

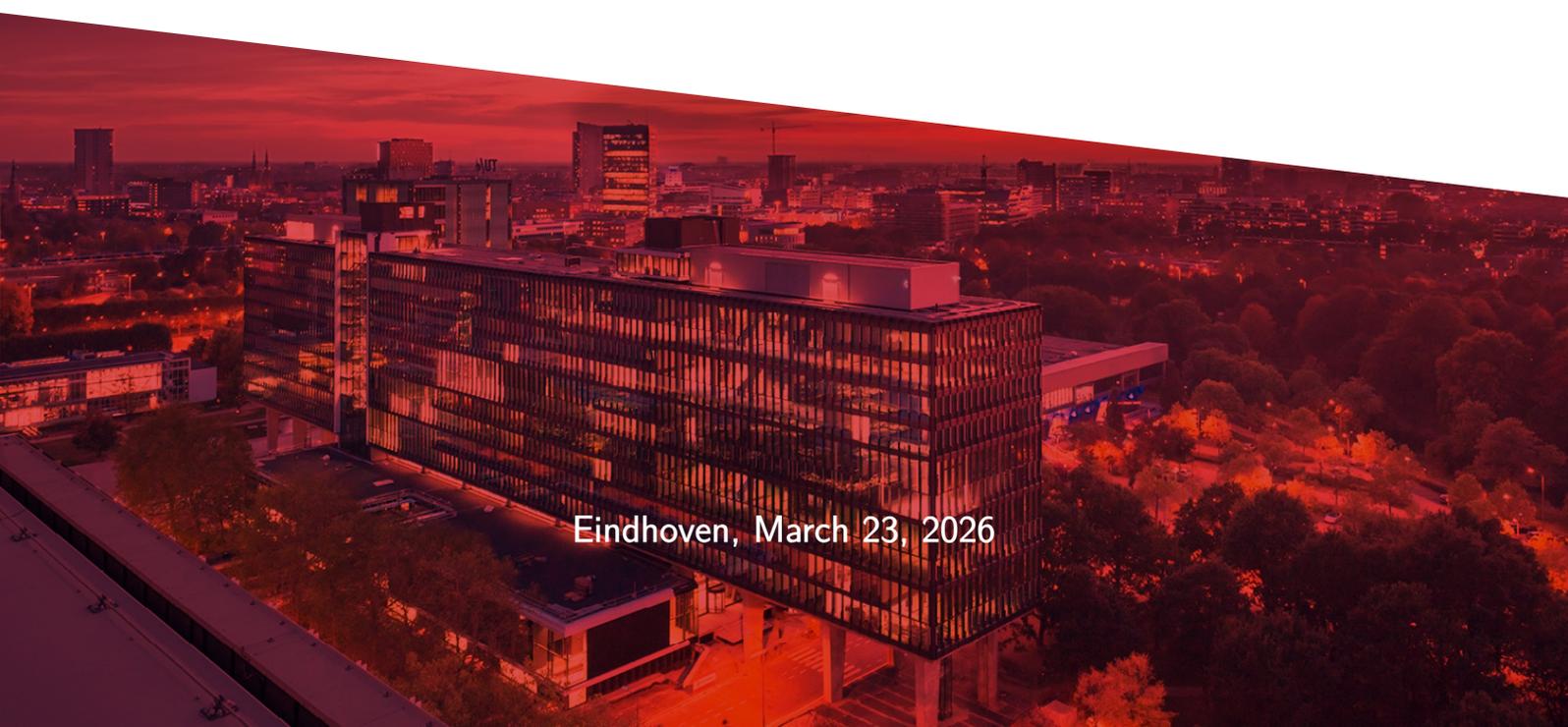
TU/e

4GC10 (2024-2) Mechanical design
project

Group 5

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Contents

- 1 Introduction** **1**

- 2 Proposed Design Configuration** **2**
 - 2.1 Structure 2
 - 2.2 Mirror steering mechanism 2

- 3 Detailing the Parts** **3**
 - 3.1 Structure 3
 - 3.2 Mirror steering mechanism 3

- 4 Theoretical requirements verification** **5**
 - 4.1 Structure 5
 - 4.2 PKM analysis: 5

- 5 Future work** **7**

- 6 Conclusion** **8**

- 7 References** **9**

- A Appendix A** **10**
 - A.1 Cube design 10
 - A.2 PKM design 11
 - A.3 Lessons learnt in manufacturability 12
 - A.4 accesibility considerations 12

- B Appendix B** **13**
 - B.1 Structure 13
 - B.2 Mirror manipulation 14

- C Appendix C** **17**

List of symbols

Table 0.1: List of symbols

Symbol	Dimension	Unit	Unit abbreviation
A	Area	meter ²	m ²
c	Stiffness	Newton/meter	N/m
c	Rotational stiffness	Newton/radian	N/rad
E	Young's modulus	pascal	Pa
F	Force	Newton	N
I	Second moment of area	meter ⁴	m ⁴
i	Transmission ratio	-	-
l	Length	meter	m
m	Mass	kilogram	kg
θ	Angle	radians	rad
σ	Stress	pascal	Pa

1 | Introduction

Over time, communication protocols have been moving towards LASER-based technologies as a replacement for traditional radio waves. This approach has a few advantages over traditional ways of communication, including greater bandwidth, enhanced security, and improved efficiency. However, a major challenge is that successful signal transmission relies on maintaining a direct line of sight between the sender and receiver. The design problem involves developing a mounting structure and adjustment mechanism for a steering mirror in a LASER communication satellite. The steering mirror is crucial for accurately directing the LASER beam toward a target in space. The team must develop a compact, lightweight, and precise mirror mounting system that integrates seamlessly within the satellite while maintaining high precision and stability under operational conditions. One of the primary constraints is the limited space within the satellite, thus, the mounting structure must fit within the available design space without interfering with other components. Additionally, the design must incorporate a gyroscope interface while ensuring structural stability. High precision is required, with the system needing to achieve specific resolution, accuracy, and repeatability thresholds to maintain beam alignment. The project is further constrained by material limitations, as only predefined materials such as cardboard, PLA, nuts, bolts, and mirrors can be used. Therefore, proper assembly methods must be used to have low play and high stiffness. The final design must be tested to ensure proper alignment and mechanical stability using a dedicated LASER test setup. When looking for a viable design, the goal was to create a simple but stiff design that is backed up by design principles.

