

AN EMBEDDED-SYSTEM AND IMPLEMENTATION OF A TELESCOPIC
GLASS FOR VISUALLY IMPAIRED

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**DESIGN AND DEVELOPMENT OF MOTORIZED TELESCOPIC EYEGLASS
SYSTEM FOR LOW VISION PROBLEM**

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ABSTRACT

This thesis presents the design, hardware, control, and experimental validation of a motorised telescopic eyeglass system developed to enhance visual perception in individuals with low vision. Unlike the fixed-focus or manually adjustable telescopic systems commonly used in the literature, this study introduces a motor-controlled magnification and focusing mechanism that can dynamically respond to the user's immediate needs. The system can be controlled remotely via Bluetooth or a smartphone application; focusing and magnification movements are achieved through the mechanical movement of telescopic tubes produced using FDM 3D printing with lightweight polymer materials. The system is a wearable structure that integrates optical, electronic, and mechanical components. The optical system uses epoxy-based lenses produced in a laboratory environment, with both cost and production ease considered during assembly, and supports variable magnification ratios. Focusing and zooming functions are provided by a sliding system within the telescopic tubes; a linear stepper motor connected to the outside of the tube enables precise and rapid focusing by moving the tube horizontally. The motor's actual position is tracked using a magnetic encoder, ensuring precise control in a closed-loop system. System management is fully implemented on a custom 4-layer PCB built around an ESP32 microcontroller.. Step motor control is provided by signals sent to the STEP and DIRECTION pins. The DIRECTION pin determines the direction of rotation of the motor, and each signal sent to the STEP pin causes the motor to take one step. The number of steps determines the position, while the signal speed determines the motor's rotation speed. The motor's actual position is tracked using a magnetic encoder, and precise closed-loop control is achieved through a PID algorithm. The hardware is designed with low-power consumption components and can operate for 5 days on average when used 50 times per day with a 170mAh Li-Po battery. During the experimental validation phase, the prototype system was subjected to a series of performance tests in a laboratory environment; parameters such as focusing speed, position accuracy, image clarity, and energy consumption were measured, and the wear tolerance of the tube mechanism was examined. Additionally, field tests were conducted

with a limited number of users to collect feedback on usability and ergonomics. In conclusion, the developed motorised telescopic glasses system aims not only to offer a low-cost design but also to surpass existing telescopic glasses systems both technically and ergonomically, thereby emerging as a portable and effective assistive device for individuals with low vision.

Keywords: Motorised Telescopic Glasses; Low Vision; Wearable Optical System; Embedded System Design; Lens Design

ÖZ

Bu tez çalışmasında, düşük görme (low vision) problemi yaşayan bireylerin görsel algısını artırmak amacıyla geliştirilen motorize teleskopik gözlük sisteminin tasarımı, donanımı, kontrolü ve deneysel doğrulaması sunulmaktadır. Literatürde yaygın olarak kullanılan sabit odaklı veya manuel ayarlamalı teleskopik sistemlerin aksine, bu çalışmada kullanıcının anlık ihtiyaçlarına dinamik şekilde yanıt verebilen, motor kontrollü bir büyütme ve odaklama mekanizması geliştirilmiştir. Sistem, kullanıcı tarafından Bluetooth üzerinden uzaktan kumanda ya da akıllı telefon uygulaması ile kontrol edilebilmekte; odaklama ve büyütme hareketleri, hafif polimer malzemeden FDM 3B yazıcıyla üretilen teleskopik tüplerin mekanik hareketi aracılığıyla gerçekleştirilmektedir. Sistem; optik, elektronik ve mekanik bileşenlerin entegre edildiği giyilebilir bir yapıdadır. Optik sistem, laboratuvar ortamında üretilmiş epoksi bazlı mercekler kullanılarak elde edilmiş olup, montaj sırasında hem maliyet hem de üretim kolaylığı göz önünde bulundurulmuştur ve değişken büyütme oranlarını desteklemektedir. Odak ve yakınlaştırma işlevleri, teleskopik tüplerin içinde yer alan kızak sistemi ile sağlanmakta; tüpün dışına bağlanan lineer step motor, tüpün yatay ekseninde hareketini gerçekleştirerek odaklamanın hassas ve hızlı olmasına imkân tanımaktadır. Manyetik enkoder ile motorun gerçek pozisyonu takip edilerek, kapalı çevrimde hassas kontrol sağlanmaktadır. Bütün bu sistem yönetimi, 4 katmanlı ve ESP32 tabanlı bir mikrodenetleyici kullanılarak tasarlanan bir pcb aracılığıyla gerçekleştirilmektedir. Step motor kontrolü, STEP ve DIRECTION pinlerine gönderilen sinyallerle sağlanır. DIRECTION pini motorun dönüş yönünü belirler, STEP pinine gönderilen her sinyal motorun bir adım atmasını sağlar. Adım sayısı konumu, sinyalin hızı ise motorun dönme hızını belirler. Manyetik encoder ile motorun gerçek pozisyonu takip edilerek, PID algoritması ile hassas ve kapalı çevrim kontrol sağlanmaktadır. Donanım, düşük güç tüketimli bileşenlerle tasarlanmış ve 170mAh kapasiteli Li-Po batarya ile ortalama günde 50 kere kullanılması durumunda 5 gün çalışması sağlanmıştır. Deneysel doğrulama aşamasında, prototip sistem laboratuvar ortamında bir dizi performans testine tabi tutulmuş; odaklama hızı, konum doğruluğu, görüntü netliği ve

