## 7.3.1 Vibration Test

A mechanism which is supposed to work on a satellite must sustain launch and on-orbit loads. The dominating loads during the ascent phase are created by vibrations and shocks. As [60] states just random vibration loads the tests through out this report are limited to a random vibration test in three axes.

### 7.3.1.1 *Test specification*

Figure 57 depicts the proposed test setup for the vibration analysis. The block at the bottom is a placeholder for the actual attachment to the shaker table. Due to simplifications in the setup the mechanism is placed completely at the outside of the attachment. The wire going from the panel to the attachment, the heat wire, is used to press the three depicted rubber pads to the attachment. Unlike in the Figure the wire will tight, so it wouldn't be visible below the attachment.

The test will be performed in as random vibration test in three axes using the power spectrum density from [45] (see table 2) and should validate the computational analysis and the survivability of the design during launch and prove the survivability of the design.

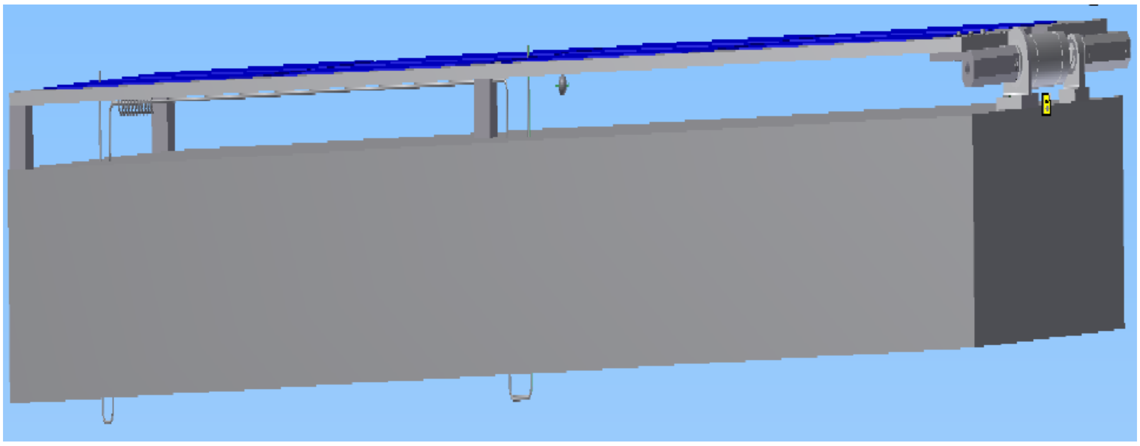

*Figure 57: sketch of the test setup for the vibration analysis*

#### 7.3.1.2 Test Procedure

The test should be performed by following these steps:

1. Attach the accelerometers at the desired positions
2. Screw hinges to attachment
3. Move panel to the locked position.
4. Attach heat wire to panel and shaker attachment with a force in the wire of 10 N.
5. Run test for one direction.

*Table 2: Power Spectrum Density for the random vibration test*

| Frequency (Hz) | Qualification ASD Level ($G^2$ / Hz) |
|---|---|
| 20 | 0.026 |
| 20-50 | + 6 dB/octave |
| 50-800 | 0.16 |
| 800-2000 | - 6 dB/octave |
| 2000 | 0.026 |
| Overall | 14.1 $G_{rms}$ |

6. Repeat steps 1 to 5 for the other two directions

### 7.3.2 Thermal Test

While the vibration test focuses on the launch environment, temperature induced stresses are important in the on-orbit operation.

#### *7.3.2.1 Test Specification*

The test setup is similar to the vibration test. However, it is not required to use the heat wire to keep the mechanism in its position, as the temperature changes happen in the deployed state. Earlier analyses suggest that the largest stresses appear in the shafts and the attachments to the satellite. The complete pattern in including the extremes will be measured by the use of photo-elasticity. The temperature change will be in the order of 83 degrees Celsius.

#### *7.3.2.2 Test Procedure*

The test should be performed by following these steps:

1. Cover desired faces with photo-elastic layer
2. Screw hinges to attachment
3. Put assembly in thermal chamber
4. Increase the temperature of the mechanism by 83 degrees Celsius.
5. Measure the resulting strains at the desired points.

# 8 Conclusion

This thesis presented a collection of mechanisms for actuation, guidance, damping, control and release that can be used for used in space missions. It also discussed different types of solar cells and materials. These were evaluated for the use in CubeSat missions. Other aspects like thermal and vibration issues or the design of solar panels are addressed briefly. It was shown that the power generated from a solar panel can be increased by a factor of almost 3 by the articulation around one axis. Based on the stated requirements and the literature review a new design for an articulated solar panel is suggested. It includes of a panel manufactured as a PCB. This is locked in the stowed position by a heat wire. After release it can be articulated by a small stepper motor with a precision of 0.6 degrees in half step mode.