2 | Proposed Design Configuration

2.1 | Structure

The structure was kept as simple as possible while maximizing stiffness but remaining lightweight. The dimensions are 150 mm x 400 mm x 240 mm. All faces of the structure are precisely laser cut and are glued at the edges. This method of building has been chosen in place of cutting and folding the cardboard as it reinforces the edges, with the help of glue, and avoids unwanted forces created by manufacturing errors as much as possible. The base is inserted into a base plate made of several cardboard sheets. This way of attaching the structure to the provided metal plate eliminates any out-of-plane forces, shifting everything into tension/compression, but with the trade-off being the weight and the extensive manufacturing process. The structure also includes a maintenance hole on top, which could be used to make adjustments to the mechanism inside or do some repairs or replacements of parts if they break. This hole has two doubler plates, which ensure that minimal stiffness is lost [1].

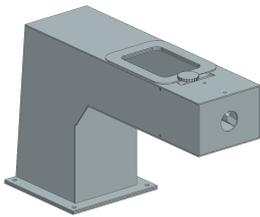


Figure 2.1: Design of the structure with the mechanism in it

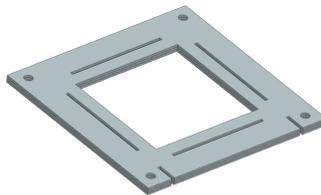


Figure 2.2: Base plate

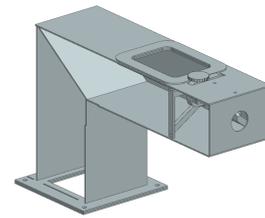


Figure 2.3: The inside of the structure with the mechanism in it

2.2 | Mirror steering mechanism

The mirror steering mechanism, or the PKM, which stands for precision kinematic mounting, is composed of two flexure assemblies with a transmission ratio attached to the structure and a mirror mounting. The dimensions are 101 mm x 80 mm x 106 mm. Flexures were used to achieve the desired transmission ratio, as they are suitable for the small displacement required. With the complexity of this design, the trade-offs that resulted were the time spent on achieving a working prototype but also the manufacturing difficulties that appeared throughout the process. The flexures are operated using bolts with dials on the ends that ensure that the mirror can be positioned as accurately as possible by making the transmission ratio very small without decreasing the stroke.

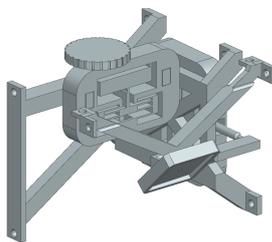


Figure 2.4: PKM mechanism assembly

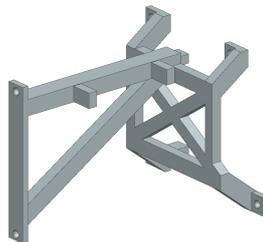


Figure 2.5: Supports connecting the mechanism to the structure

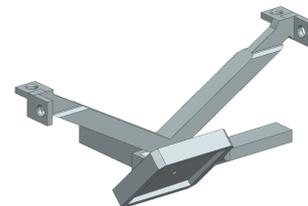


Figure 2.6: Mirror mount

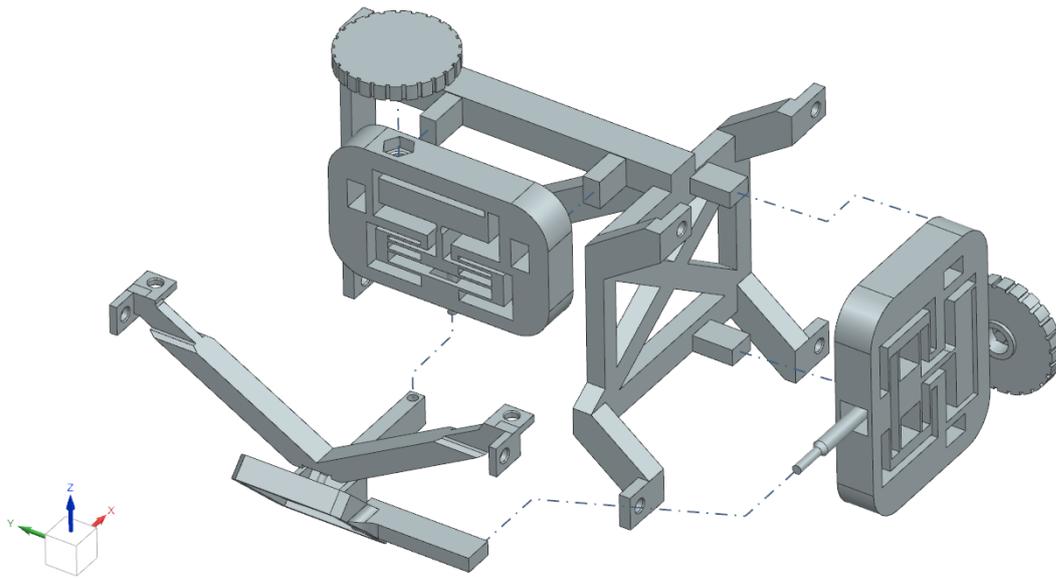


Figure 3.2: Exploded view of the mirror manipulation system

3.2.1 | Support: Design choices

A cross brace is incorporated into the design to increase the torsional stiffness. The support is strategically placed to load the structure in-plane by connecting at its corners. Additionally, square bosses enable the modular design to establish quick and rigid connections to the PKM. These bosses are placed such that in the load direction of their respective flexures they are oriented in their in-plane directions. Furthermore, the mirror is held in place by a toroidal flexure which is in turn held by a simple V support. This support is loaded out of plane but this is not an issue due to the toroidal flexure being very compliant and only acting as a pivot point for the mirror to turn around. Its position is therefore fully determined by the flexure module actuation pins.