enerji tüketimi parametreleri ölçülmüştür ve tüp mekanizmasının aşınma toleransı incelenmiştir. Ayrıca sınırlı sayıda kullanıcıyla saha deneyleri gerçekleştirilerek, kullanım kolaylığı ve ergonomik geri bildirimler toplanmıştır. Sonuç olarak, geliştirilen motorize teleskopik gözlük sistemi, yalnızca düşük maliyetli bir tasarım sunmakla kalmayıp aynı zamanda var olan teleskopik gözlüklerden hem teknik hem de ergonomik açıdan mevcut sistemlerin ötesine geçenmesi, düşük görme problemi yaşayan bireyler için taşınabilir ve etkili bir yardımcı cihaz olarak öne çıkması amaçlanmıştır.

Anahtar Kelimeler: Motorize Teleskopik Gözlük; Düşük Görme (Low Vision);
Giyilebilir Optik Sistem; Gömülü Sistem Tasarımı; Lens Tasarımı



*Dedicated to Derya,
the strange sea inside me I don't drown in, but that makes me..*

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LIST OF SYMBOLS

f :	focal length
d :	distance between lenses
θ :	angular rotation or deflection angle
V :	voltage
I :	electric current
R :	electrical resistance
t :	time
n :	number of steps / samples / data points
μ :	micron prefix, 10^{-6}
λ :	wavelength
x :	linear displacement (tube position)
P :	power
L :	length (e.g., tube, lens, or interval)
C :	capacitance
A :	area
Δx :	change in position
α :	angle of incidence or curvature (optical)
r :	radius
ϵ :	permittivity
ϕ :	optical phase angle
T :	temperature

LIST OF ABBREVIATIONS

I ² C:	Inter-Integrated Circuit
3D:	Three-Dimensional
ADC:	Analog-to-Digital Converter
AI:	Artificial Intelligence
AREF:	Analog Reference
BLE:	Bluetooth Low Energy
CAD:	Computer-Aided Design
CNC:	Computer Numerical Control
ESP:	Espressif Systems Processor
FDM:	Fused Deposition Modeling
GND:	Ground
GPIO:	General-Purpose Input/Output
I/O:	Input/Output
IMU:	Inertial Measurement Unit
LDO:	Low Dropout Regulator
LED :	Light Emitting Diode
LiPo:	Lithium Polymer Battery
OTA:	Over-the-Air
PCB:	Printed Circuit Board
PID:	Proportional-Integral-Derivative
PLA:	Polylactic Acid
RAM:	Random Access Memory
RTC:	Real-Time Clock
RTV-2 :	Room Temperature Vulcanizing – 2 Components
RX:	Receive Data
SCL:	Serial Clock Line
SDA:	Serial Data Line
SLA:	Stereolithography Apparatus

SWD:	Serial Wire Debug
t2D :	Telescopic Two-Directional control board
TX:	Transmit Data
UART:	Universal Asynchronous Receiver-Transmitter
USB:	Universal Serial Bus
VCC:	Voltage Common Collector
VCNL:	Vishay Capacitive/Proximity Sensor Series
WHO:	World Health Organization
μA :	Microampere
μm :	Micrometer

2. INTRODUCTION

1.1. Problem Definition and Significance

Vision loss is a significant public health problem that affects individuals' daily quality of life. Individuals with low vision face various difficulties in social interactions, work, and daily activities. The causes of vision loss include age-related macular degeneration, diabetic retinopathy, glaucoma, cataracts, and genetic diseases [1,2]. This situation causes individuals to have difficulties in education, career choices, and social integration processes [3]. For example, individuals with low vision often face serious limitations in reading, writing, driving, and performing other daily tasks [4,5].

Current solutions are often inadequate. Traditional glasses and magnifiers, while useful in some cases, may not be effective, especially for individuals with more advanced vision loss [6,7]. Although various optical devices have been evaluated for their ease of use and potential for improving vision, many individuals complain of inadequate comfort and functionality when using these devices [6,8]. In addition, current technology and lack of financial support limit access to appropriate devices for many individuals. For example, financing high-standard assistive devices required for low vision rehabilitation is difficult or often impossible [3,4].

Although some interventional devices and treatment methods attempt to improve vision loss, their use is generally limited and they fail to fully meet the needs of individuals. For example, some technological solutions proposed for individuals with neuro-visual impairments (e.g., smart glasses) have not yet been sufficiently tested [9]. In addition, further research is needed on the acceptability and effectiveness of the system by users.

Motorized telescopic eyeglass systems offer a more distinguished solution among optical devices. These glasses are designed for individuals with vision loss to continue their daily life activities. Motorized telescopic glasses specially designed for individuals with low vision problems provide clearer visuals by magnifying images and increase their

interaction with the environment [10]. These systems have the potential to support users' mobility and independence by increasing their control over their visual field.

