Department of Mechanical and Industrial Engineering

MTP-K-2023-02 - Bachelor thesis

Mechanical configuration of telescope matrix for improved and cost-effective astronomical observation

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REPORT BACHELOR THESIS

Title (Both in Norwegian and English)

Konfigurasjon av teleskop matriseramme for forbedret og kostnadseffektiv astronomisk observasjon

Configuration of telescope array frame for improved and cost-effective astronomical observation

Project number

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Short abstract (Both in Norwegian and English)

The thesis encompassed around developing a telescope for an experimental site test in the Dolomite mountains, Italy. It was the aim of the project to develop and compare compositions of different telescope arrays for optimization of costs, seeing as the project was set to a low budget, as well as assessment of environmental standards. This was done by executing several methods of analysis such as through simulations and hand calculations. The array performance was then reviewed in consideration of terrain, life cycle, among other factors. The goal was to lay the grounds for new developments in design and instrumentation of telescope arrays. The project would later be published in an international peer-reviewed journal with the student and supervisors credited as authors.

Oppgaven handlet om å utvikle et teleskop for et utviklende observatorie i Dolomittene, Italia. Det var hensikten av oppgaven å utvikle og sammenligne komposisjoner av forskjellige teleskopmatriser for optimalisering av kostnader, ettersom at prosjektet var satt til et lavt budsjett, i tillegg til undersøkelse av miljøstandarder. Dette var gjort ved å utføre flere metoder av analyse gjennom simulasjoner og håndkalkulasjoner. Ytelsen av matrisen var deretter evaluert med hensyn til terreng, livssyklus, og andre faktorer. Målet var å legge et grunnlag for utvikling av design og instrumentering av teleskopmatriser. Prosjektet vil senere bli publisert i et internasjonalt fagfellevurdert tidsskrift med studenten og veilederne som forfattere.

Stikkord:	Keywords:
Mekanisk konfigurasjon, CAD, simulering, optimalisering, vedlikehold, kostnadseffektivitet	Mechanical configuration, CAD, simulation, optimization, maintenance, cost-effectiveness

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Preface

This thesis was written in collaboration with the University of Padua and concludes my bachelor program for mechanical engineering, specializing in machine construction at the Norwegian University of Science & Technology in Trondheim, Norway. The work was carried out on the campus of Gløshaugen NTNU. All research, theoretical and physical, was done using resources from NTNU. Throughout the project, I have gained further insights into research and development (R&D), site testing, and interpreting of astronomical criteria. Using skills attained throughout their education, I have constructed a simple telescope array.

Overall, the thesis aims to contribute to the site test project initiated by ANAtOLIA (Atmospheric moNitoring to Assess the availability of Optical LInks through the Atmosphere) funded by the European Space Agency, as well as the general field of telescope development, although a simple design was constructed. The development of a functional telescope prototype provides a practical example of the integration of mechanical engineering and astronomy, paving the way for possible future advancements in the field.

I want to give my sincere gratitude to my associate professors Chiara Bertolin and Stefano Cavazzani for aiding and contributing with their engagement and competence in the field of meterology and astronomy. In addition, I'd like to thank my professor Anna Olsen for her general input and advice advancing me further.

Abstract

The thesis encompasses around developing a telescope for an experimental site testing in the Dolomite mountains, Italy. It is the aim of the project to investigate and compare compositions of different telescope arrays for optimization of costs, seeing as the project is set to a low budget, as well as assessment of environmental standards. This was done by executing several methods of analysis such as through simulations and hand calculations. The array performance is then reviewed in consideration of terrain, life cycle, among other factors. The goal is to lay the grounds for new developments in design and instrumentation of telescope arrays. The project will later be published in an international peer-reviewed journal with the student and supervisors credited as authors.

Abbreviations

API Application Programming Interface

CAD Computer Assisted Design

CCD Charge-Coupled device

FOV Field of View

GOES Geostationary Operational Environmental Satellite

IAC Instituto de Astrofísica de Canarias

R&D Research & Development

WASP Wide Angle Search for Planets

CAD Computer Aided Design

FEA Finite Element Analysis

EFFICACY Energy eFFiciency building and CirculAr eCo-nomY for thermal insulating solutions

ANATOLIA Atmospheric Monitoring to assess the availability of Optical links through the atmosphere (ARTES SL005)

TEnSE Technical, Environmental, Social and Economic topics

IoT Internet of Things

CoG Center of Gravity

CFD Computational fluid dynamics

LCA Life Cycle Assessment

LCIA Life Cycle Impact Assessment

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1 Introduction

Prato Piazza is an observatory site in development located in the Dolomite mountains, Italy. The terrain is optimal for observing the astronomical and atmospheric conditions, as light pollution is considerably low and the area allows for advancements of building out the site.

The site is in early phase of development, and one of the main objectives of the construction of the site is to develop low-cost instruments to aid in scientific research. This includes the ability to produce high-resolution astrophysical images and capture ranges of electromagnetic radiation. In collaboration with the University of Padua and the Norwegian University of Science and Technology, the aim of this thesis was to design and propose a series of small telescope arrays. I aimed to compose a design that was functionally optimal to capture astronomical imagery in the area. It was a priority to contribute with a design that was low-cost, that also considered ease of installment, maintenance and sustainability.

The development of the designs was achieved through the utilization of the Computer-Aided design (CAD) software SolidWorks, as well as usage of simulation to assess the need for adjustments prior to future manufacturing. The supervisors and I discussed and compared the different benefits and drawbacks of the designs throughout the project timeline. The research provided through the thesis could aid future site tests, considering the lack of development of telescope matrices in the field.

There is a need for cost-reduction in astronomical gear and components, as high costs reduce the opportunity for further research. Since such gear is manufactured through high precision methods and often precious materials, it is difficult to reduce costs. Another factor is the low demand for gear, as the field requires a large amount of funding and often times military approval. The consequences emerge through high prices and therefore difficulty in further advancements in the field.

1.1 Thesis Statement

The thesis attempts to resolve the issue of using high-cost telescopes by proposing designs and construction of simple telescope arrays that can fill as a low-cost alternative. It is the aim to contribute to the advancement of astronomical research utilizing findings from my studies, contributing with interesting results for further development in the field.

1.2 Background

I aimed to maintain a good collaboration throughout the duration of the project. This included supervisors Chiara Bertolin and Stefano Cavazzani and other contacts as well, such as co-supervisor

Anna Olsen. The primary performance measure to maintain was the engagement of all parties. A major part of choosing the project lied in the opportunity to obtain guidance from international parties and achieve a better understanding on high scale project management. Another factor was the underlying personal interest in product development of astronomical gear as it is a high precision field. The background of interest achieved a higher sense of motivation. It was the intention to convey useful designs that could be further developed and aid for a telescope that is considerably lower-cost.

The project also got chosen based on the fact that I wished to immerse myself in product development, project building (seeing the running theme, how all components are dependent on each other) and 3D modeling.

1.3 Goals & Measures

An early initiative for the thesis was to have a preliminary report finished. The preliminary report consisted of establishing the achievements the thesis would make, and specifically listing the goals to achieve them. The goals were characterized in two sections; performance goals (outcome goals) and performance measures. The goals are listed in the section below, as well as in the preliminary report in the attachment section.

1.3.1 Performance Goals

Performance goals refer to goals of the project to achieve within the set time frame or scope. The performance goals in question were:

- **Research on previous models from different site tests**
- **Compose concept designs that are drawn with consideration to data accumulated**
- **Design models in CAD**
- **Assess and test models according to cost, maintenance and sustainability**
- **Produce prototypes**

1.3.2 Performance Measures

Certain aspects of performance measures were essential to consider for the project to be successful. Performance measures are actions or criteria that must be carried out for the performance goals to be achieved.

- **Clarity of thesis statement:** At all times during the writing of the thesis it was expected that the thesis statement was a precursor to all that is written. Additionally, that the statement was simple to understand for all parties.

- **Literary quality:** The importance of the literary quality was substantial. The thesis was to be comprehensive and to provide a thorough understanding of the field in question. It was to be well-written, organized, and presented concisely.

- **Research methodology & data collection:** Various research methods were utilized in order to optimally retrieve necessary information. Mainly qualitative research has been conducted, which translates into documents and articles being used for research thus far. As well as quantitative research through collection data from said articles.

- **Originality & contribution to the field:** The thesis was to be of importance and provide an original contribution to the respective field. New insights and perspectives were to be expected. Furthermore, additional research and need for feedback was necessary as there was a lack of similar design concepts. The originality to the thesis would therefore contribute as an asset, should it succeed.

- **Time management:** The thesis was to be completed within the given time frame, and a timeline was set up as a guideline to complete the milestones set. I mainly prioritized the deadlines set by the university, as well as internal ones, such as deadlines set by the supervisors.

- **Ethics of project decisions:** Lastly, it was important to consider the ethics and credibility of the information from the research conducted. This meant examining possible issues such as informed consent and confidentiality. Another factor considered was the environmental and economical sustainability of the project. It was my responsibility to ensure that the design and choice of materials, as well as maintenance, was sustainable and did not impose any serious negative effects on the environment. This has been discussed later in the thesis, see Section 4.4.3 in Results.

1.4 Organization

1.4.1 Plan of Action

The originality of the project was preserved due to the fact that there currently are few utilizations of telescope matrices. The execution of the project will therefore aid in providing new insights into this style of telescopes. Research has been conducted based on similar site tests and further used the supervisors as a resource. The results of the project will later be published in an international peer-reviewed journal. I, Cecilie Olsnes, as well as the supervisors Chiara Bertolin and Stefano Cavazzani will be credited as authors, respectively.

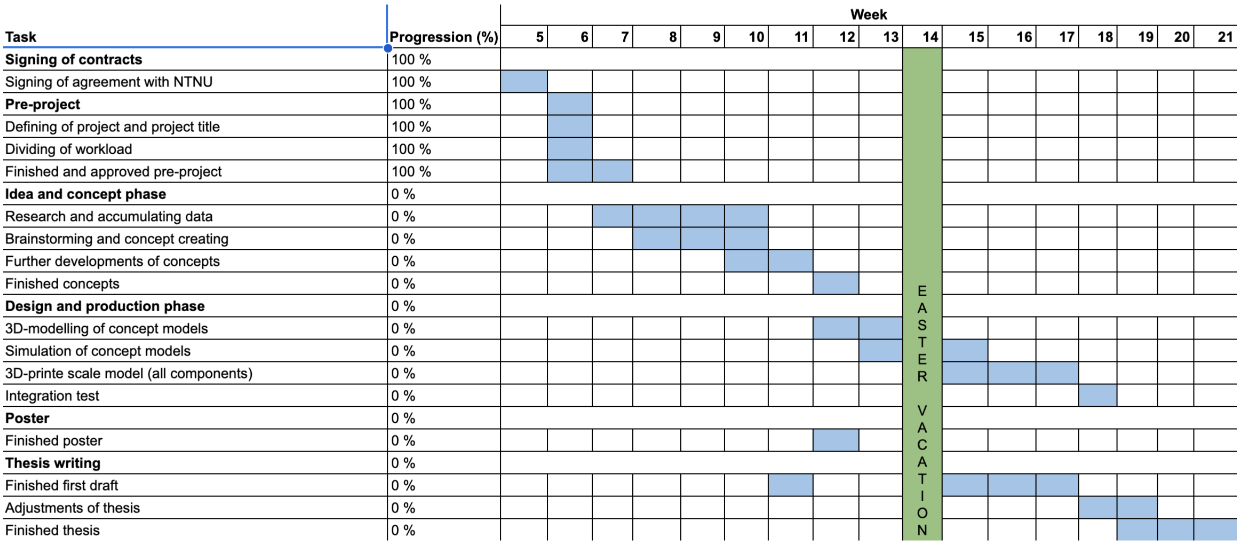


Figure 1.1: Gantt Chart for the duration of the project

1.4.2 Limitations

Physical integration in Prato Piazza was not possible to carry out. I was situated in Trondheim, Norway, while the Prato Piazza site is located in Italy. Although the situation was not optimal, an insightful thesis could still be produced. It was therefore decided to use digital tools and small scale testing to produce a semi-sophisticated design. Limitation of hands-on activities entailed to usage of theoretical and empirical data retrieved through research articles and earlier tests conducted.