3.2.2 | Flexures: Design choices

The low transmission ratio of the flexures improves the stiffness of the design and allows for more precise manipulation of the mirror. The flexures also take advantage of a parallel guide built into them after the transmission ratio (lever), making sure that the movement of the steering rod is perfectly perpendicular to the steering arm of the mirror mount. This ensures that for each degree of freedom of the mirror mount, the actuation will be perfectly straight and not incur any deviations in mirror angle. The flexures play a pivotal role in the transmission between input (dials) and output mirror movement.

4 | Theoretical requirements verification

4.1 | Structure

In order to validate the structural integrity of the assembly, a FEM analysis has been performed to see where the weak points are located. Initial tests of the unoptimized structure resulted in an initial result of a maximum nodal stress of 6.694 MPa and a maximum displacement of 3.324 mm.

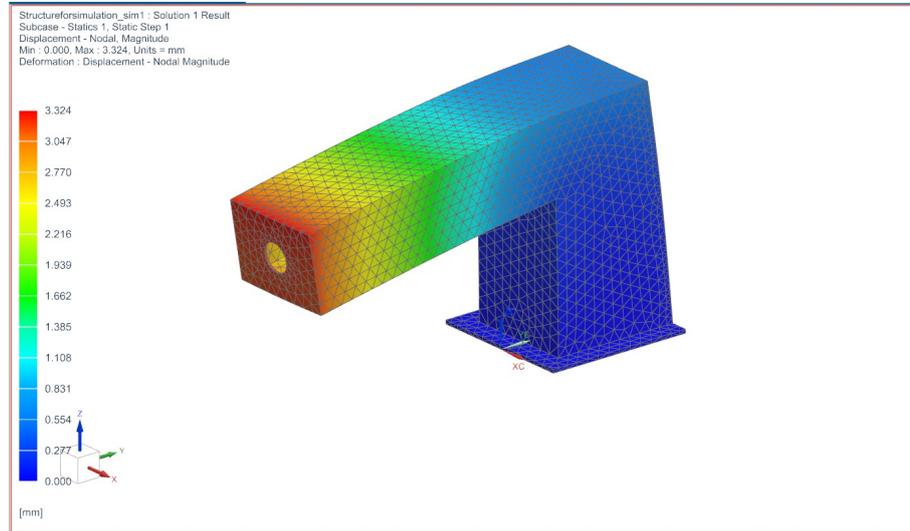


Figure 4.1: FEM analysis of an initial structure prototype

This second simulation was done on a structure with an arm that was made 1 cm higher, thus further optimizing the use of the available space. A significant improvement in the deflection of the structure can be found; the maximum displacement of the structure at the end of the arm went from 3.324 mm to 2.969 mm. The maximum nodal stress was also reduced from 6.694 MPa to 5.353 MPa. This improvement resulted from distributing the stress that is located in the corner of the structure. This iteration comes in at a weight of 400 g.

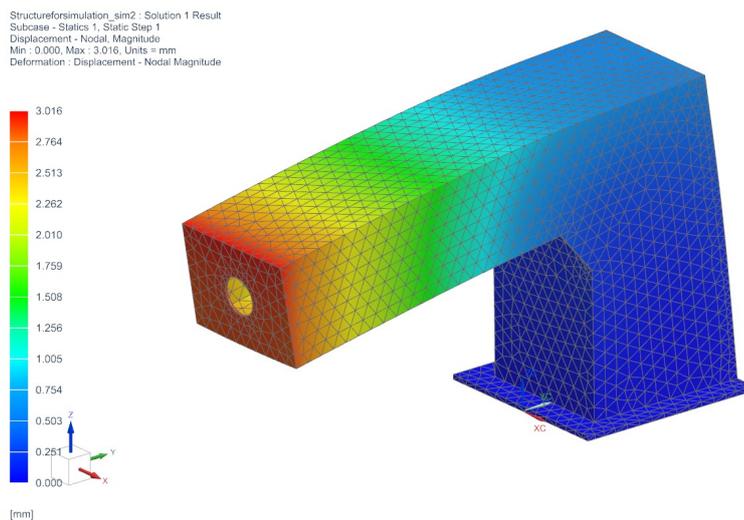


Figure 4.2: FEM analysis of the final structure

4.2 | PKM analysis:

When looking at the PKM flexure, the analysis begins by defining the axial and lateral displacement stiffness for the two components of the transmission. The formulas below are used to calculate the stiffness

for each part.

$$c_{axial} = \frac{EA}{l_{rod}} c_{lat} = \frac{3EI}{l_{lever}^3} \quad (4.1)$$

Notice that the lever and the axial rod are connected in series and thus the series stiffness formula needs to be applied:

$$c_{total} = \left(\frac{1}{c_{axial}} + \frac{1}{c_{lat}} \right)^{-1} \frac{1}{i^2} \quad (4.2)$$

These formulas were included in a MATLAB script (found in Appendix C), along with $i = \frac{F_{input}}{F_{mirror}}$ a transmission ratio of 0.493.

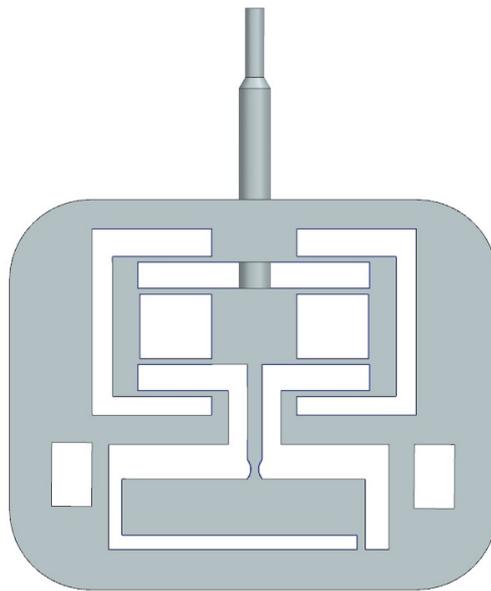


Figure 4.3: Flexure

5 | Future work

To transform the current prototype into a fully operational space-ready component, several improvements are necessary. One of the primary considerations is weight reduction, as minimizing mass is critical for efficient transport and deployment in space. This can be achieved by optimizing the structural design, removing material, but keeping the original stiffness of the structure.