The expected temperature range for the stepper motor lies within the operational range given in the data sheets. Thermal induced deflections and stresses exceed the limits of some of the selected materials. It is necessary to change the material of these parts from aluminum to steel. The deflections resulting from the vibrational analyses are sufficiently small to avoid damage to the solar cells, solar panel or the outside faces of the satellite.

# 9 Future Work

The design presented in this paper was validated by computational analysis. Due restrictions resulting from the analyses it is necessary to redesign the attachment parts with new materials, e. g. steel. The previous analyses have to be verified by practical tests, i. e. the proposed vibrational and thermal test. In addition to the suggested thermal tests thermal cycling tests using the simulated on-orbit temperatures should be performed to validate the reliability of the complete mechanism over the complete mission duration. The influence of other parts of the space environment like atomic oxygen or particle radiation on components and materials should also be further analyzed in the further efforts to achieve a mature design suitable for launch. Lubricants currently used in the motor and gears have to be replaced by others that have a sufficiently low vapor pressure to sustain the vacuum of space.

In addition to the determined approximated temperature cycle a more precise thermal analysis should be done to ensure that all components stay within the acceptance temperature limits. The vibrational simulations might also need further refinement, as the mass distribution in the final panel might be different due to changes in materials and the harnessing inside of the panel.

The tests might also imply changes to the design, i. e. changes in the material of some components. Apart from these changes it might also be necessary to adjust the design to the actual structure of the satellite the solar panel will be attached to. For cost reasons, it might be also reasonable to do further research into alternative mechanisms.