As a consequence of this, the meetings with supervisors were mainly held digitally.

During the process of writing the thesis, I decided to part ways with my thesis partner as the labor scope of the project was too large. The themes of the project were also inconsistent with one another, reflecting in the material that was written thus far; this further instigated that the thesis' be written separately. The workload has therefore been reduced approximately by half, considering the amount of people working on the thesis as well as the short duration left of the project. An extension of ten days was granted by the subject manager.

To salvage the situation, the advisors and subject manager have been my main resources going forward. I thank them greatly for their help and advice.

1.4.3 Gantt Chart & Timeline

2 Theory

This chapter follows the theoretical information relevant for the apprehension of the thesis.

2.1 Weather Characterization through Satellite Observation

A crucial factor for determining effective placement of an observational site is the atmospheric transparency. A surrounding area of dense cloud cover and low stability gives off too much noise and disturbance to provide optimal imaging and retrieving of data. It is therefore of interest to review both the short- and long-term trends of cloud coverage in Prato Piazza, and compare them to alternate sites. This was also done to address the possible alterations to be made for the telescope matrix for Prato Piazza.

Previous astronomical sites in Chile and the United States have utilized satellite site testing for short- and long-term trends (at a duration of maximum 10 years) [7]. The benefit of using satellite data instead of ground data, such as for example heliographs, is the ability to detect temperatures at different altitudes. That is, seeing the parameters that induce cloud coverage. The data was gathered from the Geostationary Operational Environmental Satellite (GOES), using primary instruments to sense emissitivity from Earth's surface. The different infrared thermal bands display the nocturnal cloud coverage, with differing bands registering different altitudes. Using a geostationary satellite such as the GOES-12 provides a larger field of view (FOV) compared to a polar satellite [6].

Seeing as there is no standard criteria of classification for satellite-stable nights, one is dependent on comparisons retrieved from earlier research. Which is what was used in this case. Figure 2.1 shows the comparison between the night-time cloud cover and stability of Izaña and S. Pedro Martir in the years 2008 and 2009, respectively [7]. Although the data for stable nights has not been assessed directly at Prato Piazza, one can make estimations based on local climate and short-term weather casts. Prato Piazza is located in a mountainous region (specifically the Dolomite mountains), which is typically exposed to colder temperatures as well as higher wind speeds. At the same time, the altitude allows for less disturbance of cloud- and dust cover, which is optimal for measuring astrological data. Additionally, the terrain is rich in vegetation, which is shown to prevent turbulence and the effect of high-altitude wind. [12]. Viewing the short-term weather data allows for an estimate one can compare with the sites of Izaña and S. Pedro Martir. Comparing these statistics with Prato Piazza, shows that the climate is generally more mountainous, wetter and forest dense.

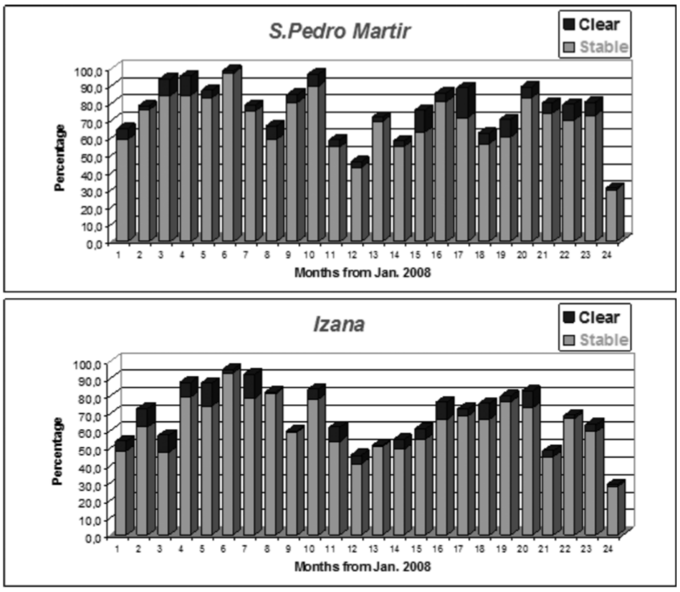


Figure 2.1: Distributions of night-time cloud cover and stability of sites at Izaña and S. Pedro Martir in the year of 2008. (Data obtained from [7])

2.2 Beaufort Scale

The Beaufort wind force scale is a scale of measurement used in environmental circumstances. Its intended use is to measure the qualitative wind conditions instead of the wind speed directly. It is to some degree a subjective unit of measurement, based on observed effects of the wind force. It was initially used in naval voyages to estimate the size of waves by use of the scale. Today, the wind scale is used both at sea and on land. The scale ranges from 0 to 12, with 0 being calm (less than 0.5 m/s) and 12 being Hurricane-force (more than 32.7 m/s).

One can calculate the estimated wind speed using the extended 1946 Beaufort scale (although this scale is mainly used in countries suffering from typhoons). The wind speed is calculated by the following formula:

$$v = 0.836B^{3/2}m/s \tag{1}$$

Where v is wind speed at 10 meters above sea level and B is the Beaufort scale number.

The Beaufort scale is relevant as to how much a structure or stature can withstand the occurring wind speed. Most buildings in the 21st century can withstand even the most destructive scales of winds, as it is crucial for safety of use. Smaller scale structures, like telescopes, are not as crucial in regards to safety. Therefore, while such constructions should withstand large wind speeds, it is not necessarily a requirement to withstand Hurricane-scale winds.

2.3 Computational Fluid Dynamics

Computational Fluid Dynamics, shortened to CFD, is a branch of fluid mechanics used to analyze the effect of flow from fluid mediums. There are three main categories of fluid flow: laminar, turbulent, and transition region, which is a transition from laminar to turbulent. The medium applied may vary; the most common ones being water and air. A CFD analysis would be able to simulate wind on an object and provide results on the maximum wind force the object is able to withstand before deformation occurs.

Through the use of CFD, one can additionally calculate the drag coefficient, which states the air resistance for the given object. The drag coefficient is given as:

$$C_D = \frac{2F_D}{\rho v^2 A} \tag{2}$$

Where F_D is the drag force (force in the flow direction), ρ is the density of the medium, v is the velocity relative to the medium, and A is the cross sectional area being subjected to flow.

2.4 Astronomical Site Testing

In astronomy, seeing refers to the blurring, twinkling, or fluctuating distortion that can be seen when an astronomical object's picture is degraded, owing to turbulence in the Earth's atmosphere.

As mentioned previously, it is in best interest to investigate previous test sites and to compare the statistics on cloud coverage and satellite seeing from each site. Accordingly, to analyze and evaluate factors that determine the performance of Prato Piazza as an optimal test site. Research articles of relevance were sent from supervisor Stefano Cavazzani to obtain the methods and interpretation of fraction of clear skies and astronomical seeing.

In the research articles concerning the fraction of clear skies and astronomical seeing, hereby referred to as [5] and [8], the method of analyzing the fraction of available time were temporal, i.e., once a month, rather than continuous weekly analyses [5]. The reason for that was to obtain more comparable statistics with less progressively inaccuracy. The articles also conducted the quality of cloud coverage in the areas of Mt. Graham, La Palma, Tolonchar, La Silla and Paranal. In addition, with different topographic conditions in relation to stable-, covered-, and clear and unstable nights in an essence to differentiate them what is more optimal for each site. Moreover, each site then required different adherence according to the topographic conditions. Furthermore, the articles conducted the concept of satellite seeing utilizing the GOES12. The data were analyzed from the sites of Cerro Paranal in Chile, and Roque de Los Muchachos in Spain.

Both articles mentioned that all collected data are either derived from ground-based data in the logbooks, or satellite data from the GOES12 satellite. It was asserted that a satellite measures a wider range of celestial events than ground-based data. This was shown at each location of the test sites. This was characteristic for all of the sites included in the research articles. Therefore, it would be advantageous to draw ideas from the collected data of previous sites to determine variable criteria for Prato Piazza.

2.5 Dragonfly Telephoto Array

The Dragonfly is a multi-lens telescope array that was designed for detection of faint astronomical objects. The telescope was developed in Toronto, Canada at the University of Toronto, commissioned in 2013. The purpose for the development of the telescope was to observe ultra-low surface brightness structures.

The array was initially comprised of 8 lenses in 2014, which increased to 48 lenses (comprised of 2 clusters of 24 lenses each) in 2016. The array uses high-end Canon 400mm f/2.8 L IS II USM telephoto lenses each coupled with commercial CCD cameras. Each lens individually has an aperture of 143mm, but when assembled together, there is a significant increase in aperture. The aperture further increases as additional lenses are integrated. The focal length remains the same at 400mm. Assembled, the array forms a hexagonal shape acting as a "compound eye" using a common framework. Yet all lenses act as a self-contained unit; should one of the lenses fail, 47 lenses are still operative. Each lens is equipped with anti-reflection coatings that aid in reducing scattered light. This allows for imaging of structures with a surface brightness that is significantly low.

The mount used for the telephoto array was the Paramount Taurus 600 mount, manufactured by Software Bisque Inc.. It provides multiple, free levels of rotation. The weight limit of the mount stands at 70kg, which is why the maximum amount of cameras cannot exceed 24, and an additional cluster was produced.

Certain aspects of the telescope were of interest. Each lens is installed into a circular custom unit, of which these units are directly diagonally or vertically attached to one another. The usage of these individual units is what allowed for ease of further lens installments, which has been done frequently over the last few years. Housing the lenses in units also allowed for protection against friction and potential damages on the lenses and other sub-components [1].

(a)

(b)

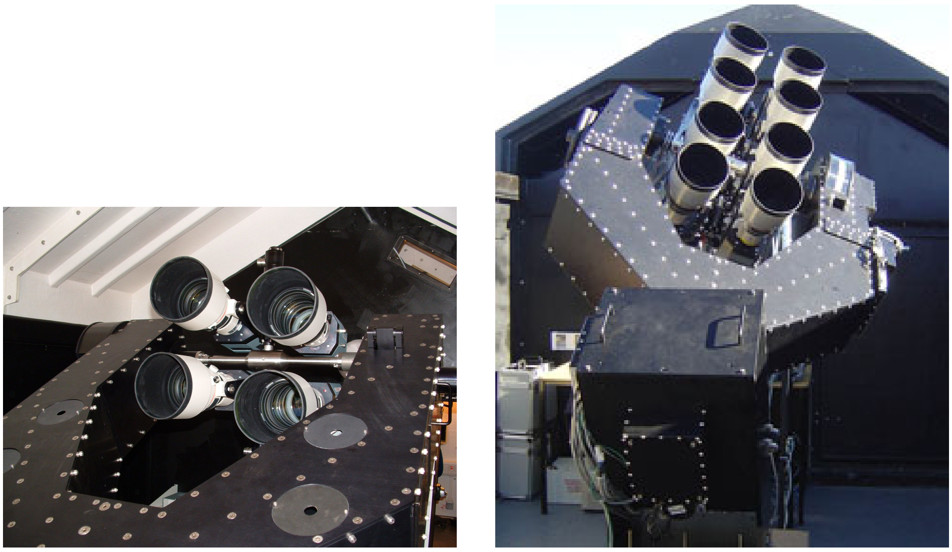
Figure 2.2: The development of the Dragonfly Telephoto Array. (a) The 10-lens configuration, attached to a dovetail plate of a Paramount ME II mount. (b) The final 24-lens configuration mounted to the Paramount Taurus 600.