In addition to structural modifications, the choice of materials plays a critical role in reducing weight. The prototype currently uses materials suitable for demonstration purposes, i.e. cardboard and PLA, but for a functional space component, advanced lightweight materials such as aerospace-grade aluminium alloys (such as Al-6061 or Al-7075), titanium (such as Ti-6Al-4V), or carbon fibre composites should be considered as they provide exceptional strength and corrosion resistance, though they are more challenging to machine. These materials offer the necessary strength while significantly reducing mass. As the temperature in space is significantly lower than on Earth, the methods of glueing the structure need to be revised as well.

Another essential aspect is the selection of materials for the flexures. Since these components are responsible for precise movements and alignment, they must be made from materials that exhibit high resistance to creep. Prolonged exposure to mechanical loads and temperature variations can cause material deformation over time, leading to performance degradation and risk of failure. To prevent this, creep-resistant materials such as beryllium copper, titanium alloys, or specialized high-performance polymers should be used. The selection of materials should balance manufacturability, durability, and performance under space conditions, including exposure to vacuum, temperature fluctuations, and radiation. Surface treatments such as anodization, coatings, or radiation shielding layers may also be necessary to enhance durability.

Lastly, the mirror used in the prototype is quite simple and low-grade. For use in space, a higher-grade mirror will be required. The mirror has to be resistant to space conditions, such as temperature fluctuations. To ensure accuracy, mirrors similar to those used in space telescopes should be used. By implementing these changes, reducing weight, utilizing lighter materials, and selecting creep-resistant materials for flexures, the prototype can be refined into a fully functional, space-qualified component capable of performing reliably in the challenging conditions of satellite-based LASER communication systems.

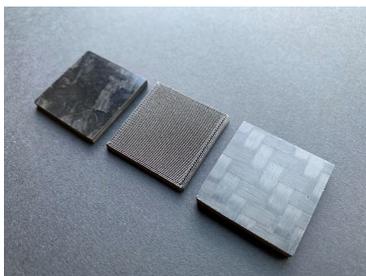


Figure 5.1: Different types of carbon fiber weaves



Figure 5.2: Titanium



Figure 5.3: Reflective coatings

6 | Conclusion

The developed prototype meets the design goal of making a prototype mounting structure and a mechanism to steer the mirror. The design is made to be as lightweight and stiff as possible so that the structure meets the requirements for orbit in space. This is done through careful design choices, including a side plate made of a singular piece of cardboard, a diagonal rib to minimize buckling and laser-cut pieces to ensure 90° corners. Furthermore, the baseplate minimizes the out-of-plane forces, resulting in optimal load distribution. A FEM analysis provided important insight into the required thickness of the baseplate before changes became negligible and where the weak points of the construction are.

The mechanism uses flexures which consist of a lever and a parallel guiding system to deliver precise and small displacements. These precise and small displacements are also created by the manipulation dials which when combined create a transmission ratio of 0.493. This prototype has advantages like modularity, which allows for future adjustments or improvements to be easily implemented. Moreover, the high stiffness-to-weight ratio, makes it more lightweight and cost-effective to launch into space. Lastly, the flexures provide precise control over the mirror, which can also be changed accordingly due to the modularity.

Just like all designs certain risks are present. One of these risks is the manufacturing risks with laser-cutting and 3D printing which can be challenging. Understanding how materials behave through different manufacturing methods was a big challenge to overcome, as the geometry and stiffness of flexures must be precisely calculated. With manufacturing also comes the assembly, these risks include the glue failing or the cardboard separating which can become prominent over longer periods in space. Despite said risks, the prototype achieves a balanced performance against the weight, manufacturability, and stiffness for its intended application.

7 | References

- [1] T. H. G. Megson. *Aircraft Structures for Engineering Students*. Butterworth-Heinemann, 2016.
- [2] Herman Soemers. *Design Principles for precision mechanisms*. University of Twente, 2010.

A | Appendix A

During the design process for this course, multiple iterations of the mirror steering mechanism have been made. In the following, the crucial ones that significantly accelerated the progress and the ones that left valuable lessons behind will be shown. Two designs have been developed in parallel. The precision kinematic mirror mount (PKM) and the cube design. Below, the iterations of the cube design are shown first as finally the decision was made to develop the PKM as the final mirror steering mechanism.

A.1 | Cube design

The lessons taken from the iterations shown below are not to print the thread in the 3D print itself, but a better option is to leave space for a nut. This ensures that the thread will not wear out and therefore the adjustment will remain precise. The second iteration showed how much precision the steering flexures can add. The version of the design using strings was very promising; however, as it later turned out, strings were not allowed, and using filament was not a viable option.

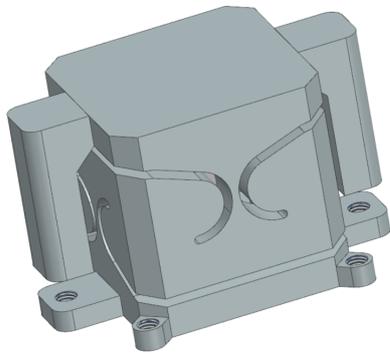


Figure A.1: Cube design with place for steering bolts and mounting points

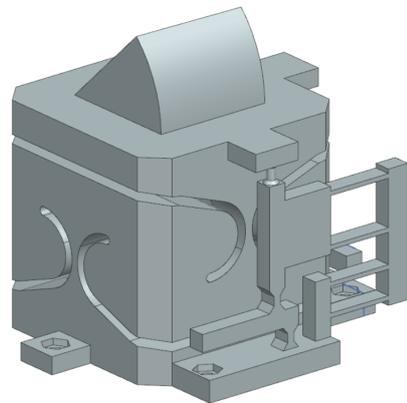


Figure A.2: Cube design with flexures for steering for added precision

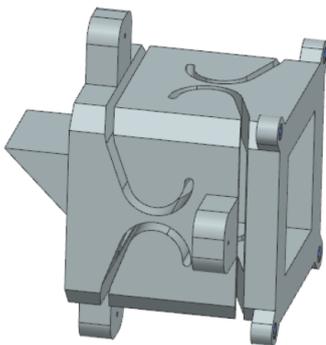
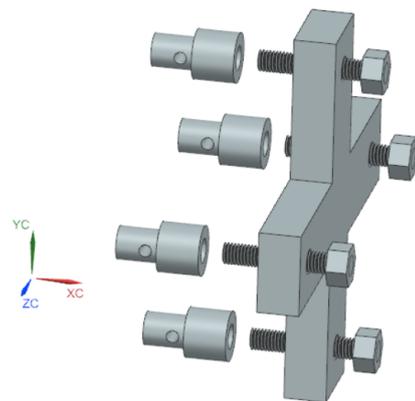