Continuous innovation and development are essential for individuals with vision loss to achieve a better quality of life. Motorized telescopic eyeglass systems emerge as a technological field that can ease the daily lives of these individuals and increase their visual independence [11]. Therefore, the design and development of these systems have become a critical need for individuals with low vision. In summary, since existing solutions are not sufficient, efforts to develop motorized telescopic eyeglass systems pave the way for new and effective strategies aimed at alleviating the problem of low vision.

In the following sections, we will present a detailed study for the design and development of a motorized telescopic eyeglass system and examine the positive effects of this innovative technology on the lives of individuals with vision loss. In this context, it will be possible to take important steps in better understanding the problems of individuals and integrating them with technology [12]. Motorization of eyeglass systems will also provide a reward for the efforts spent in terms of providing a user-friendly experience.

In conclusion, the difficulties faced by individuals with low vision and the inadequacies of existing solutions reveal the necessity of a motorized telescopic eyeglass system. With developing technology, such innovative solutions have the potential to increase the quality of life for individuals with vision loss. Therefore, studies to be carried out in this field aim to increase social inclusion by strengthening the socio-economic status of individuals.

1.2. Thesis Objectives and Scope

The main purpose of this master's thesis is to design and develop a motorized telescopic glasses system for individuals with low vision problems. Vision loss causes individuals to experience significant restrictions in their daily lives, which seriously threatens their independence. Existing vision support systems are generally inadequate to fully meet user needs; therefore, the development of a motorized telescopic glasses system comes to the fore as an innovative approach. This study aims to combine information from different

disciplines in order to produce solutions for users' needs and improve existing technologies.

The scope of this thesis covers a wide range, starting from the establishment of the theoretical basis of the motorized telescopic eyeglass system to the implementation of prototype applications. In the first stage, a detailed literature review will be conducted on the causes of low vision and existing solutions. This review will provide a solid foundation for understanding the effects of vision loss on individuals' lives and the deficiencies of existing systems. Then, the design phase of the motorized telescopic eyeglass system will be initiated, technical requirements will be determined in detail, and a prototype development process will be designed in line with engineering principles. After the development of the prototype, the system will be improved by analyzing the experiences, opinions and interactions of users on this system.

Since this study was designed considering the needs and expectations of a specific target group, it aims to offer an innovative assistive device that will enable individuals with low vision to gain more independence in their daily activities. The specially designed motorized telescopic glasses have adopted a user-friendly design approach in terms of both functionality and aesthetics. During the design process, the ergonomics of the glasses and user comfort will be prioritized. In addition, a special emphasis will be placed on the ease of use and practicality of the system, and the degree to which individuals interact with these devices will be increased.

Another important goal of this study is to determine how the developed motorized telescopic glasses system affects the daily life quality of users and how it solves existing problems. The ultimate goal is for the motorized telescopic glasses system to meet the expectations of individuals with vision loss and make them more independent in their daily lives.

As a result, this thesis aims to design and develop a motorized telescopic eyeglass system for low vision, as well as to present an innovative approach in this field. By creating a solid foundation supported by prototype studies and user interaction analyses, it is aimed to develop an effective solution that will meet the needs of individuals with vision loss. This study has the potential to increase the interaction between health technologies and engineering disciplines and aims to contribute to similar projects in the future.

1.3. Thesis Structure

This thesis consists of seven main chapters. In the first chapter, the motivation for the study is introduced, the problem is defined, and the objectives and scope of the thesis are explained. In the second chapter, the literature study on low vision problems, telescopic eyeglass systems, and related technologies is presented. In the third chapter, the design approach and methodology followed based on user and system requirements are explained. In the fourth chapter, the design and prototyping process — including optical, mechanical, and electronic components of the motorized telescopic eyeglass system — is discussed in detail. In the fifth chapter, the performance of the developed prototype is evaluated through various tests and the obtained findings are reported. In the sixth chapter, the test results are analyzed, compared with the literature, and the strengths and weaknesses of the system are discussed. In the seventh and final chapter, the general outcomes of the study are summarized, and broader implications of the work are evaluated from technical, economic, social, and environmental perspectives.

2. LITERATURE REVIEW

2.1. Low Vision Problems and Available Vision Aids

Low vision (low vision) is the condition in which individuals' visual abilities fall below a certain level and usually occurs as a result of various eye diseases, genetic factors or congenital causes. According to WHO data, low vision impairment affects at least 2.2 billion people worldwide, and one billion of them are reported to have vision loss [13]. According to the World Health Organization (WHO), 285 million people worldwide live with mod-severe vision loss, approximately 39 million of whom are completely blind [29]. A visual acuity between 20/70 (0.3) and 20/200 (0.1) is defined as low vision, and these individuals require various assistive devices to maintain independent living activities [6, 7].