2.6 The WASP Telescopes

The WASP (Wide Angle Search for Planets) Telescopes served as an influence on how to execute the design choices with the telescope matrix. The WASP was composed by the Isaac Newton Group, Instituto de Astrofísica de Canarias (IAC) and six universities from the United Kingdom. The WASP are a collection of telescopes that observe exoplanets through transit photometry on both the Northern and Southern hemisphere, respectively. There are multiple telescopes in operation, such as the SuperWASP-North and WASP-South, which consists of an array of eight Canon 200 mm f1.8 lenses backed by high quality CCDs. The Canon lenses provide a large FOV given the focal length, at about 490°.

I specifically took inspiration from the Mini-WASP telescope, a telescope at a smaller scale than at the other WASP observatories. The reason for this was in regards to the constraints of the project, specifically time-management and cost optimization. The Mini-WASP consists of an array of four fitted telescopes, with three SKY-90 scopes with M26C OSC CCDs and a Megrez 80 guide scope. In the center of the array, there are counterweights which act as stabilizers to balance the telescope according to its position, specifically on the mount. The components are fastened on a hollow rectangle with 4 cylinder cut-outs. The rectangle is mounted to a Paramount ME (bought separately). The Mini-WASP also has an Altair Astro finder eyepiece, fastened at the top of the square. In general, the components of the Mini-WASP are fairly inexpensive, while still delivering great results. One of the drawbacks of the Mini-WASP telescope is the low FOV, as the SKY-90 scopes possesses a focal length of 90 mm. It is possible to integrate different scopes with differing focal length and aperture to satisfy the telescopes application.

It is of interest to take the base design of the Mini-WASP and SuperWASP and transform its design according to the criteria of the project, as well as taking into consideration how a larger array may affect further design choices.



(a) (b)

Figure 2.3: The SuperWASP that is located in La Palma, Spain. (a) The initial array of cameras. (b) The finished telescope in operation.

2.7 Methodology of Product Development

Product development is a major priority within all designs in engineering disciplines. It involves designing and creating new products or improving existing ones. Some criteria for successful product development contains meeting customer needs, being cost-effective, utilizing sustainable materials and processes, and meeting safety and regulatory requirements. Once the requirements are defined, the design process begins, whereby engineers, designers and manufacturers work in collaboration to create a concept for the product. The concept is then refined through various prototypes and testing until a final design is selected.

In terms of product development in engineering, there are several processes involved from the preliminary phase until the end phase, e.g., conceptualization, design, prototyping, testing, and the finally manufacturing. The process starts with the identification of a certain problem or need from the customer, followed by brainstorming and concept development. The design phase refers to detailing the concept idea. For example, by creating 3D models and conducting simulations to test the products functionality and performance. Prototyping and physical testing are crucial to ensure that the certain product meets the desired specifications and requirements, as well as safety measures. After all the criteria have been fulfilled, one can finally manufacture the product the customer needs in order to be successful for the market.

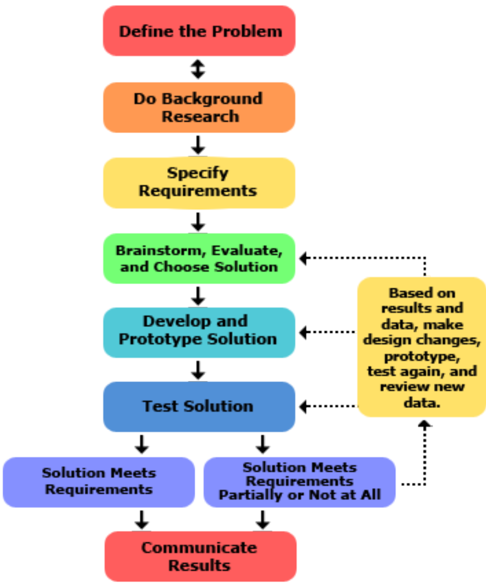


Figure 2.4: Distribution of The Engineering Design Process [21].

2.8 Optics of Telescopes

There are many possible calibrations to produce a telescope most fitting to its application. One must assess the available instruments and choose them accordingly to the observations one wishes to achieve. The mirrors, or lenses, which go under the name of the optics, are a crucial influence on what data one wishes to retrieve.

As mentioned in the previous paragraph, there are two main types of optical telescopes, refracting telescopes, which uses lenses to form images, and reflecting telescopes, which uses mirrors. There is also a third variety of optical telescopes, catadioptric, which combines both the use of mirrors and lenses. There are certain advantages in reflecting telescopes, a primary case being that optical mirrors can be much larger in size, which increases its ability to gather light, resulting in greater image quality. This is why larger observatories often utilize reflecting telescopes over refracting ones. Although in smaller scale observatories, refracting telescopes are preferable and possesses attributes that can be advantageous given the circumstances. Refracting telescopes serve as superior in regards to terrestrial observations, as they produce an upright, non-inverted image. They also require less maintenance, as they do not need much realignment (most refracting telescopes are installed with finder scopes) and are not as affected by aerosols or other particles, in which mirrors are very sensitive to this. Lenses are much less prone to degradation over time than mirrors are, giving them an upper hand in longevity. In my case, with regards to the constraints of the project, I have chosen to work with refracting telescopes.

The lenses in a refracting telescope are set in a tube, with the larger lens, called the objective lens, in the front, and the smaller lens, also called the eyepiece, located at the back of the tube. This is also where the viewer places his eye to observe a given image. When light enters through the objective lens, the lens refracts it to a focus point, which is then magnified through the eyepiece, creating an image (See Figure 2.5). This magnification will vary according to the ratio of the focal length. The focal length is then measured as the distance from the main optical element to the focal point. When the focal length increases, so does the field of view (FOV), yet the quality of the image proportionally declines. Whereas a shorter focal length also shortens the FOV, yet yields a sharper image [3].

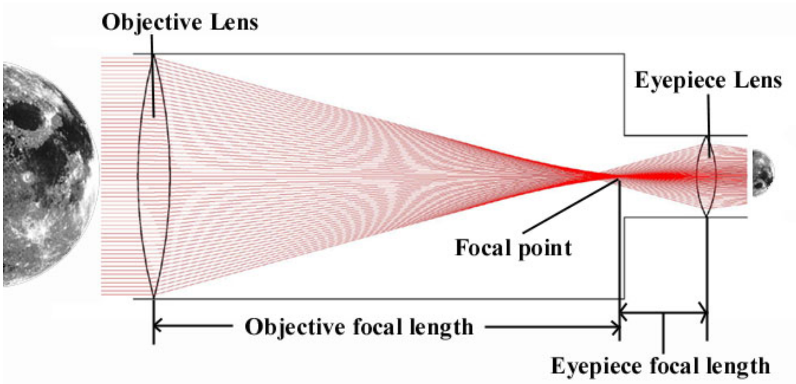


Figure 2.5: Diagram of a two-lens telescope that produces an inverted image [18].

Another component affecting the image quality is the aperture of the objective lens. Aperture is the diameter of the main neural (objective lens or primary mirror) in which light enters. The larger the aperture, the more light is able to enter, resulting in an sharper imaging. The aperture size is also directly proportional to the resolving power, which further distinguishes the details in images. Subsequently, larger apertures are higher in cost, as they have a higher performance than smaller ones.

2.9 Camera Arrays

A fairly new concept in the world of optics is the use of multiple cameras or lenses to capture imagery, also known as camera arrays. Camera arrays are generally used to capture images by using slightly different angled cameras to produce a Mosaic-like image. This concept can also be applied in astrophotography. There are numerous advantages to using multiple cameras for imagery rather than one. The main advantage is the cost efficiency. Products that are sold in large quantities are relatively cheaper than products sold in low quantities [22]. This is independent of the complexity of the product. For example, in assembling computers it has shown to be favorable and less expensive to use multiple commodity processors rather than build a custom high-end processor.

Furthermore, the usage of multiple cameras gains the ability to provide multiple viewpoints gathered into one, providing both a larger FOV as well as higher precision in imagery. A further baseline distance provides a larger FOV, though it may reduce the quality of the output. In addition, it is easy to recognize noise in defect cameras, should it occur. The cameras can be synchronized simultaneously as well as with a differing offset time, providing dynamic imagery.

There are multiple arrangements of camera arrays. The most common is parallel arrangement, where the cameras optical axes are identical to one another. This can occur both linearly (1D) or in an area array (2D). This arrangement provides many overlapping FOVs and parallaxes. Depending on baseline distance, the array can possess both a single projection center or multiple projection centers. Another common arrangement is radial arrangement, in which the cameras are formed in a circle (2D) or hemisphere (3D) [22].

2.10 Structural Stability

In designing telescopes, the mere purpose of the frame or mount (whichever is hoisting up the telescope) is to act as a ”skeleton” that can support all sub-components. The structure must be able to provide sufficient support from general usage, and additionally, maintain dimensional stability under the occasion of environmental loads. In cases where dimensional stability is not fully achieved, certain mitigations can be applied. Some of the most common mitigations are to minimize stress on the structure, ”running in” (in which the telescope is subjected to repeated movement to allow the components to enter a state of equilibrium), and lastly, to reconsider the specific modulus of the material so that one may maximize the stiffness.

Calculations can be done by hand to assume the physical restraints of the structure. It is therefore important to early establish the dimensions of the frame so that the physical abilities can be assessed and adjusted accordingly.

To assess the effect of rotation, one can calculate the moment of inertia. The formula for moment of inertia varies depending on geometry. In the case of this thesis, a hexagonal frame was designed, and therefore the moment of inertia was applied for a hexagonal structure. The moment of inertia for hexagon structure is:

$$I = \frac{0.5413H^4}{36} \tag{3}$$

To calculate the moment of inertia of a hexagon that is hollow, the I_{Inner} is subtracted from the I_{Outer}. This is equivalent to the thickness of the structure.

$$I = I_{Outer} - I_{Inner} \tag{4}$$

Due to symmetry, the moment of inertia about centroidal axis X is equal to that of centroidal axis Y.

Further, the critical buckling load is also of interest to calculate. The critical buckling loads is the minimum load in which buckling occurs within the structure. One can more accurately obtain the critical buckling load through use of simulation, which is described in the following Section (see 2.11). Yet, in some degree it is necessary to compare hand calculations with those done computationally. To obtain the critical buckling load, one can use Euler's buckling formula for a hollow column:

$$\sigma_{crit} = \frac{\pi^2 EI}{KL^2} \tag{5}$$

Where σ_{crit} is the critical buckling load, E is the modulus of elasticity of the material, I is the moment of inertia, K is the effective length factor, and L is the length of the column, in this case being the height of the frame. Dividing the critical buckling load with the applied (theoretical) load, gives the value of the stability factor. Optimally, the value of this factor should be greater than 1, as this means that the structure is stable and resists buckling. While a stability factor of less than 1 indicates that buckling will likely occur.

Calculations done by hand are used as grounds for comparison. Some calculations, such as load distribution and thermal expansion, are more accurately provided in the case of simulation rather than hand calculations. The complexity of these calculations applied to the structure also increases the chances of inaccuracy. It is possible to execute this, but in regards to the restrictions of the time frame, this activity was dropped.

2.11 Simulation & Singularity

FEA (Finite element analysis) was used to digitally simulate realistic physical circumstances and its effects. An example of this would be the appliance of forces, vibrations, temperatures, etc. These simulations are applied to physical parts and assemblies to assess structural strengths and weaknesses. FEA is beneficial as it allows one to see design flaws early on in the design process, and optimize the design before manufacturing.

The FEA is computed using advanced mathematics through computer generated PDEs (Partial Differential equations). Differential equations aid in describing the mechanics of physical phenomena. A large series of these equations are then solved. Hand equations can also be used, although this is time consuming and less reliable as these equations are difficult and non-linear. Several FEA software and programs have been popularized in the engineering field throughout the years [19].