Figure A.3: Cube design utilizing strings for steering the mirror



A.2 | PKM design

From the first design below, the lesson taken was that steering it with just bolts is simply not precise enough for the given task. The design with flexures left a lesson behind that all parts, especially flexures have to be printed in the optimal orientation, because during testing, one of the flexures immediately broke due to suboptimal printing orientation. The modular design showed that this way of design is promising, but many iterations of the design were needed, each making small improvements on the previous iteration.

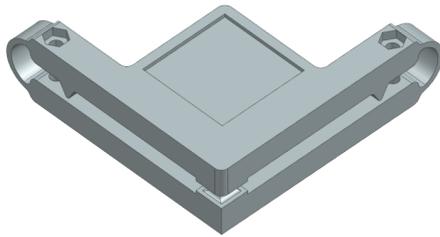


Figure A.4: PKM one part design using springs at the ends and bolts for actuation

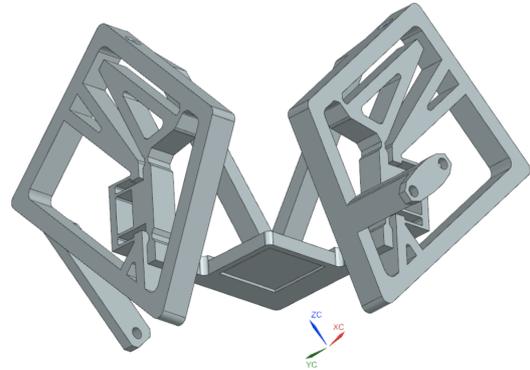


Figure A.5: PKM design with flexures added for precise steering of the mirror

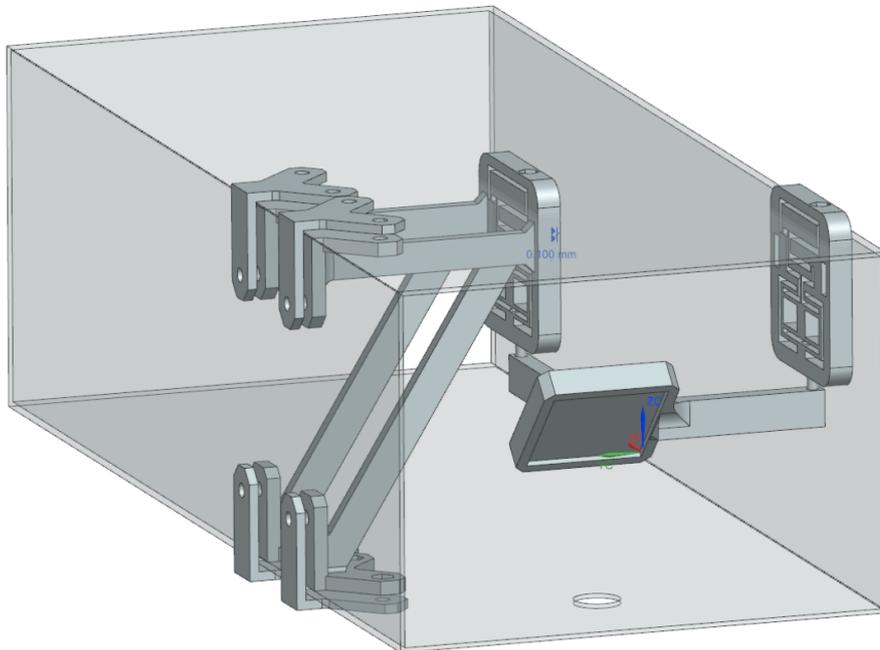


Figure A.6: First modular PKM design

A.3 | Lessons learnt in manufacturability

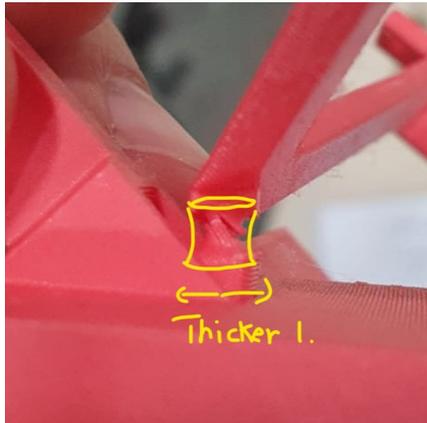


Figure A.7: Example manufacturing error (fault line)

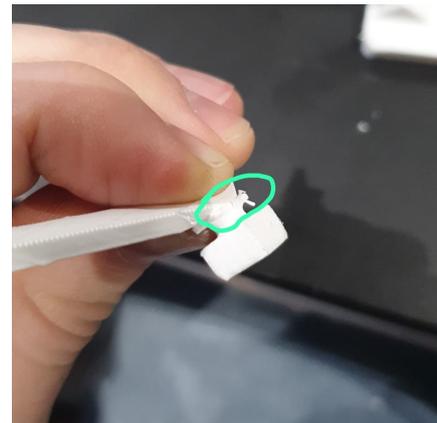


Figure A.8: Example manufacturing error (snapping)

In the images above some common issues experienced whilst assembling the design can be seen. In **Figure A.7** a common issue ran into was the design separating across layer lines. An incorrect print orientation during the 3D print often resulted in a module becoming unusable. From these errors action has been taken to print 3D models in such a way that the layer lines are strong in flexible directions. Especially flexures needed to be printed such that the plastic is loaded axially instead of in shear. In **Figure A.8** another example of a similar break can be seen. In this case, the plastic was too thin and the layer lines allowed for shear forces during use. As can be seen this results in fracture during the use of the component and this fracture results in a large fault line for the rest of the design to break along.