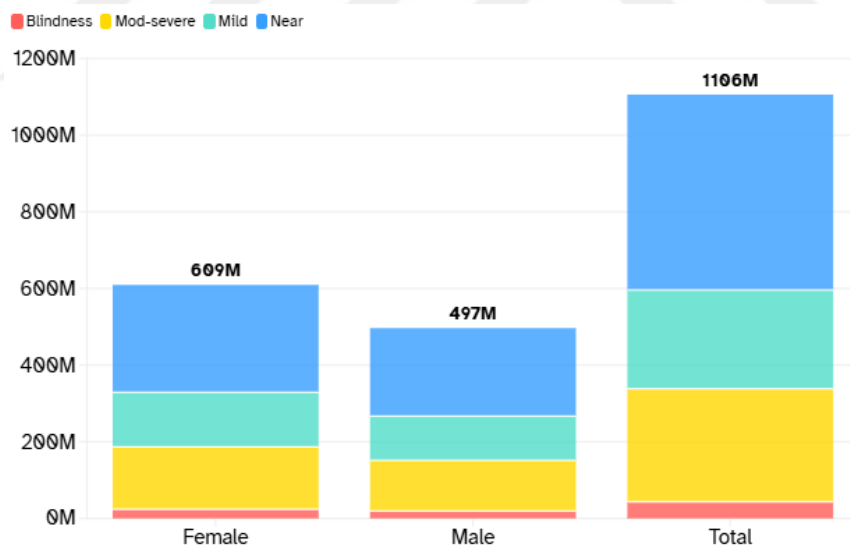


Figure 2.1. Vision Loss by Gender and Severity

(Source: Steinmetz, Jaimie D et al. *Causes of blindness and vision impairment in 2020 and trends over 30 years, and prevalence of avoidable blindness in relation to VISION 2020: the Right to Sight: an analysis for the Global Burden of Disease Study. Lancet Glob Health.* 2021;9(2):e144–60.)

Low vision problems can manifest themselves with symptoms such as decreased visual acuity, night vision problems, and impaired color perception. The main diseases that cause this condition include glaucoma, cataracts, age-related macular degeneration, diabetic retinopathy, and retinitis pigmentosa [14]. Low vision causes psychosocial problems such as social isolation, depression, and decreased general quality of life in individuals; it also negatively affects education and social integration processes [15,16].

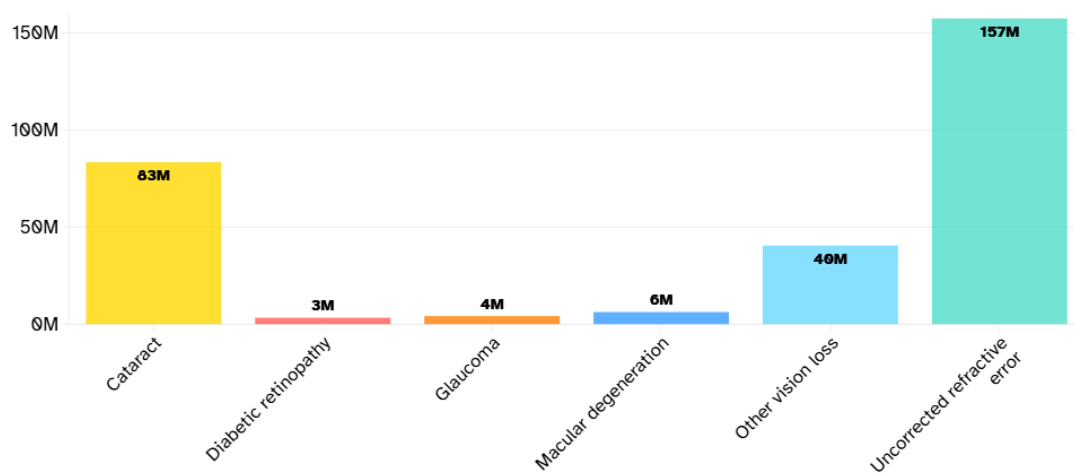


Figure 2.2. Global Causes of Vision Loss

(Source: Steinmetz, Jaimie D et al. *Causes of blindness and vision impairment in 2020 and trends over 30 years, and prevalence of avoidable blindness in relation to VISION 2020: the Right to Sight: an analysis for the Global Burden of Disease Study. Lancet Glob Health.* 2021;9(2):e144–60.)

The most common visual aids developed to improve the quality of life of these individuals are magnifiers, telescopic glasses, and electronic image enlargement systems. These tools utilize optical and digital technologies to increase the visual performance of individuals [6,17].

- Magnifiers:

Magnifiers are the most basic and widely used optical aids for individuals with low vision problems. Hand-held magnifiers, desktop magnifiers and electronic versions allow texts and objects to be seen larger [18].

Advantages: They are easy to carry, low-cost and can be used in any environment.

Limitations: They can narrow the field of vision, require stationary work and may be insufficient for individuals with both distance and near vision loss [6,19,20].



Figure 2.3. Visual for Non-Illuminated Stand Magnifiers

- Telescopic Glasses:

Telescopic glasses are optical devices developed using lens systems to see distant objects more clearly. They can be integrated into existing glasses and customized according to the users' eyeglass prescription [21].

Advantages: They clarify distant vision without carrying an extra device.

Limitations: Balance problems may occur during use, periodic adjustments may be required, may be incompatible with natural eye movements, and are only suitable for individuals with distance vision problems [6,20].



Figure 2.4. Visual for Telescopic Glasses

Below various telescopic glasses models are given with important specifications from different brands.