For the analysis to take place, a mesh is made. At a fundamental level, a mesh is what splits a part into a large, yet finite amount of small pieces, that together construct the part as a whole. Each of these pieces, or elements, play an integral part in all calculations. These elements have different shapes depending on the curvature of the model. A finer mesh results in more, smaller elements, which subsequently gives higher accuracy in the analysis. Yet this also yields a demand for more calculations to take place, which takes longer time to process.

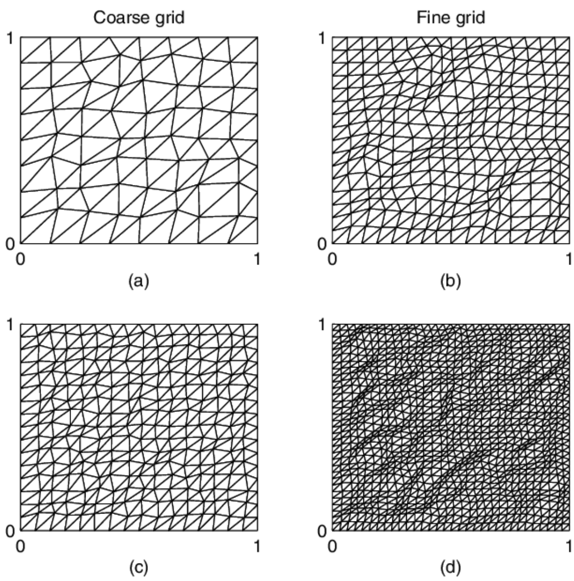


Figure 2.6: Figure demonstrating the variations of fine mesh to a coarse mesh [13].

3 Method

The method section consists of the different methodologies used to compose and prototype the telescope design.

3.1 TEnSE Method

As a guideline to fulfill each of the demands of the project, the TEnSE method was used. The TEnSE method was developed by the EFFICACY (Energy eFFiciency building and CirculAr eConomY for thermal insulating solutions) project team, specifically suggested by the advisors. The chart consists of four different aspects to consider. Certain of these aspects have a more critical impact than others, which roughly decides the decisions that are to be made. Throughout the thesis, the TEnSE method was acknowledged throughout the project to ensure satisfactory conditions and to select the optimal telescope array.

- **Technological:** Consideration of the technological aspects. Which improvements can be made to ensure a product that is highly advanced as well as simple to assemble, maintain and utilize?
- **Environmental**: Consideration of the environmental aspects. This revolves around the assessment if a project is "green" or not, for example calculating and evaluating the amount of CO_2 produced throughout the life cycle of the product and if it is feasible considering the resources that are provided from the project.
- **Social:** Consideration of the social aspects. This explains what the general purpose of the project is, whether it is for scientific findings, learning or other purposes. The social aspect defines the demand of the project, which can be singular or multiple purposes (e.g. data collection, astronomical findings, etc.).
- **Economic:** Consideration of the economic aspects. This mainly consists of reducing costs and the use of resources as much as possible, while still acquiring a product that is feasible. To an extent, it is directly affected by the technological aspect, as the development of high-performing machines requires the appropriate funds during all stages of its life cycle.

In the next secondary chapters, I will discuss each phase for the methodologies of my thesis. The phases 1 through 3 will contain a relevant TEnSE chart as an evaluation to all steps that have been taken.

3.2 Phase 0: Preliminary phase

3.2.1 Requirements & criteria

General astronomical requirements must be adhered to in pursuit of a site that is optimal. This means that many conditions must be considered before beginning construction of an observatory. In the case of Prato Piazza, this was done by completing several surveys and site testing campaigns. It was mainly the logistics that were taken into account, which were the costs of operating and maintaining the observatory. A list of parameters account for these logistics. The parameters considered for the case of Prato Piazza is described in table 3.1 below:

Astronomical criteria		
Parameter	Importance	Comment
Light pollution	5	It is of high interest to choose a location that is exposed to as little light pollution as possible, as this acts as noise against faint astronomical objects. This means that there should be little to no artificial lights such as from houses, street lights among other things.
Aerosol pollution	5	Similar to light pollution, aerosol pollution is a disturbance to astrophotography and the measuring of astronomical parameters. Higher aerosol pollution is proportional to the proximity of towns and cities, as well as terrain circumstances (e.g., desert sites, humidity since moisture can lead to unstable air).
Accessibility	3	Simultaneously, the site should not be too far out of reach. This is due to the time and cost of transporting instruments. Further, the accessibility also affects the willingness for employees to work or move in proximity to the site. There should be enough infrastructure to accommodate for the technical and soft needs of the site.
Altitude	4	Elevation allows for less impact from the lower layers of the atmosphere, which produces the most humidity and general pollution. It also distances the site from the general disturbance of cities (downstream light sources). Mountainous landscapes are therefore seen as optimal, yet there are certain compromises that must be considered with the terrain. Accessibility is directly associated with altitude, as difficulties arise in reaching the site. Additionally, higher altitudes have strong winds and frequent occurrences of weather disturbance. Logistics and construction must be adjusted accordingly.
Quality of microclimate	4	The immediate vicinities of the site play a major part in the success of the observatory. The microclimate is described as the local climate that might differ from the nearby surroundings. Examples of factors that fall under this category are the amount of clear sky nights, precipitation and other meteorological parameters. Microclimate can also refer to the local terrain and how it affects the surrounding area. An example of this is the presence of woodland and forest, affecting the vegetation and minimizing the amount of turbulent air. This is ideal for observing astronomical and meteorological conditions.

Table 3.1: Most common astronomical criteria for the placement of observatories

All of the requirements were set within the framework of the ANATOLIA project. There were few direct technical requirements set, except for a low-cost budget and the application of astronomical or meteorological observation. This allowed for some degree of creative freedom. At the same time, there were certain criteria to adhere to. The criteria for the instrumentation of the telescopes were as follows:

- Evaluate number and size of telescope array (e.g., 3x3 of 40cm or 4x4 of 30cm).
- Perform research on existing models, considering costs, detection outcomes, and maintenance requirements.
- Evaluate possible configurations of the matrix: square, pentagon, hexagon, et cetera.

In addition to the ANATOLIA project requirement, general criteria were listed for each TEnSE aspect. These criteria were set in background of common constraints from previous telescope development projects (such as the Dragonfly telescope mentioned in Section 2.5).

Technical:

- Criteria 1: The design has low complexity and is simple to manufacture and assemble.
- Criteria 2: The design allows for a light weight finish.
- Criteria 3: The design has a desired FOV (4" most common).
- Criteria 4: The design is symmetric and therefore stable when in use.
- Criteria 5: The design is relatively easy to install and assemble.
- Criteria 6: The design needs low maintenance.

Environmental:

- Criteria 7: The design is moderately wind resistant (Beaufort scale 8).
- Criteria 8: The design is environmentally feasible to manufacture.
- Criteria 9: The design possesses ease of assembly and is therefore easy to transport.
- Criteria 10: The design yields little or no disturbance to the surrounding environment.

Social:

- Criteria 11: The design fulfills its technical purpose.
- Criteria 12: The design is seen as useful and economical by the general public.

- Criteria 13: The design aligns with the UNESCO standards.
- Criteria 14: The design is able to gather relevant data and information.

Economic:

- Criteria 15: The design is as low-cost as possible.
- Criteria 16: The design allows for multi-use (installment of different telescope lenses, measuring of different parameters, etc.).
- Criteria 17: The design has a high longevity (LCA).
- Criteria 18: The design is simple to reproduce.

3.2.2 Software

Certain digital tools were used in the project. This mainly consisted of designing CAD models, as well as mechanical drawings and analysis in SolidWorks. There was previous experience established in the program, and it allowed for more complex designs and simulations compared to for example Autodesk Fusion 360. SolidWorks Simulation, an add-in in Solidworks, allowed for the Finite Element Analysis (FEA) of the framework and other components.

Otherwise, Google Sheets and Microsoft PowerPoint, as well as Overleaf were used to lay out the Gantt-diagram as well as the bachelor presentation, respectively.

3.2.3 Research Study on available documents

Several documents and information were provided by the supervisors. I was acquainted with the development of previous observational sites, specifically the Astrophysical Observatory of Asiago was studied, as well as the Izaña Atmospheric Observatory in Spain and the National Astronomical Observatory in California, USA. The sites were studied in regards to climate, terrain and protocol according to weather conditions (e.g. wind, rainfall, and cloud cover).

3.3 Phase 1: Design Phase

The design phase would be initiated by doing research on previous telescope construction to familiarize oneself with the typical constraints to consider in design choices. Subsequently, concept drawings would be made and presented to the supervisors for advice and further adjustments. Lastly other factors such as material, thickness and suitable components would be evaluated during this phase.

There was an initial agreement to develop a design for a refracting telescope rather than a reflecting telescope. With mirrors as the main component, a reflector would likely over-complicate a telescope array, as well as exceed the budget scope. Second, it was a priority to keep the design simple and at a small scale, seeing as the complexity could come as a challenge for integration of sensors and other components. Existing reflecting telescopes configurations could be used as grounds for inspiration, yet there would be no integration of the use of such telescopes.

3.3.1 Frame Structures

A few different sketches were modeled. The designs were initially simple, but would be further built upon once decided on the final geometry. There were certain benefits and drawbacks recognized for each design. The final decision weighed heavily on the informed opinion of the supervisors, who pointed out which concept would align best with the requirements of the site. Each concept was also analyzed through the TEnSE method, mainly considering the aspects of technological and economic benefits, as social purpose was established early on, and the environmental aspect would be looked at at a later point. Additionally, all designs were modeled in CAD and simple static simulations were executed. The chosen design was also based on research conducted of previous telescopes, in which one could observe a pattern in the geometry of choice.

3.3.2 Final Geometry

From research done in the preliminary phase, there was a noticeable pattern of use of hexagonal shapes in telescopes, in both refractors and reflectors. There are several reasons for choosing a hexagon shape. Mainly it is the symmetry across all sides, which means that the weight distribution is equal on all sides. The triangular geometry distributes the load evenly, which reduces flexure and strengthens the rigidity. Another attribute in designing a hexagon frame, is that it has less perimeter, which results in less material and therefore a frame that is lightweight, while still maintaining that the geometry is considerably strong to withstand wind and vibrations. The frame shape also allows for more space for all elements of assembly, compared to other designs. Lastly, the geometry provides a wider FOV and aperture efficiency, with the "Mosaic" composition of the lenses allowing for a larger aperture area. This is because the large width catches light from a wider area of the sky. The increase in aperture area also means that more light is collected, and results in better resolution for astrophotography.

The frame design was further encouraged by the supervisors, and dimensions were suggested to fully house needed telescopes. The diameter of the hexagon would be 3 meters, housing six telescopes in each vertex, as well as one in the center. Ideally, the telescope in the center would act as a guide scope. Each telescope would be approximately 40cm.

To fit and position each telescope in the array, a telescope holder was designed. The telescope holder possessed the same hexagonal shape as the frame, as it would be easier to manufacture and fit according to the same geometry as the frame itself (vertices aligning up with vertices). The telescope holders would be slightly larger in diameter than the telescopes, approximately 60cm, giving wiggle room for potentially larger telescopes to be fitted. The telescope holder has three Ø M10 screws on each end, allowing for the screws of two scope rings to be fitted inside. The telescope holders would be attached by using ring harnesses.

3.3.3 Material of Choice

The SuperWASP, as well as the Dragonfly Telescope, uses a black anodized aluminum alloy [1]. This gave a baseline for which material to consider. Aluminum alloys are used due to their superior strength-to-weight ratio. The aluminum is anodized as a coating to protect the aluminum, further strengthening the material. The anodization gives the material additional corrosion resistance, while preserving the structure of the aluminum underneath. Furthermore, it is affordable to manufacture, reflecting in the price points for consumers [17].

The properties of anodized aluminum alloy was evaluated through the technical aspect of the TEnSE method, from the criteria listed in the preliminary section. The same goes for the general astronomical usage criteria.