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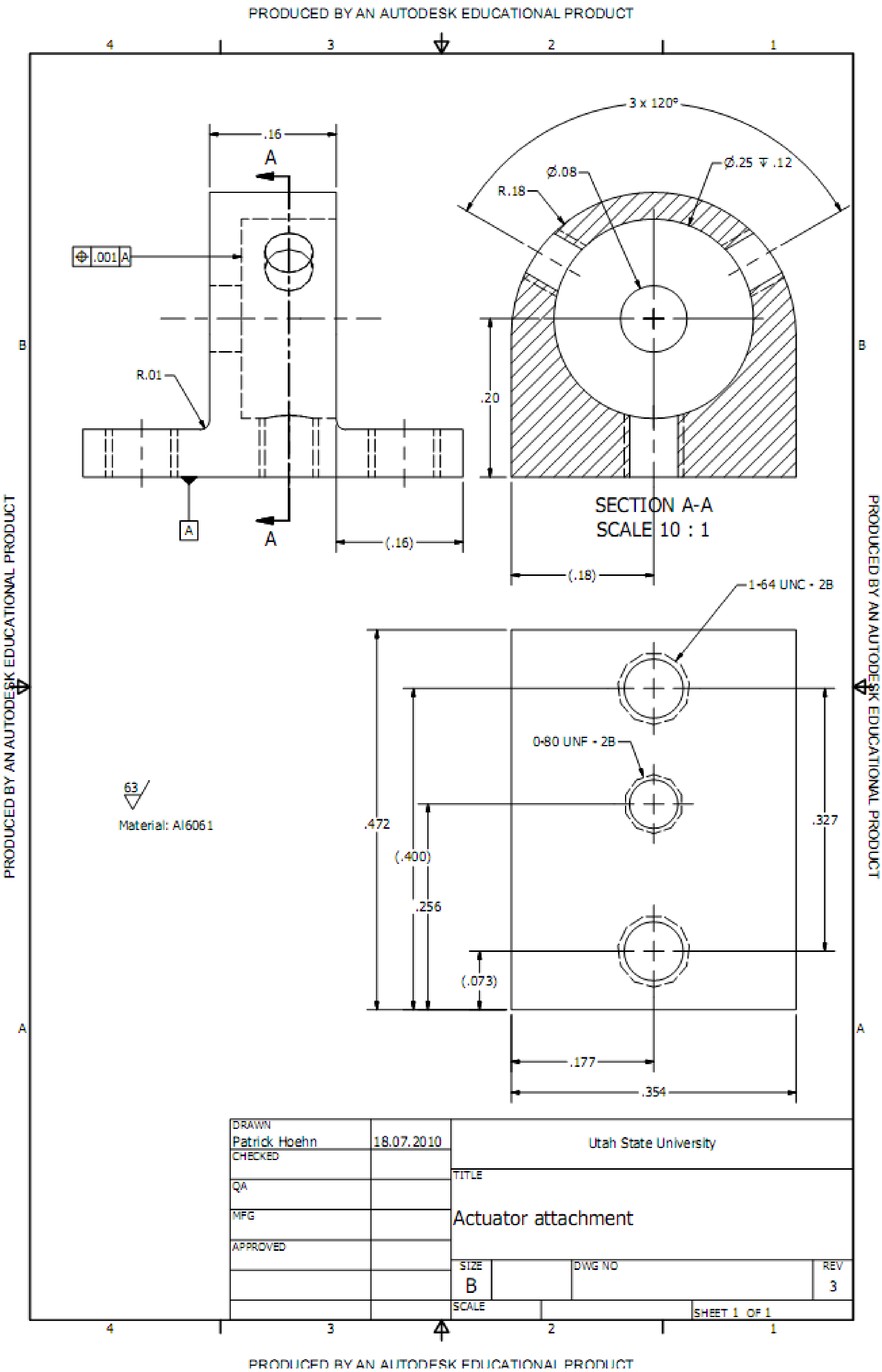
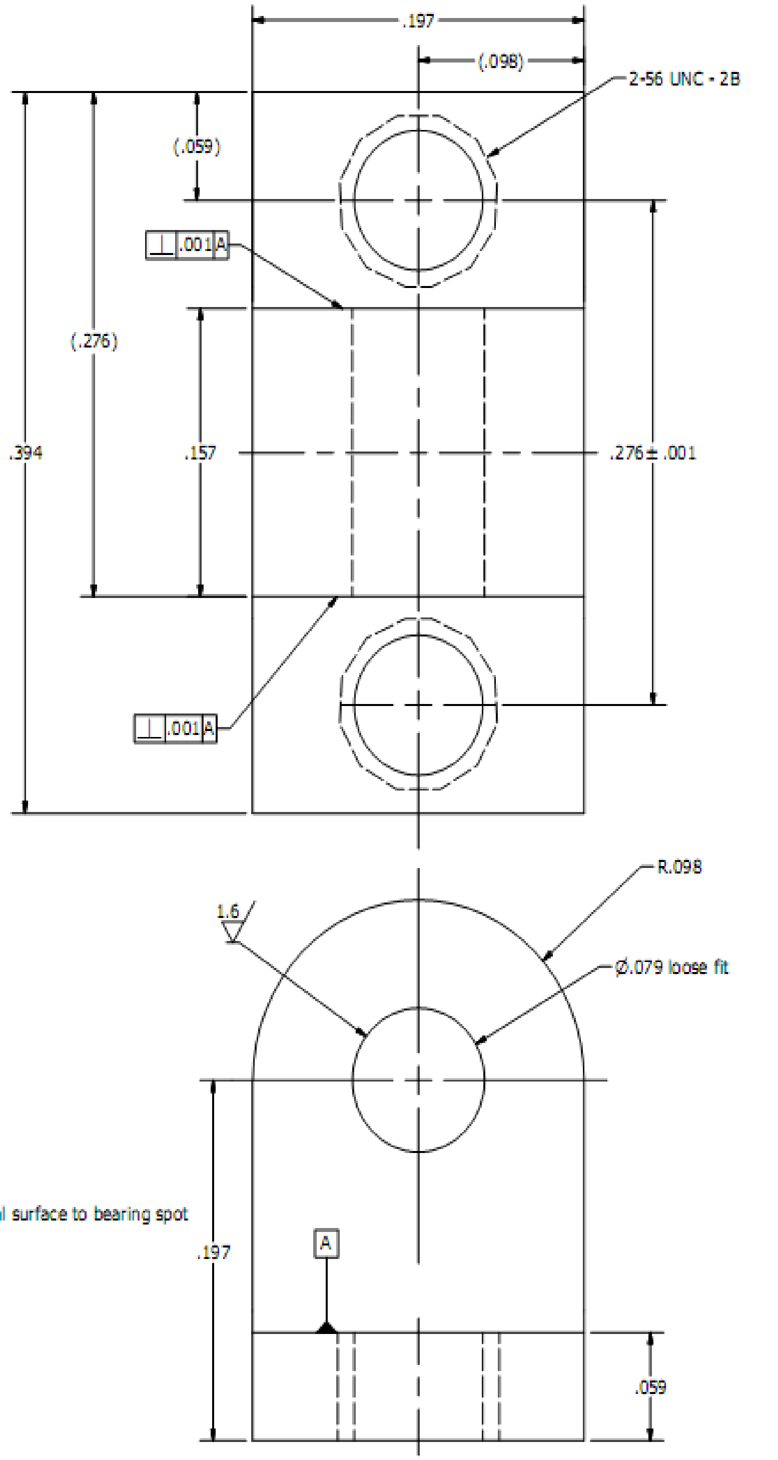
# Appendix