Table 2.1. Comparison of Telescopic Glasses of Different Brands/Models

Product (Brand/Model)	Magnification Type	Weight (g)	Length (mm)	Volume (cm ³)	Dynamic Speed	Cost (USD)
Ocutech VES Falcon	Fixed (Auto- focus)	90	50	30–35	<1 sec	\$3,900
Ocutech SightScope	Fixed	50 (est.)	35	20	Manual	\$1,000
eSight 4	Adjustable Digital	560	120	400	Real- time	\$6,000
Ocutech Sport Bioptic	Fixed	65	45	25	Manual	\$1,400
IrisVision Inspire	Adjustable Digital	400	130	500	Real- time	\$4,300

- Electronic Image Magnification Systems:

These systems magnify visual content through digital screens and cameras and offer advanced features such as high contrast, color adjustment, and fast magnification [22]. They facilitate daily tasks such as reading, writing, and facial recognition.

Advantages: Provides flexibility and is suitable for versatile use.

Limitations: Expensive, requires technological literacy, and has limited portability [18].



Figure 2.5. Visuals for an Electronic Image Magnification System

In recent years, advances in technology have offered more innovative solutions for low vision rehabilitation. While smartphones and tablets have become accessible to visually impaired individuals, artificial intelligence-supported technologies such as deep learning-based object detection systems contribute to individuals' independent movement, especially in complex environments such as the kitchen [23]. However, the social acceptability and psychological effects of such devices should also be taken into account. For example, some individuals may avoid using these devices due to fear of being noticed outside [24].

Effective life strategies need to be developed for individuals with low vision. In the educational environment, difficulties experienced by children with low vision in interacting with their peers can have negative effects on social and emotional development [15]. Therefore, supporting teachers and families with special educational

materials, teacher training and raising awareness are of great importance [25,26]. In addition, social programs that encourage integration into social life should be an integral part of this process [27].

Although existing assistive devices partially meet the needs of individuals with vision loss, they do not offer ideal solutions for every user. These systems can sometimes restrict users' interactions with the environment, narrow the visual field, or cause discomfort during use. Therefore, it is vital to consider factors such as comfort, practicality, social acceptance, and visual field during the design of new systems.

In this context, the motorized telescopic eyeglass system planned to be developed is aimed to overcome the limitations of existing systems and contribute to individuals' more independent and comfortable movement in daily life activities. In addition to improving visual performance, this system aims to improve the quality of life of individuals with low vision by offering advantages such as user-friendly features, increased field of view, and high portability.

As a result, low vision is an important health and social problem that affects the quality of life of individuals in a multidimensional way. In the solution of this problem, not only medical and technical devices are sufficient, but also social awareness, support of the education system, and strengthening social integration play a critical role. While developing technologies and innovative devices offer promising steps towards improving the quality of life of these individuals, existing solutions need to be continuously evaluated and improved [28].

2.2. Project Objectives

This project seeks to address the major limitations of conventional telescopic glasses by introducing an innovative alternative that is lightweight, cost-effective, adjustable, and customizable. The proposed system replaces traditional glass lenses with polymer-based optics, significantly reducing both weight and production costs. Additionally, it features a mechanical design with a dynamic focal length capability, allowing users to view objects at varying distances without switching devices or relying on fixed magnification.

The overarching goal is to develop a telescopic visual aid that is more accessible, ergonomic, and functional. By targeting both cost and performance constraints, this study aims to deliver a viable solution for individuals suffering from advanced visual impairments, thus broadening access to assistive optical technologies.

2.3. Design Constraints and Technical Targets

This project aims to develop a compact, cost-effective, and user-friendly telescopic vision system suitable for daily use. The key goals of the project are as follows:

2.3.1. Development of a Variable Focal Range System:

The system is designed to offer an adjustable focal range between 30 cm and 400 cm, covering a total span of 370 cm. This wide range of focal adjustment is intended to enhance the system's adaptability to dynamic visual scenarios, allowing users to clearly focus on objects located at various distances with ease. Such flexibility is especially valuable for individuals who need to frequently shift focus between near and far objects in everyday environments. The system provides optical zoom by adjusting the focal length from 30 cm to 400 cm.

2.3.2. Weight Optimization for Enhanced Usability:

A critical consideration in the design is the total weight of the device, which includes both the optical lens and the mechanical adjustment components. The goal is to limit the total weight to no more than 25 grams. Maintaining a lightweight structure is essential not only for user comfort but also for ensuring long-term wearability and minimizing fatigue. This makes the product more suitable for extended daily use, especially for individuals who require continuous visual assistance.

2.3.3. Compact Design Through Volume Constraints:

The device is also subject to strict volumetric constraints, with a maximum allowable volume of 15 cm³. This compact form factor is intended to support portability and integration into wearable systems such as glasses or head-mounted devices. A smaller volume contributes to a more discreet and aesthetically pleasing design, enhancing user acceptance and convenience in everyday social settings.

2.3.4. Affordability Through Material Innovation:

To make the product accessible to a broader audience, the entire system will be manufactured using polymer-based materials. This choice not only contributes to reduced weight and ease of manufacturing but also significantly lowers production costs. While existing telescopic glasses typically range from \$1500 to \$5000, this project targets a production cost of just \$15 to \$20, thereby offering a highly economical alternative. The substantial cost reduction has the potential to increase the availability of telescopic vision aids for populations with limited financial resources, including in educational, medical, or developing-world contexts.