T6 6061 aluminum is the equivalent of the aluminum used in the previously mentioned telescope frames, and was applied as material in CAD and FEA. Beforehand, each property of the T6 6061 aluminum was evaluated through comparison with the average metal, as well as the importance of the property it serves. For example, the recyclability of aluminum is among the highest of all metals and that serves the technical benefit of ease of deconstruction and replacement of the frame [10]. The properties are fully listed and evaluated below.

Where the minimum 1 is considered lowest and least feasible while 3 is maximum and most feasible.

Another material considered was carbon fiber, although after some consideration it was dropped. Carbon fiber possesses high durability, while being considerably more lightweight than aluminum. This allows for higher ease of portability. Regardless, carbon fiber was not used due to its high cost, costing $20 to $30 per kilogram, while the price for aluminum is approximately $2 per kilogram. Additionally, carbon fiber has a lack of cold resistance, potentially being affected by the climate that might occur in the mountainous terrain.

3.4 Phase 2: Test Phase

The test phase was executed in order to assess the strengths and weaknesses of the structure in practice. The tests were simulated to act as realistic events that would likely occur in real life events.

Weights			
Parameters (Aluminum 6061)	Value	Technical	Astronomical usage
Strength:			
Tensile strength	290 MPa	1	1
Yield strength	241 MPa	2	2
Durability:			
Elongation (%)	17%	3	3
Young's modulus	68.9 GPa	2	2
Poisson's ratio	0.33	2	2
Fracture toughness (K_{ic})	29 MPa$\sqrt{m}$	1	1
Sustainability:			
Emissions (kg) per kg	2 kg	2	1
Recyclability (%)	95-98%	3	3
Other:			
Corrosion resistance	Medium high	3	2
Density	2.70 g/cm^3	3	3
Total	N/A		

Table 3.2: Properties & evaluation of T6 6061 Aluminum

3.4.1 Toolbox Error

As SolidWorks was used, the toolbox was necessary in order to produce the fasteners. The license was issued from the university, and opened in ProgramFarm, the University's local program site. Using the toolbox, I encountered an issue in retrieving the screws. The issue required local IT-guidance, which was further communicated to the administrators of the IT department. As the problem could not be resolved before the middle of June, which is past the due date of the thesis, the fasteners were modeled by hand. This could result in a few affects on the simulations. The main possible issue would be the tolerances affecting the simulations. If the tolerances were too small, the forces applied would produce greater stress on the screws, thus resulting in fatigue or other problems. On the other hand, if the tolerances were too big, the screws would lose the ability to hold the components in place. This is especially crucial for the screws containing the brackets, which contain the telescope holders. The screws would then not be able to provide the support needed to contain their appropriate force.

3.4.2 FEM Analysis

A structural-, buckling- and vibrational- (as well as CFD airflow) analysis was executed on the main frame, as well as the full assembly with all sub-components mated through the use of M16 fasteners. Should deformation or high stress points have occurred, the constraints have been iterated to accommodate the stress points.

Buckling analysis: There was an interest in looking at buckling to assess the maximum stress the telescope array would tolerate without resulting in deformation. The results of the analysis plots out the points of the structure where the highest danger of buckling and deformation occur, as well as the relative resultant vibrational amplitude (AMPRES in SolidWorks).

Static analysis: Similar to buckling, static analysis was executed in order to assess the location and effect of the maximum stresses as well as the location and values of the displacement and strain. A force equivalent to the weight of the telescope lenses plus camera was applied to the lower plate of the telescope holder. The telescope holders were fixed at the location of the brackets.

Frequency analysis: To evaluate the structure's resistance to ground-based inertia, natural frequency and vibrational tolerances were studied. Same as for buckling analysis, the result of the study measures in the local SolidWorks unit of AMPRES [20].

3.4.3 CFD & Airflow Analysis

A CFD analysis was simulated using the Flow simulation add-in in SolidWorks. Another option would have been using a more suited program such as OpenFOAM or Autodesk, as these software are generally better suited for CFD. Yet, this was moved away from, as the familiarity with SolidWorks allowed for an effective analysis. Additionally, the files were already in the cloud of the program, whereas transport of the files to another software would have resulted in errors with the assembly or fasteners.

The analysis was done for a Beaufort scale of 7 (61 km/h), 10 (102 km/h) and 12 (118 km/h), respectively. It was optimal for the framework to be able to withstand weather circumstances equivalent to a Beaufort scale of at least 7. As this scale of weather conditions has the tendency to occur in the environment of Prato Piazza. For the analysis, parameters were set beforehand. First, the framework itself would stand still and only be affected by two variables: gravity and simulated wind velocity. Second, air was used as flow material. In a real life scenario, this was nominal if precipitation was equal to zero. Yet if there was precipitation and rain water was contributing to flow, then this was not considered for the simulation and could cause potential stress. Rainwater was overlooked, the reason being the lack of options in flow medium alternatives. Third, the boundaries were set with no internal flow, as the aluminum bars would not be hollow or have any medium flowing through them internally - only external flow would occur. The direction of the flow was towards the front of the frame, the air directly hitting the telescope lenses. This angle of attack was most realistic and of upmost interest. Additional wind forces could be applied if needed.

3.4.4 Further Testing

Due to time and resource restrictions, further sophisticated testing could not take place. Nevertheless, in case of further development, both theoretical and physical testing could provide sufficient data. For example, investigating thermal characteristics, such as thermal expansion and thermal stability would provide insight to the need of minimizing thermal distortions that might occur. In the future, it would also be interesting to take additional environmental parameters into account, such as disturbances like dust and high humidity.

A prototype would allow for an integration test, in which the sub-components would be fitted and checked for stability and fitting. Realistically, I realized what is most optimal is the physical testing, which can provide direct data.

3.5 Phase 3: Validation Phase

The validation phase would take the results from the design and test phase to further evaluate for future developments. Results from hand calculations and simulated results would also be compared. Finally, a life cycle assessment (LCA) was done as an initiative to look at the practicality of the frame and compared to the current market. See the Results section for these assessments.

4 Results & Discussion

4.1 Phase 1 Results: Design Phase

4.1.1 Rejected Designs

- **Quadratic frame:** The quadratic frame was relatively small and simple. There were two plates acting as front and back plate. These plates were hollowed with 4 holes of 120 mm diameter to house three 90 mm diameter Sky 90 telescopes for imaging and one Megrez 80 mm acting as a guide scope. Scope rings would be inserted into each hole to fasten the telescopes. The frame would be attached to the mount using a dovetail on the bottom of the frame. Considering that the telescopes weight 2.8 kgs each, a counterweight was installed on the front plate.

  The drawbacks for this type of frame would primarily be the lack of complexity in such a small array and would therefore produce lackluster imagery. It would be feasible to have a larger array, as buying in bulk would prove to be less costly proportionally to the increasing performance. This is the main reason for moving away from this design.

  A simple structural analysis further proved the inability for the frame to hold the telescopes, as the weight of each telescope would prove to heavy. The analysis resulted in deformation. This could have been avoided by thickening the aluminum sheets and increasing the size of the front and back plate, although it would achieve a design that was too large and heavy in comparison to its performance.

- **Rectangular frame:** The rectangular frame was considerably larger than the quadratic, as well as housing a larger array of 2 x 5. Several bars were implemented in the center to combat buckling. The aluminum sheets had a thickness of 25 mm. It immediately distinguished itself from the quadratic frame, as the rectangular frame would possess a larger FOV as well as giving improved image quality. Simultaneously, the non-uniform shape would result in difficulty rotating the frame around its axis. As the supervisors preferred a geometry of ease of mobility, this design was rejected.

The designs were evaluated through the use of the TEnSE chart method. The different parameters of each design was extracted and then assessed further. The chart measures the advantages of each design. The score for each criteria ranges from 1 to 3, where 1 is the lowest score, meaning that the design criteria ranks as least optimal, while 3 is the highest score, meaning that it ranks as most optimal. The higher the total score, the more feasible the design is. Below certain criteria are listed in each respective field of the TEnSE chart, as well as general astronomical criteria. In Section 3.2.1, one can find the listed criteria mentioned in the chart 4.1 below. For this table, the designs were ranked directly based on feedback from the advisors as well as through general research on optimal telescope geometry.

Criteria	Technical					
	C1	C2	C3	C4	C5	C6
Quadratic	3	3	1	3	3	3
Rectangular	3	2	2	2	3	3
Hexagonal	2	1	3	3	3	

(a)

Criteria	Environmental			
	C7	C8	C9	C10
Quadratic	1	3	3	3
Rectangular	2	1	3	3
Hexagonal	2	2	3	3

(b)

Criteria	Social			
	C11	C12	C13	C14
Quadratic	2	N/A	3	2
Rectangular	2	N/A	3	2
Hexagonal	3	N/A	2	3

(c)

Criteria	Economic			
	C15	C16	C17	C18
Quadratic	3	2	2	3
Rectangular	3	2	2	3
Hexagonal	3	3	3	3

(d)

Table 4.1: TEnSE Based on design features.

4.1.2 Design Results

A final frame was evaluated and has been proposed as an optimal telescope array considering the price points for construction, maintenance and performance. The geometry of the frame is proven as more complex, but outperforms other arrangements in comparison. The complexity also offers ingenuity and an original arrangement that can be further improved upon.

The adjustment of the scope rings on the telescope holders offer a range of different telescopes that can be integrated, not only the suggested Sky 90 scopes and Megrez scope. Should one or multiple telescopes need to be replaced or removed, the array would still be able to function and operate, although not necessarily at maximum capacity.

4.1.3 Weight & Weight Optimization

The weight of the components were estimated by SolidWorks when the material was applied. All non-COTS components had 6061 T6 Aluminum applied, except for the fasteners, in which case stainless steel was applied. The weight of each component was the following:

Main hexagonal frame: 936 kg

Telescope holder: 112 kg

Scope ring: 6.26 kg

Harness fastener: 6.88 kg

Angled harness fastener: 4.20 kg

Fasteners (M16 x 0.278): 0.278 kg

For further testing there is the necessity of looking at more sophisticated simulations as well as