A.4 | accessibility considerations

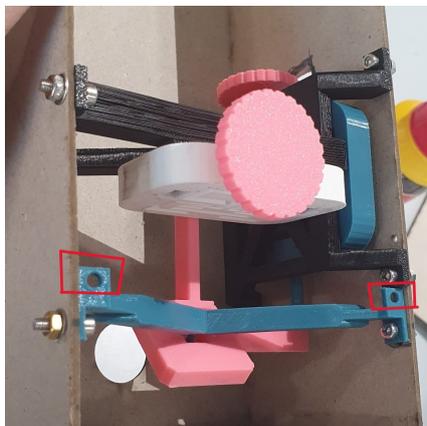


Figure A.9: Hard to reach bolts on the front



Figure A.10: Hard to reach bolts at the bottom of the design

Throughout the project the importance of accessibility became more apparent. Especially when assembling the design, the accessibility of each component allowed or didn't allow it to be mounted correctly. Both **Figure A.9** and **Figure A.10** show bolts that were difficult to reach due to obstruction of other parts. Assembling these components proved challenging at certain points. For example, in the left figure, the top plate had to be put upside down to be able to let the bolts go through. If mounted upwards these bolts would fall into the structure which had just been glued and would not allow this component to be mounted correctly. Therefore when designing these parts in the future it is a clear objective to have accessibility as an important goal that should be taken into account at every step of the design process.

B | Appendix B

B.1 | Structure

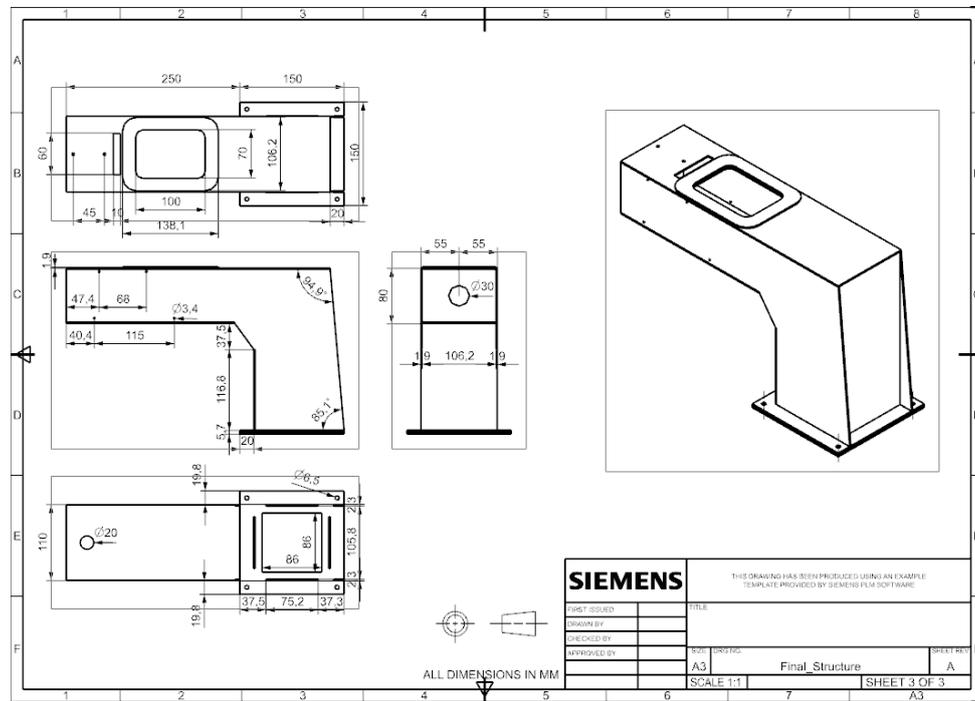


Figure B.1: Technical drawings of the structure

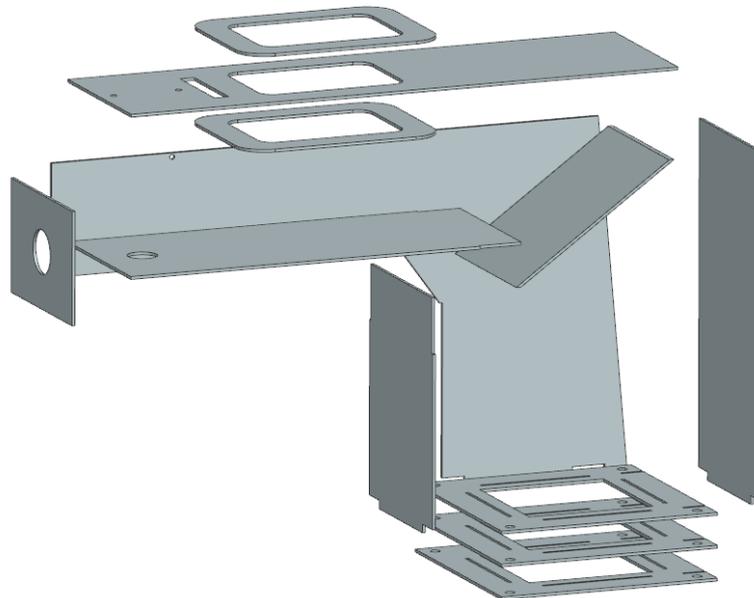


Figure B.2: Exploded view without side panel to show separate parts before assembly