Through these objectives, the project aims to deliver a novel optical system that balances performance, practicality, and affordability—qualities that are often mutually exclusive in current market offerings. The resulting product is expected to have meaningful applications in a variety of fields, including low-vision assistance, educational tools, and precision tasks requiring variable magnification.

2.4. Approach and Methodology

The proposed system is based on the Galilean telescope architecture, which consists of a convex objective lens and a concave eyepiece. This configuration is chosen over alternatives such as the Keplerian system due to its advantages in weight, compactness, and upright image orientation.

The optical design involves the dynamic adjustment of the distance between the two lenses, allowing real-time variation in focal length. This is achieved through a 3D-printed tubular structure with interlocking segments, designed to slide and reposition the lenses relative to one another. By selecting lenses based on back focal length calculations and simulating optical behavior using platforms like ZEMAX, the design process ensures alignment with empirical data. Simulated results are then validated through experimental setups on an optical bench.

Once suitable glass lenses are verified, equivalent polymer lenses are fabricated using epoxy resin within silicone molds, followed by polishing to improve clarity. These polymer components are integrated into the mechanical housing, forming the complete prototype.

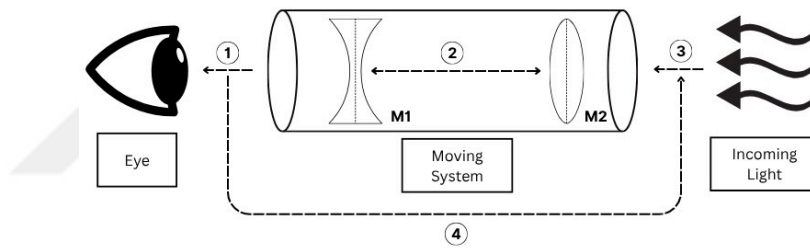


Figure 2.6. Telescope Diagram

The overall operation of the system is depicted in the block diagram shown in Figure 2.6. The setup consists of two lenses: M2, a convex lens characterized by a thinner edge, and M1, a concave lens with a thicker edge. These lenses are mounted within an adjustable-length tubular assembly. Light originating from the observer's focal point follows the path indicated by label 3, first passing through the convex lens (M2). Subsequently, the light traverses the tube and reaches the concave lens (M1), where it is converged to form an image at the focal plane. In cases where the observer is unable to achieve a clear image, the inter-lens distance within the region marked as 2 is adjusted via a movable tube mechanism. The system is then re-engaged to accurately determine the optimal focal point.

3. SYSTEM DESIGN

3.1. Selection of Telescope Configuration

At the outset of the design process, an appropriate telescopic architecture was selected. Given the project's requirement for simplicity, compactness, and lightweight construction, the Galilean telescope system was deemed the most suitable. Although multiple telescope configurations are described in the literature, including the more complex Keplerian design, the Galilean system offers several critical advantages.

The Galilean system produces an upright image, eliminating the need for additional optical correction components required in the Keplerian system, which inverts the image. Furthermore, the Galilean design has a shorter focal length and overall length due to the use of a concave lens as the eyepiece. This results in a more compact and lightweight configuration, ideal for integration into eyewear-based assistive devices. The system's simplicity—comprising just a convex and a concave lens—also reduces manufacturing complexity and cost. If it is to be explained in more detail, the Galileon telescope offers significant advantages, particularly for optical design and eyewear prototypes. This telescope system helps enhance imaging capabilities without affecting the user's visual perception. The primary advantage of the Galileon telescope is that the perceived direction on the ground plane remains unchanged, providing the user with a natural visual experience. While other telescope types have the potential to create different perceptual experiences through head movements and eye rotations, the Galileon telescope minimises these issues, offering a more accurate and natural visual experience. The cylindrical lenses used in the Galileon telescope's design allow for effective adjustment of the objective's angular orientation. When integrated with head movement-sensitive goggles, this orientation preserves the user's perception, providing a better viewing experience. Additionally, keeping the optical axis of these telescopes horizontal minimises the negative effects of head movements at certain angles on perceptual orientations [30]. Another reason I chose the Galileon telescope for my prototype is the aesthetic and

ergonomic advantages it offers. The perfectly integrated lens structure enhances visual perception and increases user comfort. The fact that the optical system components cause less discomfort to the user and take up less space is of critical importance for this type of application. Finally, the success of the Galileon telescope's optical design provides a model that can be referenced in the construction of other optical systems. To provide a sensitive optical measurement system, the use of Galileon telescopes in eyewear structures enhances functionality while also protecting users' eye health. Overall, the Galileon telescope method stands out as a highly suitable option for motorised telescopic glasses design.

3.2. Optical Component Selection

Following the selection of the telescope configuration, the optical components were chosen based on the requirements for focal range, size, and availability. The system necessitates one convex and one concave lens, which together determine the range of focal adjustments.

To ensure the system remains lightweight and affordable, 0.5-inch diameter lenses were selected from the inventory of the Micro Systems Laboratory. The concave lens used is Thorlabs ACN127-030-A, while the convex lens is Newport PAC028. These components were selected not only for their physical characteristics but also for their compatibility with simulation software and experimental validation on optical benches.