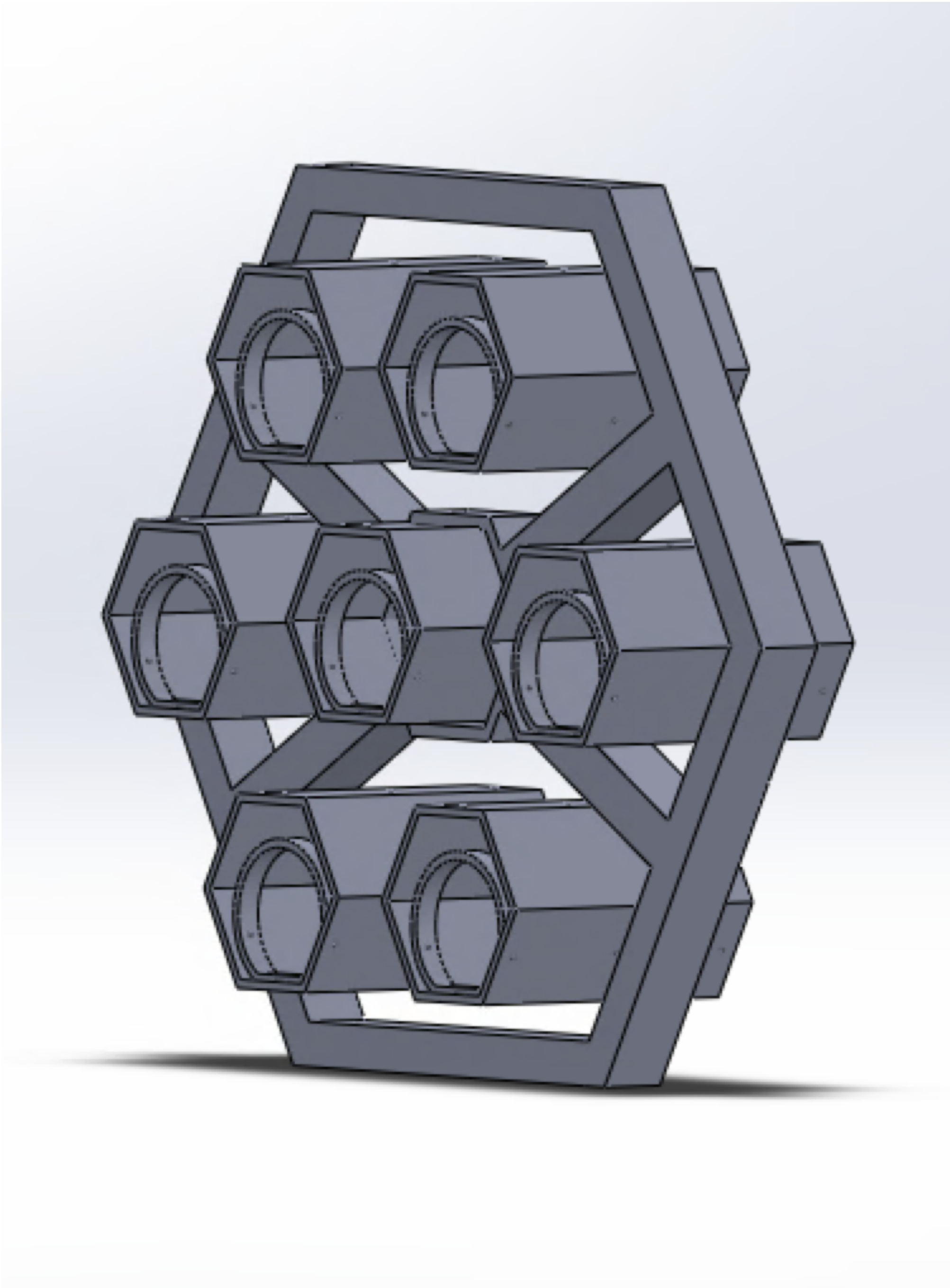


Figure 4.1: The hexagonal frame with telescope holders installed.

physical testing to be executed.

4.1.4 Assessment of Stability issues

The main goal of assessing kinematics and stability is to have a body (or multiple bodies) that is of maximum dynamic and static performance. In order to do this, one must minimize mass as much as possible while the body maintains a low CoG (center of gravity). Not only the static reference, but also the effect of wind disturbance and thermal inertia is determined by the kinematics of the structure.

While the implementation of the motorized frame would provide further insight into the kinematics, this was too advanced to execute considering the time frame and resources available, as well as the expertise of a single student. In the future, it would be of interest to further assess the motorization of the frame, and calculate the kinematics of action while looking at the physical rotation of the telescope array.

4.2 Product Results

4.2.1 List of Suggested Components

Mount It was ideal for the frame to be able to rotate fully across all axes (yaw, pitch, roll). A necessary step was to consider the mounting of the frame and how it would be able to rotate.

The mounting system from the Large Synoptic Survey Telescope (LSST) was considered. The mount was optimized to be low mass (approximately 230 tons) and have minimal inertia, while giving high performance at low-cost. Additionally, the bearings were kinematic and did not require further components to aid in flexibility. The frame would take the position of the primary mirror and be mounted by attaching the bars to each corner of the hexagon. The mount allowed for the telescope array to rotate in a pitch motion. But through further evaluation, the mount was rendered too complex, as the steel bars would have had to be attached to each corner and support the weight of the frame as well as all components. The steel bars would have to be considerably thicker to withstand the weight of the frame [11].

A rotational device was proposed by the supervisors as suitable and more simple. A long bar, approximately 5 meters, would be inserted through the center of the hexagon, with one supporting column on each side. Meaning that the frame is hanging freely, supported by the columns. The rotational device would then be attached to a dovetail plate to a mount.

I came to the conclusion that the Paramount Taurus mount used for the Dragonfly telescope had these features that were sought after. The rotational device was therefore not needed. The frame would be directly attached to the mount and no buffer component would be needed.

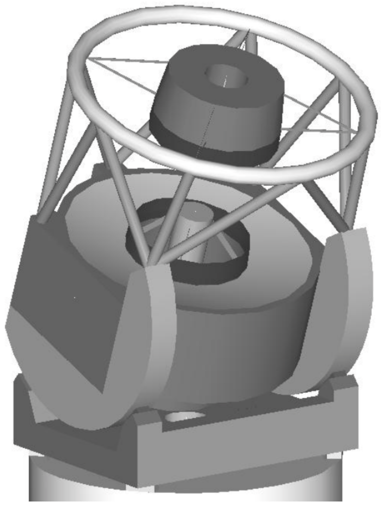


Figure 4.2: Basic structure of the LSST mount [11].

Figure 4.3: The Paramount Taurus 400 [4].

Telescope holders There were seven telescope holders for each telescope. The holders can be made fairly cheap from a manufacturing company, as aluminum is a material that is simple to shape. The holders would take a hexagonal shape as the vertices would align with the frame geometry. Commercially made telescope holders are also available on the market, yet they must be fitted for the appropriate size of the lens and camera. With the custom holders, it would be possible to extract the refractors and replace them with small reflectors, although one must consider the weight and consequences of this. A suggestion for installment of potential reflectors are the Meade 16 inch Optical Tube Assembly. The Meade Optical Tube has a high focal length at 3251 mm, and a large FOV given the aperture of f/8.

Telescope Lenses The size of the telescopes is crucial to the performance of the telescope, as the image quality is proportional to the aperture. Nevertheless, the circumstances of seeing on Earth prevents from seeing more than 4"-5" detail in aperture on most nights. Therefore, the Takahashi Sky-90, which has an aperture of 4", is ideal for this purpose [16].

The main telescopes (excluding the guide scope) would be the Takahashi Sky-90 scopes.

Cameras The Canon EF 200MM f/2.8 L USM was chosen for several reasons. It is made specifically for astrophotography. It is used in the MiniWASP configuration and provides great imagery for its size and ease of portability. This is largely due to the wide f/2.8 aperture, which allows significant amounts of light into the lens. The large aperture also allows for a reduced exposure time. The focal length provides the ability to capture distant celestial objects and enhance the visual impact.

Dome A commercial dome would be optimal in consideration of the labor to locally manufacture one. Pulsar Observatories Ltd. produces commercial domes that are secure and provide great weather protection. The company also manufactures custom sized domes, which allows for the request of a 6 meter wide dome. The price points at Pulsar Observatories stand relatively low, a standard dome on their website costing around USD $6000.

Control Computer The control computer is considered the "brain" of the entirety of the telescope system. It manages all sub-components through the commands that are received, such as movement or focus control. This is done by having all major sub-components (camera, lens controller, lenses, etc.) connected to the control computer through an Ethernet connection. The control computer additionally presents relevant data acquired from the telescope by converting the raw data (such as digital signals representing different measurements) into calibrated, functional data.

In terms of choosing a fitting control computer, the restrictions are fairly loose. The computer needs to be able to establish an Ethernet connection or through Internet of Things (IoT). The control computer should possess enough processing power to handle computational demands. Additionally, there should be enough memory capacity to store necessary data.

USB Intel Compute Stick Each lens-camera system would be equipped with an Intel compute stick to access the local network of the control computer. The compute sticks essentially act as miniature computers which control its individual sub-system. This implies that should one of the telescopes fail to operate, it will not effect the rest of the system.

Megrez 80 Guide Scope For its price point, the Megrez 80 serves as a great guide scope. This was used in the MiniWASP telescope configuration. It is light in weight, compact and easy to assemble. While it has a short focal length, it makes up for it in a wide FOV. In case the Megrez 80 is not optimal on its own, it is possible to pair it with an auto CCD guider for a wider FOV and possibly shorter exposure time.

The short focal length seems to be the primary drawback for the guide scope. Otherwise, the wide field views are sharp across all edges and possesses little false colorations as some scopes have the tendency to produce.

Counterweights Counterweights are not necessarily a component that have to be implemented, but it would likely be necessary should the weight accumulate to a point that it needs a counterweight shaft to be equalized. However, due to the symmetry and general geometry of the frame, this would likely not pose as a problem.

4.2.2 Overview of Hardware Components

Components		
Part	Category	Description
Takahashi Sky-90	Optics	Main telescopes
Canon EF 200mm f/2.8 L USM	Optics	Camera
Canon EF Lens Controller	Optics	Lens Controller
Megrez 80 Guide scope	Optics	Guide Scope
Starlight Xpress Lodestar X2 Autoguider	Optics	Guide Camera
Intel Compute stick	Converter	Compute stick connected to the camera, turning the camera into a smart device
Commercial Dome with 6 meter diameter	Dome	Standard or custom commercial dome
Paramount Taurus 400 Mount	Mount	Mount

Table 4.2: All suggested components

4.3 Phase 2 Results: Test Phase

There were several issues encountered in ensuring the validity of the testing, due to the many issues with the software utilized.

4.3.1 Results of FEA

The results of the simulations were somewhat incoherent. The quadratic frame had issues with being implemented into the simulation add-in. Seeing as it was constructed into an assembly (a file of multiple parts conjoined together), there was the issue of loading the file. This resulted in no simulation being conducted on the frame.

For the rectangular frame, a static analysis showed significant deformation occurred when a total force of 900 N was loaded vertically. This meant that the beams had to be thickened significantly in order to withhold the weight of the telescopes and sub-components. The buckling further showed that the resultant amplitude was too high, with a safety factor of 17, which was non-optimal. The vibrational analysis showed some deformation, though less than expected. At a value of circa 481 Hz was when the deformation scale was highest. This concept needed to be redesigned and re-simulagted before further testing could take place.

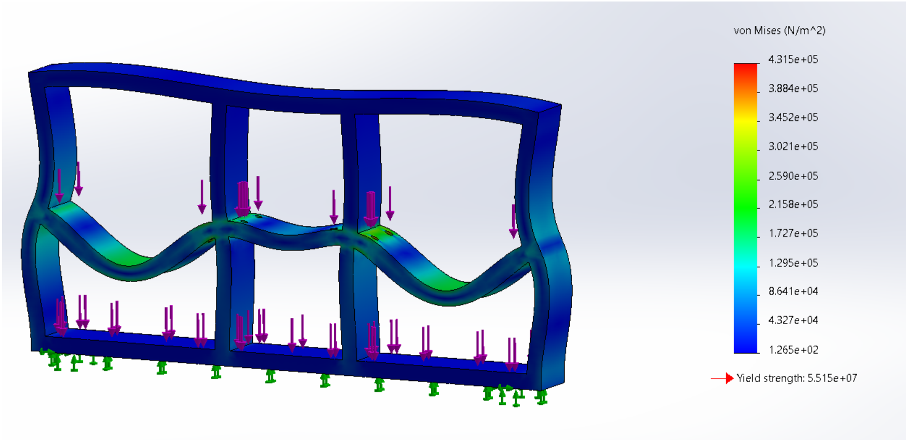
The hexagonal frame showed less deformation than the rectangular, though the stresses were still considerably high. To avoid flexure, there had to be added support through either a additional bars or a thickened base width.

The vibrational analysis showed more deformation and uncertainty. With a frequency higher than 42 Hz, significant deformation would occur.