## *Engineering Drawings for components*

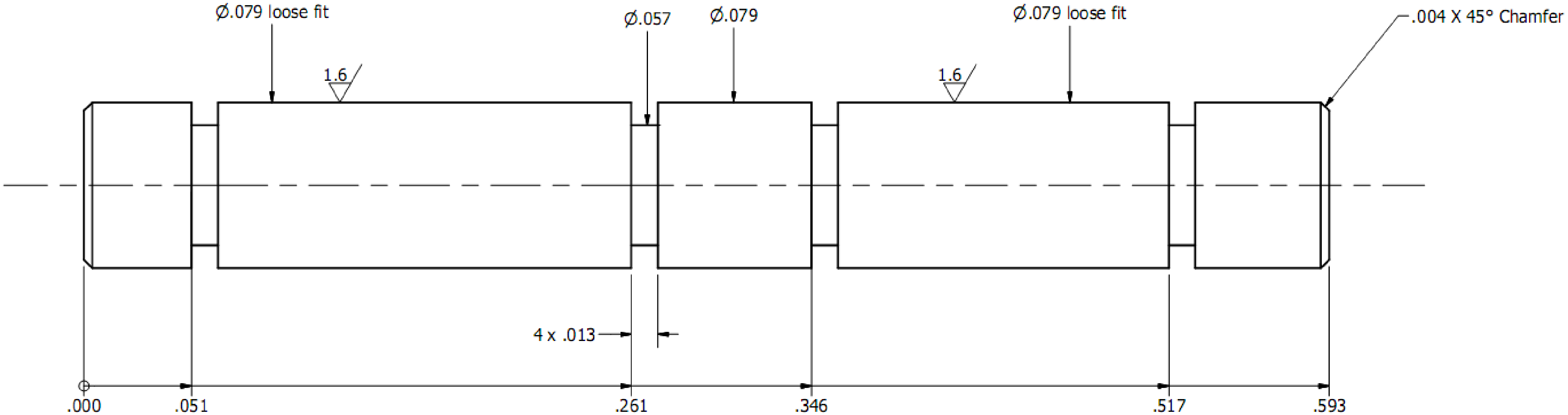


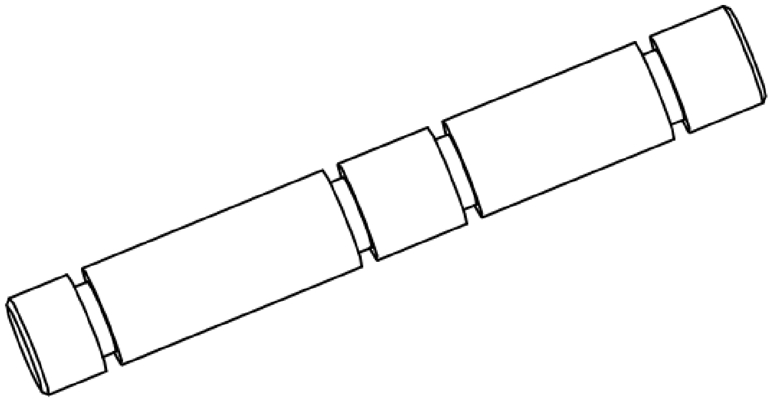



Material: Al6061

6.3 (1.6)

| | | |
|---|---|---|
| DRAWN Patrick Hoehn | 13.06.2010 | Utah State University |
| CHECKED | | TITLE Inactive Joint |
| QA | | |
| MFG | | SIZE B · DWG NO · REV |
| APPROVED | | SCALE · SHEET 1 OF 1 |