B.2 | Mirror manipulation

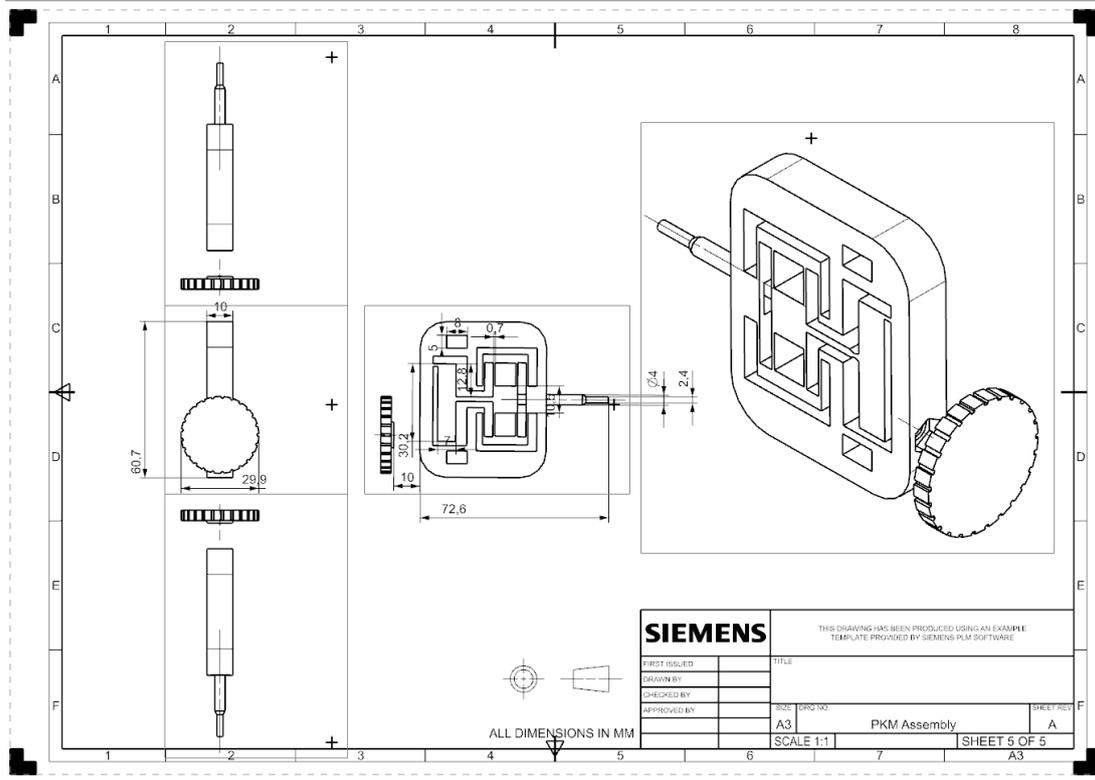


Figure B.3: Horizontal Flexure Module Technical Drawing

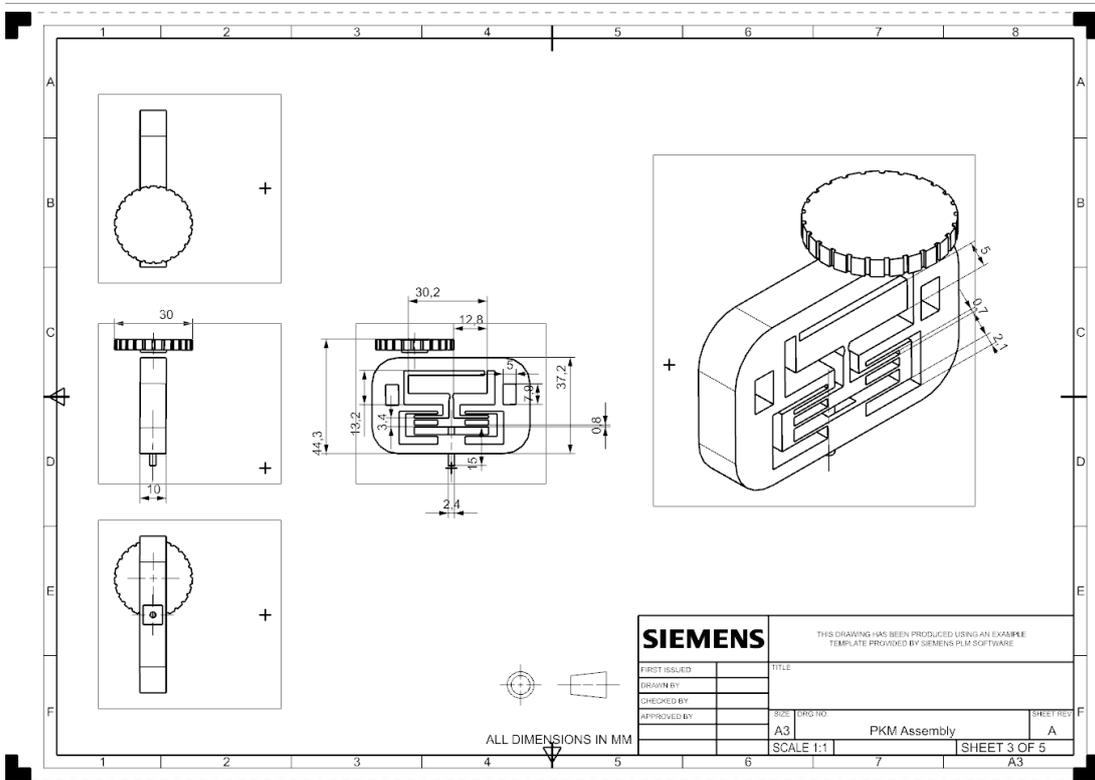


Figure B.4: Vertical Flexure Module Technical Drawing

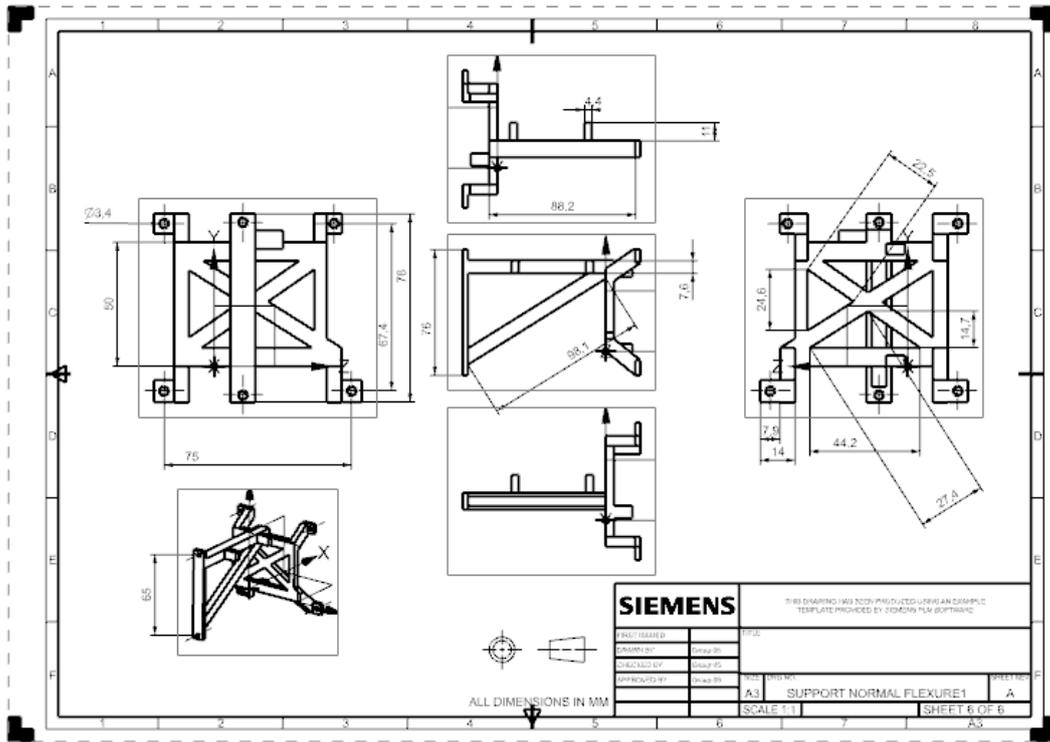


Figure B.7: Main support structure for mechanism

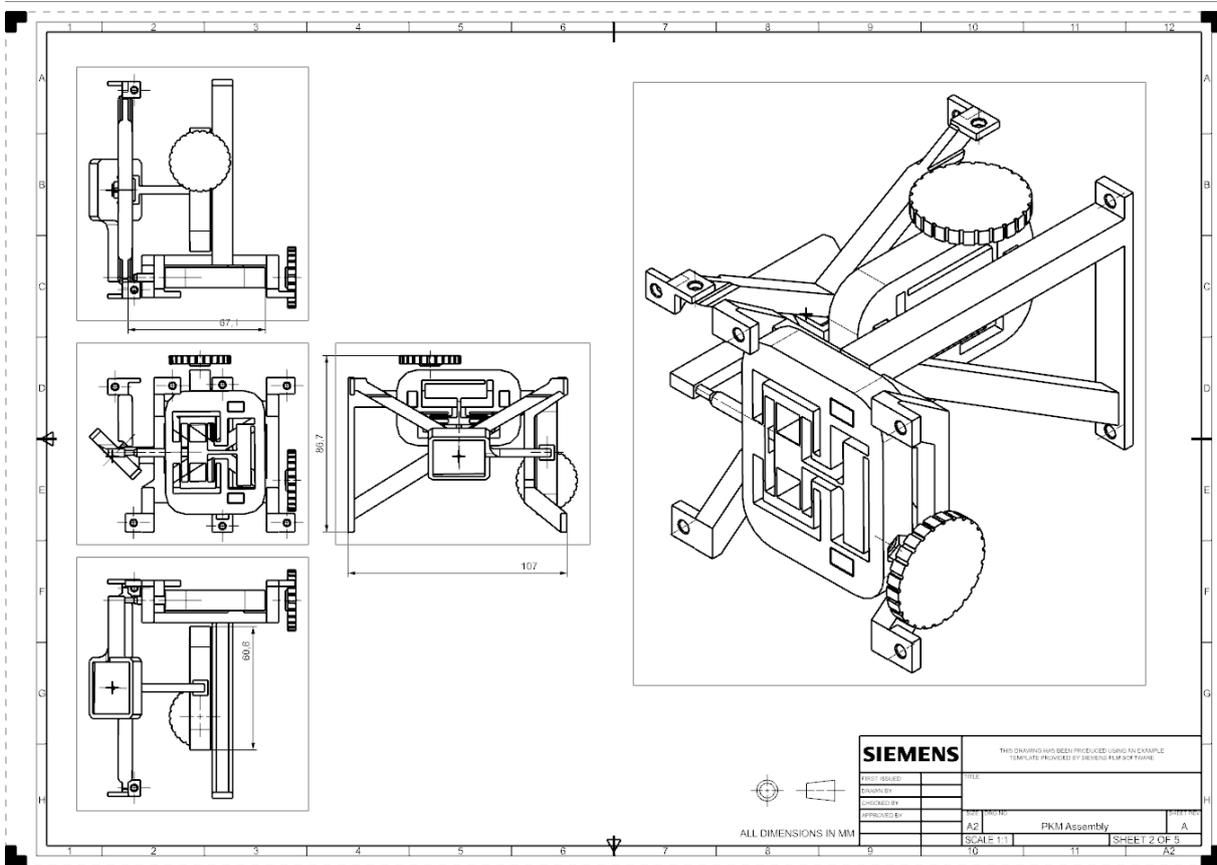


Figure B.8: A technical drawing of the entire mirror manipulating system

C | Appendix C

An iteration of the code used to calculate the transmission ratio is shown below:

```
clear,clc,close;
%Material properties
E = 3.5e9; %[Pa]
%Geometric properties (all dimensions in [m])
l_lever = 50e-3;
l_rod = 30e-3;
l_mirror = 65e-3;
b = 4e-3;
h = 8e-3;
A = b^2;
I = b*h^3/12;
%Required deflection at end of mirror mount
theta_out = 800e-6; %Accuracy requirement [rad]
dx_out = l_mirror*tan(theta_out); %[m]
%Input force wanted for this deflection
F_in = 1; %[N]
%Stiffness calculations (all in [N/m])
c_req = F_in/dx_out; %Stiffness required for wanted force and output
c_axial = E*A/l_rod; %Axial stiffness of rod
c_lat = 3*E*I/l_lever^3; %Bending stiffness of lever
c_tot = (1/c_axial+1/c_lat)^-1; %Total stiffness of lever and rod (series)
%Required transmission ratio
i = c_tot/c_req; %i instead of i^2 because c_tot is divided by i^2 and c_req is
divided by i
%Obtained deflection
dx_obtained = F_in/(c_tot/i);
```