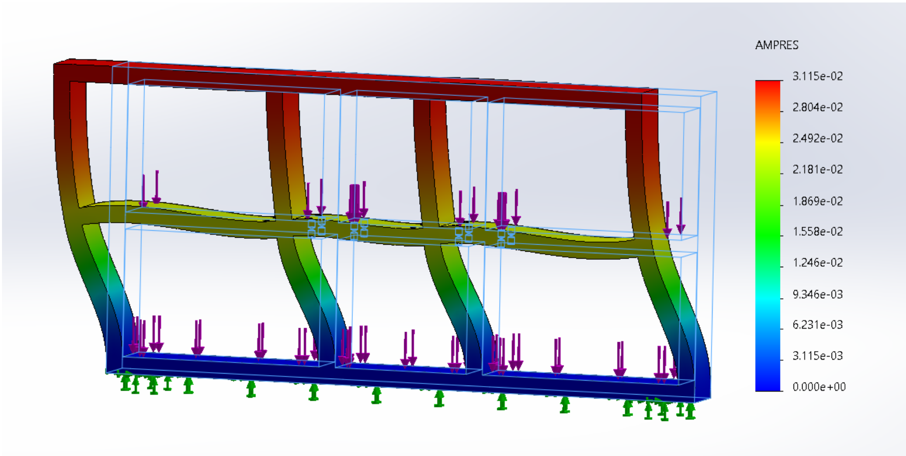
4.3.2 Results of CFD & Airflow Analysis

The CFD was only conducted on the hexagonal frame.

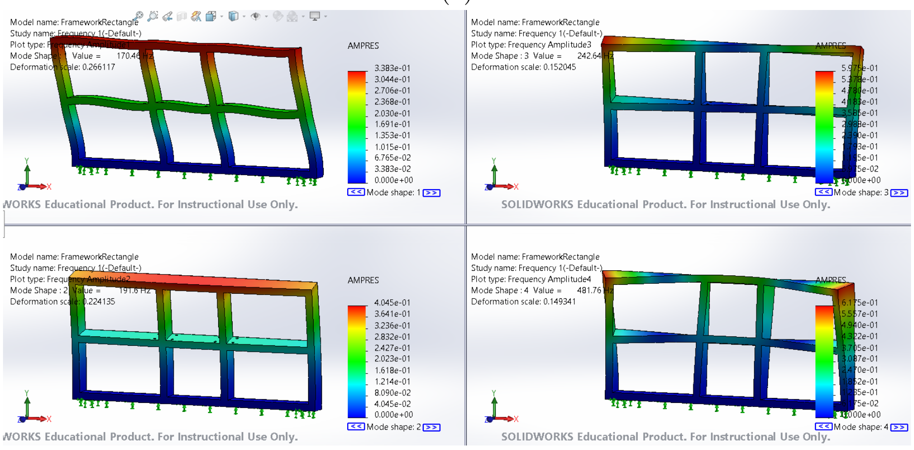
The results of the study chiefly aligned with what was estimated. Therefore, there was the notion that multiple executions were not absolutely necessary. The flow lines revealed that some stress would occur on the front of the frame, although this was not a concerning amount. This was likely due to the hollow geometry of the frame allowing for wind to pass through. The results presented as optimal, except for the wind of Beaufort scale 12, which had a relative high reduction in wind flow. The general consensus was that normal wind conditions would be tolerable for the framework and its possible sub-components.



(a)

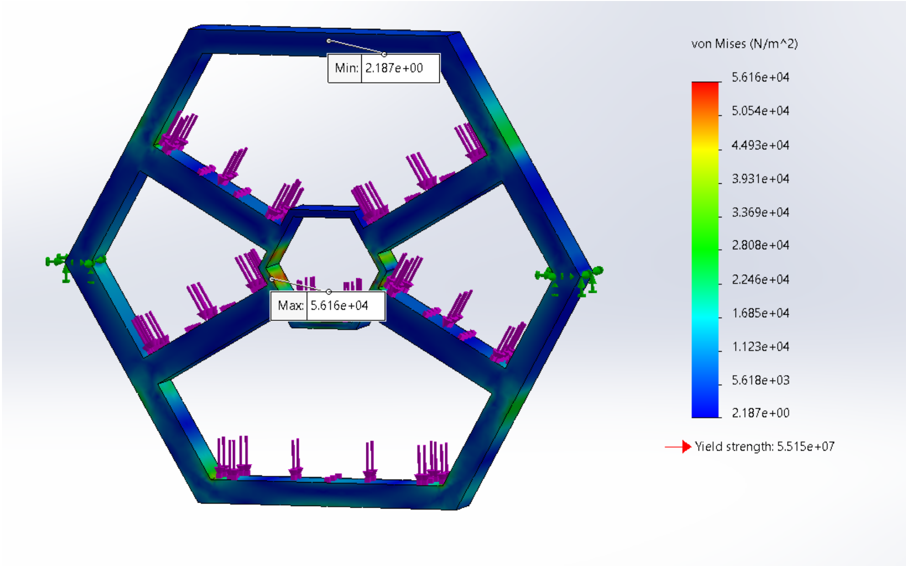


(b)

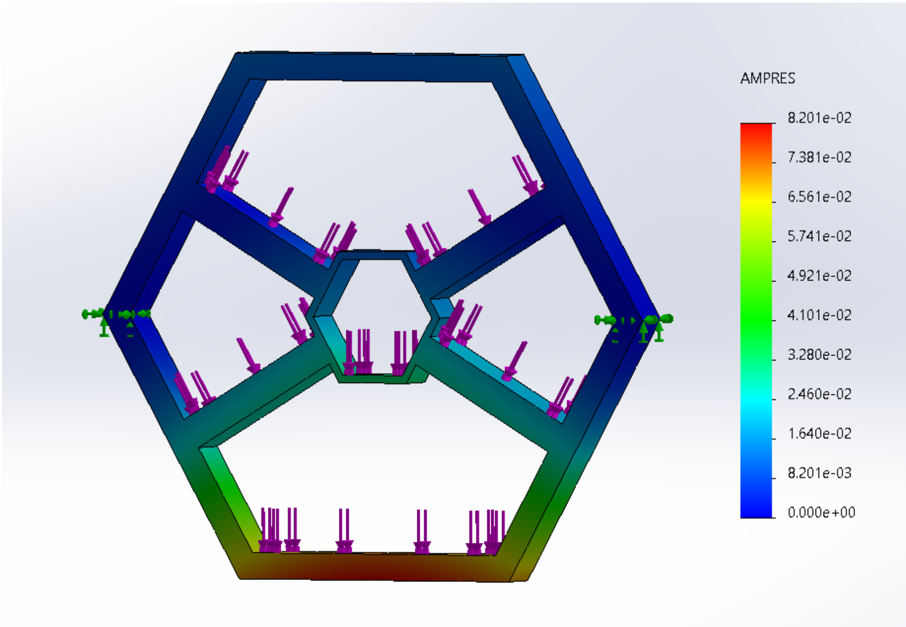


(c)

Figure 4.4: The results of each simulation conducted on the rectangular telescope frame. (a) The static simulation showing stress occurrence. (b) Showing the buckling and resultant deformation. (c) Showing 4 modules of differing frequencies.



(a)



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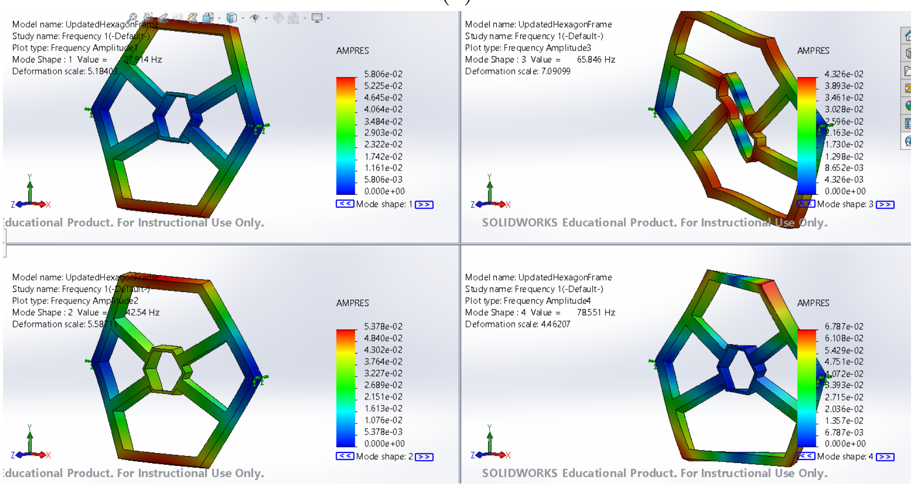
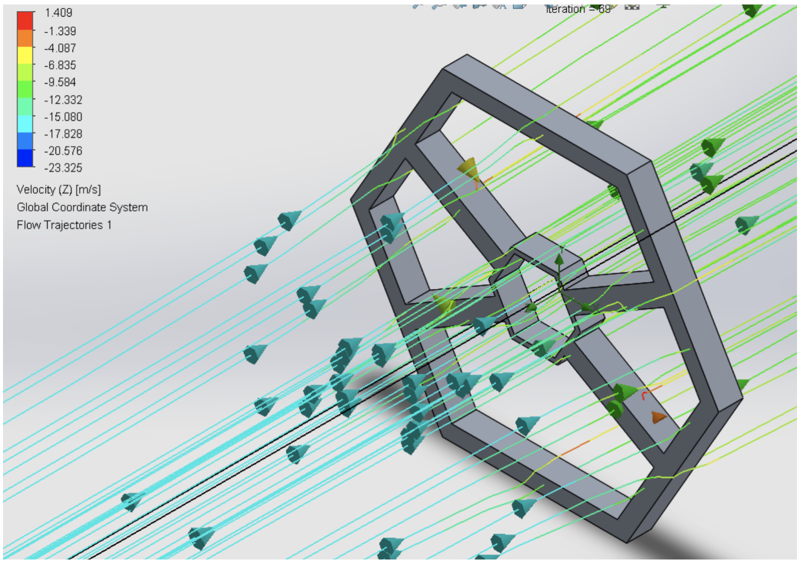
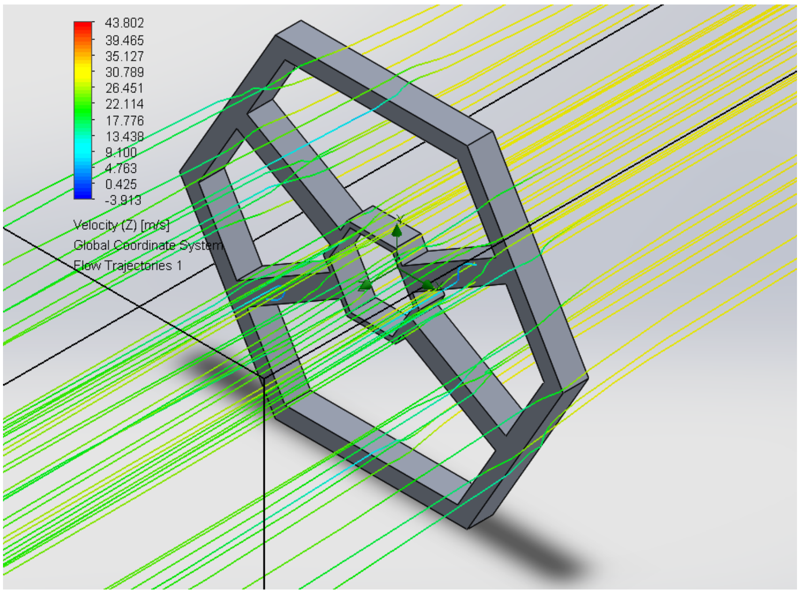


(c)

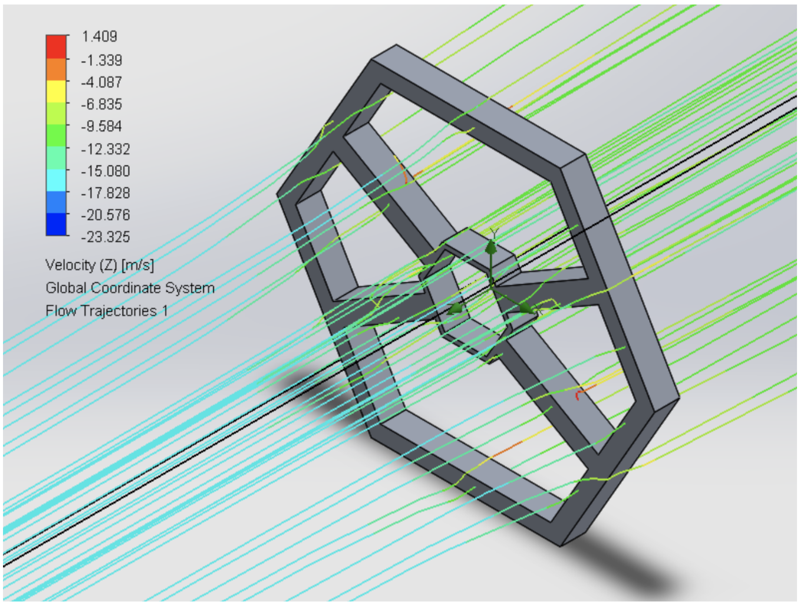
Figure 4.5: The results of each simulation conducted on the hexagon telescope frame. (a) The static simulation showing stress occurrence. (b) Showing the buckling. (c) Showing 4 modules of differing frequencies.