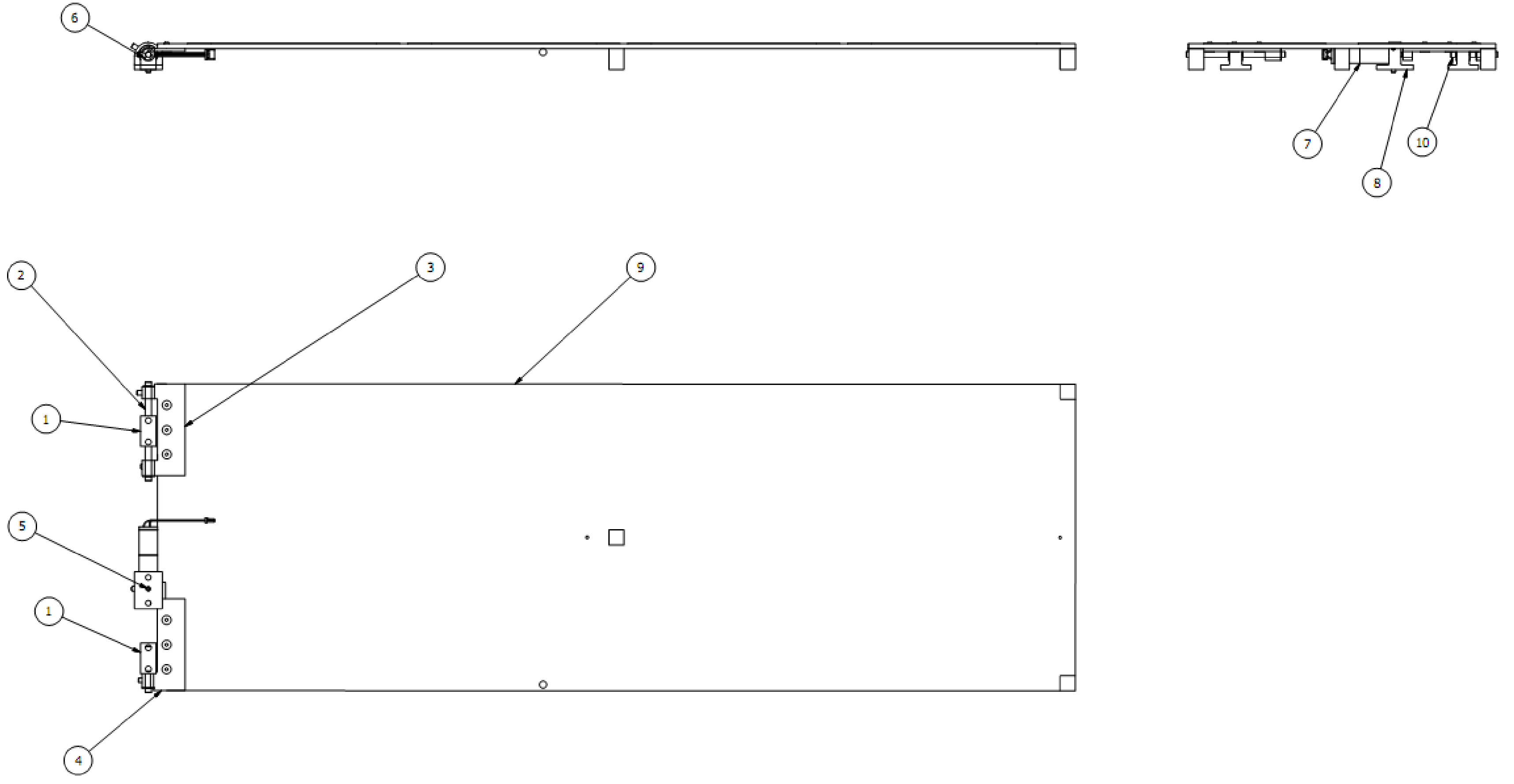



Scale: 1:20
Material: Al6061

63 (1.6)

| | | | | | |
|---|---|---|---|---|---|
| DRAWN Patrick Hoehn | 18.07.2010 | Utah State University | | | |
| CHECKED | | TITLE Shaft for first hinge | | | |
| QA | | | | | |
| MFG | | | | | |
| APPROVED | | SIZE B | | DWG NO | REV 3 |
| | | SCALE | | SHEET 1 OF 1 | |