3.3. Optical Simulation and Experimental Setup

Optical simulations were performed using Zemax OpticStudio 13 Premium, a widely accepted platform known for its high-fidelity modeling capabilities and comprehensive lens library. The simulation modeled the system using the selected lenses and a laser source (SDL-671-100T) operating at a wavelength of 671 nm, which is consistent with the experimental setup available in the laboratory.

Initial simulations revealed that when the distance between the lenses is 18.3 mm, the system focuses light at a distance of 4267.57 mm, while increasing the lens separation to 23 mm results in a focal length of 302.1 mm. These results confirmed the hypothesis that increasing the separation between lenses shortens the focal length, which is the expected behavior in a Galilean system.

In the first experimental tests conducted to verify the system's focal length variability, a stable setup was established using optical components from Thorlabs. This required not only a stable physical assembly but also accurate measurement tools and a methodical approach to data collection. A neutral density filter (ND10) was used to reduce the laser intensity for safe observation. Two mirrors were used to guide the beam through the telescope system. The lenses were housed in a three-cage mounting system to allow precise alignment and manipulation. Light from the laser passed through the concave lens, expanded, and was then refocused by the convex lens to form an image at a variable focal point.

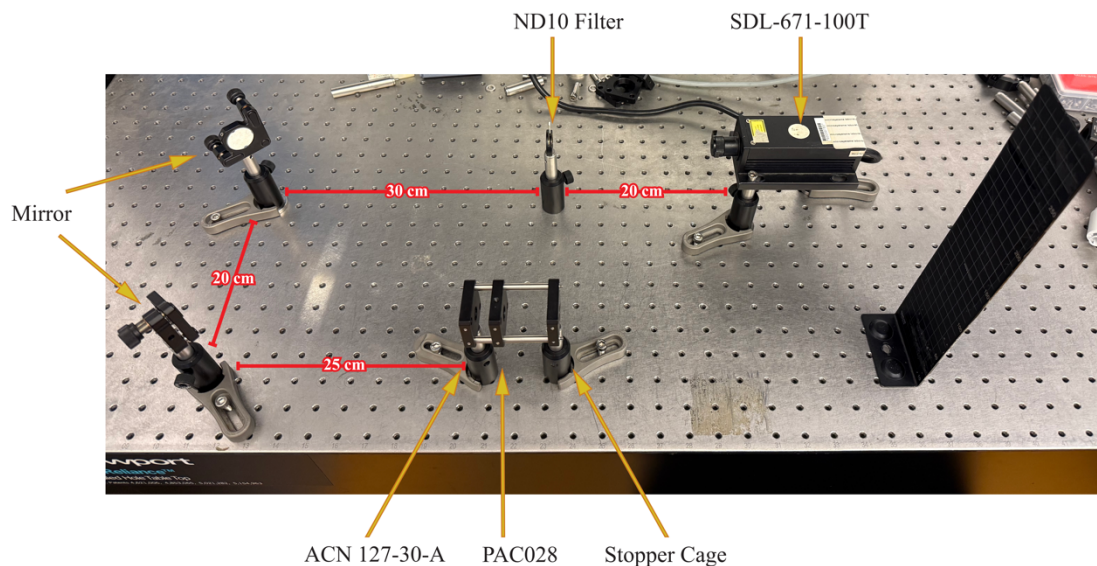


Figure 3.1. Galilean Telescope System Setup on Optic Table

During testing, a discrepancy was observed between the simulation and experimental results, attributed to the non-collimated nature of the laser beam. The beam exhibited angular divergence, increasing in diameter with distance. This prompted the calculation of the cone angle of the beam to incorporate into the simulation.

Following these initial tests, focal length measurements were conducted to characterize the mechanical tubes fabricated using a 3D printer. The experimental setup was constructed using optical components from Thorlabs, including lens mounts, clamps, a single-axis stage, and an optical table. The physical structure and key elements of the setup assembled to verify the system's effective focal length variability are shown in Figure 3.2.