(a)



(b)



(c)

Figure 4.6: The results of each CFD analysis through the front of the frame. (a) Results with a Beaufort scale of 7. (b) Results with a Beaufort scale of 10. (c) Results with a Beaufort scale of 12.

4.4 Phase 3 Results: Validation Phase

4.4.1 Theoretical calculations compared to simulation results

With the dimensions of the frame being established, it was possible to assess the calculations from section 2.10 and compare them with the results from the simulations.

The frame amounted to having a moment of inertia equal to $0.9424m^4$, which meant that the critical buckling load, assuming that K was 0.70 (due to all columns being conjoined; fixed), was equal to 2852.34 N. The value seemed logical compared to the dimensions given, and could be seen as more advantageous than that of the simulation that was executed.

4.4.2 Maintenance

While many maintenance routines are self-evident and instantly implemented, certain procedures are identified while the product is in operation. This is easily the case of this telescope array.

The main procedure to preserve the telescope array is the re-coating and rinse of the anodized aluminum. Though in the case of anodization of aluminum, it is highly durable. The hardness of the coating is second to that of diamonds, due to the strong molecular bond between the anodic layer and aluminum. The anodization is therefore highly resistant to tendencies of flaking, chipping, and peeling. The main procedure of maintenance is an annual wash and rinse with a suitable detergent. In order to access all the sub-parts and thoroughly re-coat them, the telescope array must be fully disassembled.

4.4.3 LCA

An assessment on the life cycle (LCA) was necessary to measure the environmental impact of the telescope. In LCA, a Cradle-to-Grave model demonstrates the systematic procedures of a product, from the raw extraction of the materials to its end of life. Figure 4.7 shows each building stage, respectively. For the sake of simplicity and relevance of the thesis, only the stages from A1 (raw material extraction) to A5 (construction-installation process) were assessed with further consideration. For future usage, it would be reasonable to expand the scope in regards to the general scale of the project.

Step 1: Goal and scope definition

The first step was to define the purpose and goal of the LCA. There is the possibility to delve deep into the aspects of environmental impact of each stage. The field of interest in the case for this thesis was to estimate the CO_2 emitted from each stage (A1-A5) and subsequently suggest measures to reduce these emissions. As the project was in such small scale, it would be necessary

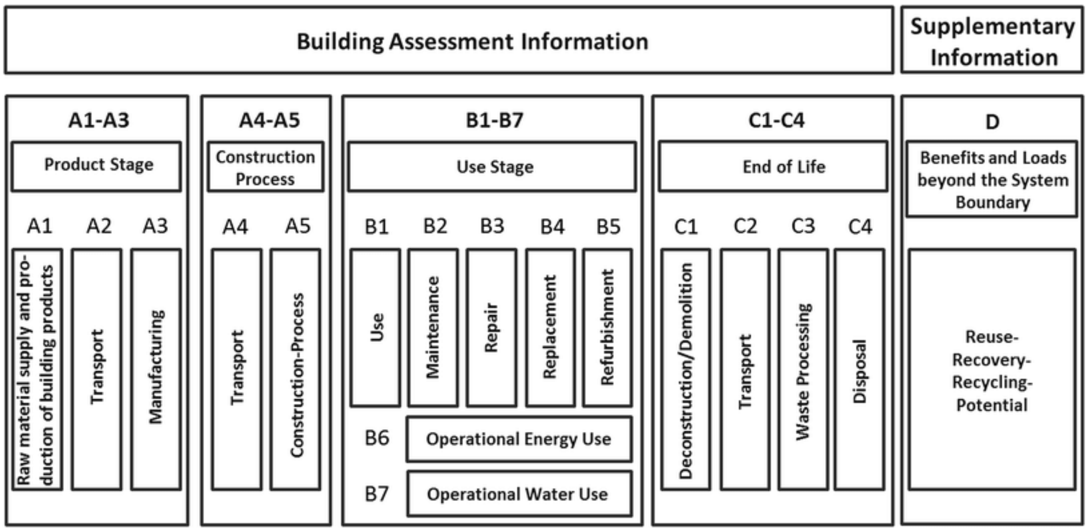


Figure 4.7: Overview of LCA stages [2].

to analyze the simplest factors for emission as to give a general estimate.

Step 2: Inventory analysis of extractions and emissions (LCI)

Once the goals and scope were defined, they were applied to each stage.

A1 (Material extraction): As mentioned in the method section (mention specific page), the emission rate of kilograms CO_2 per kilogram of aluminum is equal to 2. With the weight of the components considered, this would roughly amass to a total weight of 1 ton, which means the material extraction would emit around 2 ton CO_2. The material extraction alone contributes to high emissions. This has an effect on the later stages of the Cradle-to-Grave chart, which can be evaluated further. The main cause for these emissions is the size of the frame, as the size calls for an increase in material in order to achieve a nominal level of stability.

A2 (Transport of material): Transport is a component for two of the Cradle-to-Grave stages; namely product stage and construction stage. This makes the transportation even more crucial to assess. The factors that play into the amount of emissions from transport are primarily the amount of vehicles and their respective emission, as well as the distance of transportation covered.

Assuming that raw material is processed locally, the transport distance would likely not exceed 200 km. Estimating from [14] that the emission factor stands at 0.1 kg CO_2, it is then possible to calculate the CO_2 produced from transporting the raw material.

Calculating the ton-kilometers:

1 ton $\times 200 kilometers = 200 ton - km$

This results in CO_2 emissions equal to:

0.1 kg CO_2/ton-km $\times 200 ton - km = 20 kg\text{CO}_2$

Transporting the raw material produces an estimated 20 kg of CO_2.

A3 (Manufacturing): The manufacturing sector accounts for about a third of greenhouse gas emissions, due to the burning of fossil fuels as an energy source for production. Aluminum, the main material for the frame, has a large market for manufacturing, making up circa 2% of all gas emissions on the global scale [9]. Considering that the geometry of the frame is fairly simply and non-complex, it is assumed that that the manufacturing stage will not produce a significant increase in emissions.

A4 (Transport of product): Similar to the transport of material, the factors for estimating the amount of emissions was done by assuming the amount of vehicles necessary and the total emissions, and combining this with the distance covered by the vehicles. A difference in this case is gathering the sub-components that are bought commercially. This would likely require transportation from different locations to the main site, which results in considerably more emissions as longer distances would need to be covered, as well as a demand for more vehicles.

It is assumed all necessary components are shipped to Padova, Italy, which are then transported by truck to Prato Piazza. A freight truck is considered ideal as a transport medium in consideration of the weight and size aspect of all components.

By usage of Google Maps, the path from the city of Padova to Prato Piazza is 204 km or 126.76 miles, respectively. Assuming that the total weight of all components amass to circa 1 ton, it is possible to calculate the emissions (in metric tons CO_2) from the freight truck to transport these.

1 ton $\times 126.76 miles = 126.76 ton - miles$

Assuming through sources that a freight truck produces 161.8 grams CO_2 per ton-mile, this equals:

161.8 g CO_2 $\times 126.76 ton - miles = 20509.768 g\mathrm{CO}_2$

This equals roughly 20.5 kg CO_2 for one trip.

A5 (Construction/Installation): The assembly and installation is likely the phase that is most short-lived and also likely to release none to little greenhouse gases. Assembly should be manually operated and therefore require minimum automated assistance which could emit greenhouse gases.

Step 3: Life cycle impact assessment (LCIA)

The LCIA is the step in which one assesses the potential impact on the environment from the results when converted into impact indicators. The relevant impact indicators for the case of this project is global warming and the emission of greenhouse gases [15]. Each stage of the Cradle-to-Grave shows the estimated emissions.

Step 4: Interpretation

The table shows that the transportation of the telescope makes up for most of the emissions, as

A1	2 tons CO_2
A2	20 kg CO_2
A3	~300 kg CO_2
A4	20.5 kg CO_2
A5	~0-1 kg $C0_2$

Table 4.3: Impact Assessment

well as the manufacturing and the material extraction process. There are several mitigation steps that can be done to reduce these. One step would be to reduce the overall size of the telescope, rendering it non-optimal, yet operational, which would decrease the material needed. This would also yield less emissions in transportation as it would allow for vehicles producing less greenhouse gases to transport the necessary parts.

5 Discussion

There were several changes affecting the thesis writing after my thesis partner I was writing with went their separate way to write their own thesis. The biggest effect being the labor divided throughout the duration of the thesis. While lessened, the scope of the project was still significant, and the Gantt chart 1.1 depicted in the introduction did not follow through in the last 10 weeks. This resulted in one of the performance goals not being achieved, namely to produce a prototype of the model. This meant that no integration test could be performed. In hindsight, there should have been less time set aside for research, as research would have naturally followed through the initiation of the concept phase.

Additionally, it would have been ideal to have lessened the scope and amount of aspects to consider. For example, by excluding the LCA and component overview, as this required further time and research, as well as feedback. This would have ensured more sophisticated results as well as more precision in writing. By doing this, I could have gone more in-depth in my simulations and would have performed more advanced, thorough calculations. I assume certain mistakes could have occurred through my simulations and CFD, which impacts the conclusions that have been drawn. This part of the thesis is not done as thoroughly as wished and this is reflected in the thesis.

Overall, the results indicate progress in the design and selection of components for the telescope array. However, further testing and optimization are required to ensure the functionality and performance of the proposed system. Additionally, the results section could have been enhanced by including more specific details, such as weight reduction strategies, and a more thorough discussion on stability and hardware selection.

Nonetheless, the rest of the performance goals were achieved to a certain extent, and a finalized design was proposed.

6 Conclusion

6.1 Conclusion

The thesis proposed a functional telescope array for the location of the site test in Prato Piazza. A small series of differing concepts were initially evaluated and tested, where one was chosen based on its functionality. This design would be able to fulfill the low-cost objective and adhere to the environmental criteria that were set. Computer-aided design and simulations were employed to develop and assess the design before potential manufacturing. The research conducted in this thesis contributes to the field by providing insights into the development of telescope arrays, which are currently lacking. The findings from this study can possibly aid in future site tests and further advancements in the field.

The issue of high costs associated with astronomical gear and components were addressed through the proposed low-cost telescope arrays. The advancement of astronomical research relies on affordable and accessible equipment, and the thesis aimed to contribute to that goal.

In conclusion, this thesis serves as a small stepping stone towards the advancement of astronomical research at the Prato Piazza observatory site and beyond. By proposing low-cost telescope array designs and considering the challenges faced by the field, this study provides valuable insights and solutions. It is my hope that these findings will inspire further development and contribute to the field of astronomical research.

6.2 Future Advancements

Future, sophisticated testing needs to be conducted to verify the validity of this telescope array. There needs to be continual refinement and optimization of the design by incorporating feedback and advice from astronomers and engineers.

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