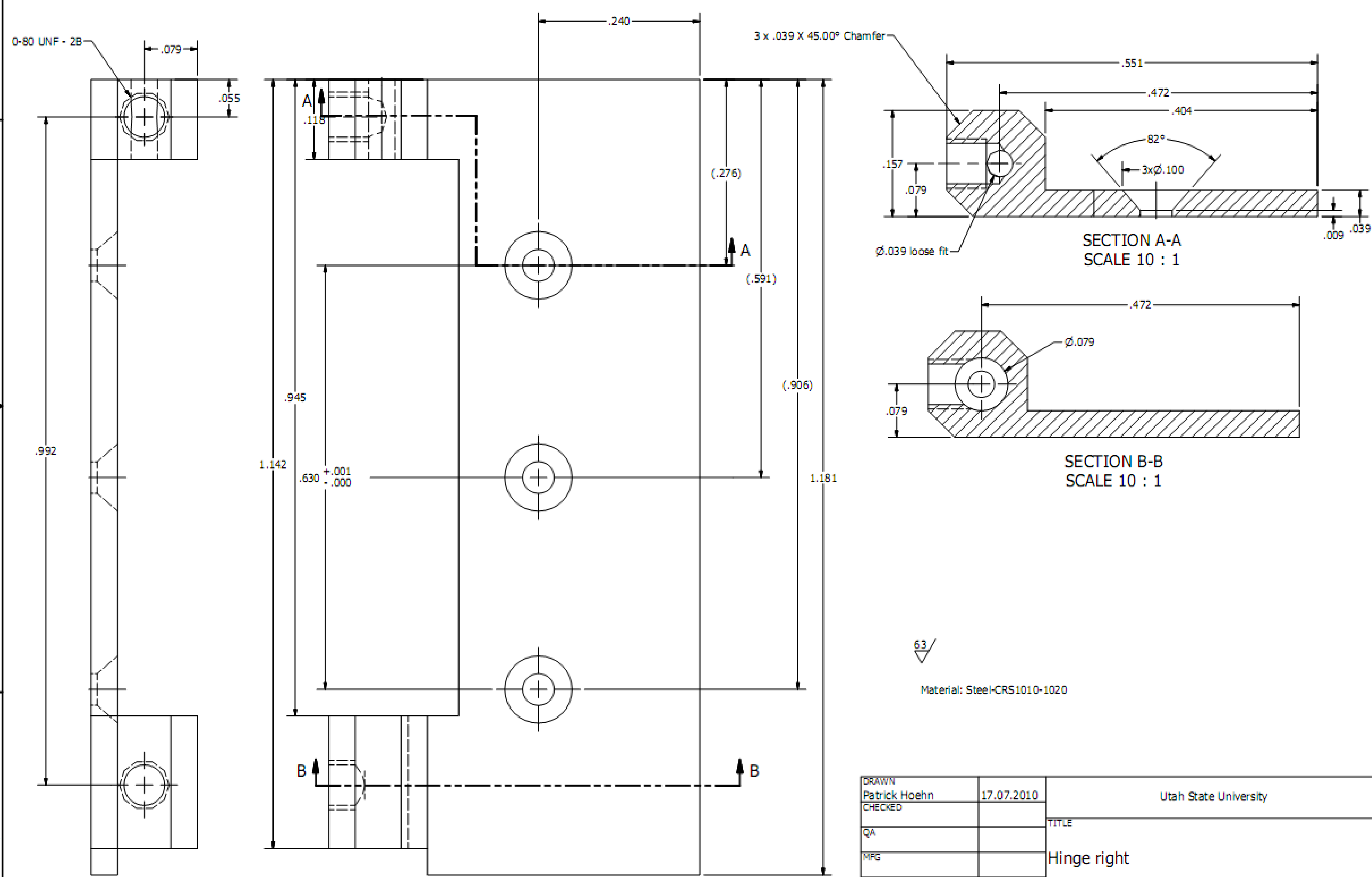
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT




| PARTS LIST | | | |
|---|---|---|---|
| ITEM | QTY | PART NUMBER | DESCRIPTION |
| 1 | 2 | General Attachment | |
| 2 | 1 | Shaft | |
| 3 | 1 | Hinge Left | |
| 4 | 1 | Hinge Right | |
| 5 | 13 | ANSI B18.3 - 0-80 UNF x 0,125 | *Varies* |
| 6 | 8 | ANSI B27.7M - 3CMI-2 | Metric Reduced Cross Section Retaining Rings - E Ring External Series - 3CMI |
| 7 | 1 | Motor GearBox | |
| 8 | 1 | Acutator Attachment | |
| 9 | 1 | Panel | |
| 10 | 1 | Shaft short | |

| | | |
|---|---|---|
| DRAWN Patrick Hoehn | 20.07.2010 | Utah State University |
| CHECKED | | TITLE |
| QA | | Assembly drawing Panel |
| MFG | | |
| APPROVED | | SIZE C · DWG NO · REV 3 |
| | | SCALE · SHEET 1 OF 1 |

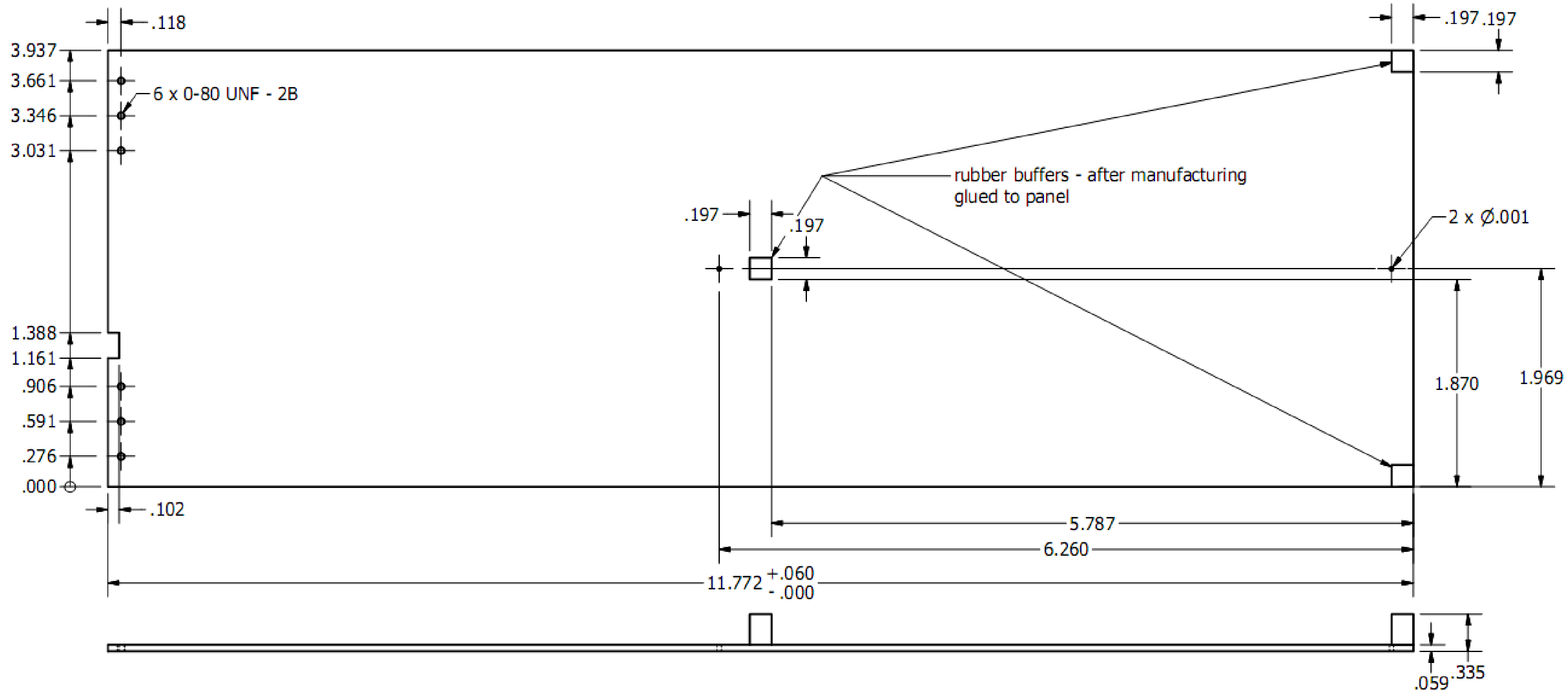
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT




Material: Steel-CRS1010-1020

| DRAWN | | |
|---|---|---|
| Patrick Hoehn | 17.07.2010 | Utah State University |
| CHECKED | | TITLE |
| QA | | Hinge right |
| MFG | | |
| APPROVED | | SIZE C — DWG NO — REV 3 |
| | | SCALE — SHEET 1 OF 1 |

PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT




Material: PCB

| | | | |
|---|---|---|---|
| DRAWN Patrick Hoehn | 18.07.2010 | Utah State University | |
| CHECKED | | TITLE Panel | |
| QA | | | |
| MFG | | | |
| APPROVED | | SIZE B | DWG NO | REV 3 |
| | | SCALE | SHEET 1 OF 1 |

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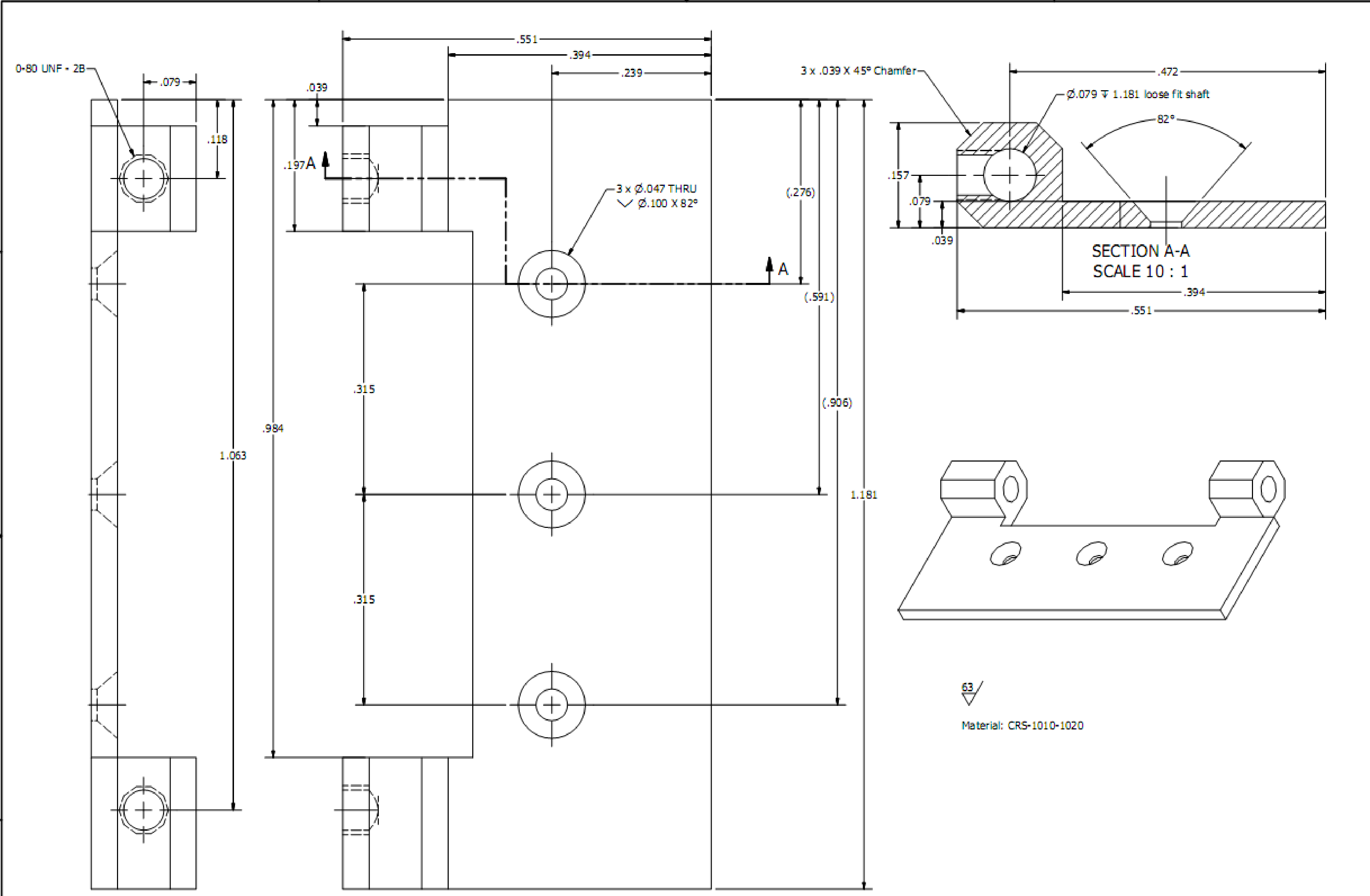
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT




| | | |
|---|---|---|
| DRAWN Patrick Hoehn | 18.07.2010 | Utah State University |
| CHECKED | | TITLE |
| QA | | Hinge left |
| MFG | | |
| APPROVED | | SIZE C / DWG NO / REV 3 |
| | | SCALE / SHEET 1 OF 1 |

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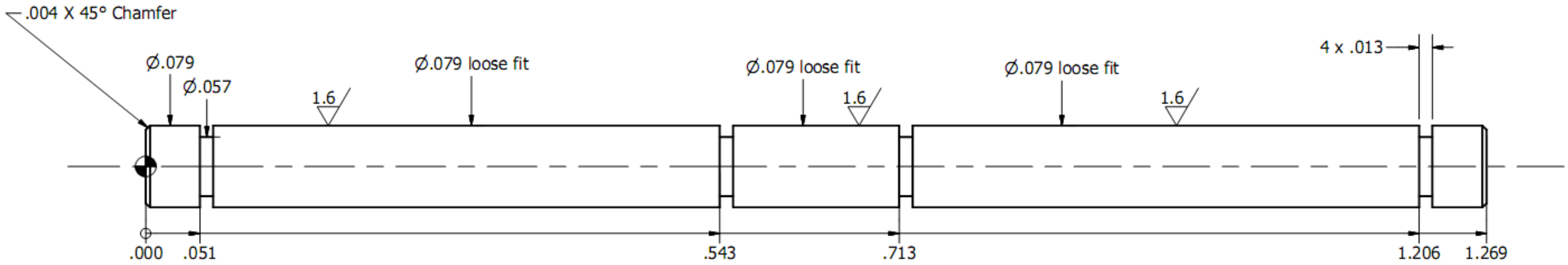
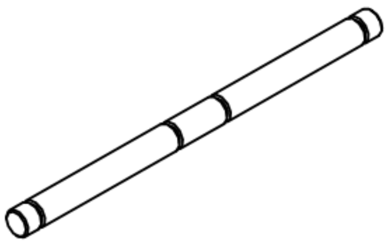
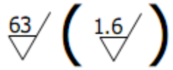
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT



Material: Al6061




| | | |
|---|---|---|
| DRAWN Patrick Hoehn | 18.07.2010 | Utah State University |
| CHECKED | | TITLE Shaft for second hinge |
| QA | | |
| MFG | | |
| APPROVED | | SIZE B / DWG NO / REV 3 |
| | | SCALE / SHEET 1 OF 1 |

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