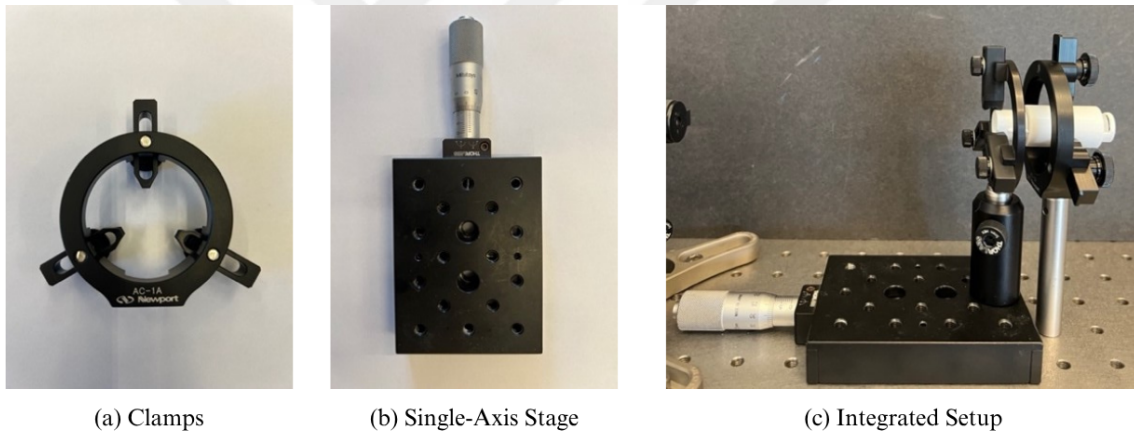


Figure 3.2. Key Elements of the Measurement Setup

To evaluate the performance and reliability of the mechanical tube system developed, a series of experimental tests were conducted to measure the system's focal length variability. These tests were designed to verify that the adjustable lens separation achieved via the sliding tube mechanism resulted in the expected changes in the focal point, consistent with both theoretical models and simulation results. Within this experimental configuration, the tubes were clamped between Thorlabs clamps (a), and two clamps were used. The outer tube was fixed to the optical table, while the inner tube was mounted on a single-axis stage (b) to enable precise movement measurements. This stage allowed the lenses to be moved closer or farther apart with 0.5 mm precision within

the predefined range of 26.5 – 36 mm. This setup (c) allowed for focal point measurements by precisely adjusting the distance between the lenses. An example of the experiment conducted with a 30 cm target distance using this setup is shown in Figure 3.3.

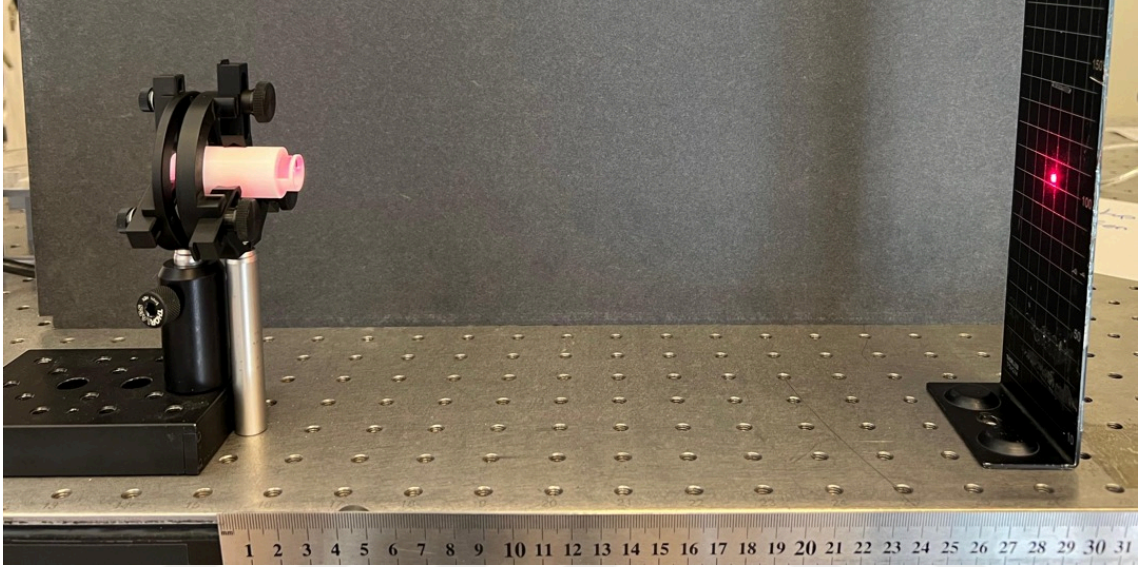


Figure 3.3. An Example for Focal Point Measurement with 30cm Target Distance

The primary objective of this stage was to establish a precise and reproducible testing setup that would allow accurate characterization of how focal length changed as the distance between the lenses varied. Achieving this required maintaining mechanical stability and ensuring precise and consistent focal length measurements throughout the tests.

3.4. Simulation and Experimental Correlation

To account for the angular divergence of the laser beam, the cone angle (θ) was calculated using the following relation:

$$\theta = \arctan\left(\frac{D_2 - D_1}{2L}\right) [31] \quad (3.1)$$

Where D_1 and D_2 are beam diameters at two different distances, and L is the separation between those measurement points. Using beam diameters of 2 mm at 100 mm and 5 mm at 2150 mm, the calculated cone angle was 0.0804° . This parameter was integrated into the simulation using the non-sequential mode of Zemax to better approximate real-world conditions.

Table 3.1. Simulation and Experimental Results

Distance Between Lenses (mm)	Simulation Results (mm)	Experimental Results (mm)
26.50	3938.50	4013.00
27.00	2273.00	2290.00
27.50	1607.50	1614.00
28.00	1279.04	1279.00
28.50	1026.62	1028.00
29.00	871.15	873.00
29.50	758.53	760.00
30.00	674.40	671.00
30.50	609.41	610.00
31.00	554.28	554.00
31.50	516.16	514.00
32.00	473.86	474.00
32.50	441.24	441.00
33.00	414.74	418.00
33.50	390.96	400.00
34.00	368.60	368.00
34.50	352.10	353.00
35.00	336.24	334.00
35.50	321.44	322.00
36.00	305.47	300.00

As the distance between the lenses decreases (e.g., 26.5 mm), the focal length extends to approximately 4 m, while as the lenses move further apart (e.g., 36 mm), the focal length shortens to approximately 30 cm. As shown in the Table 3.1, there is a highly consistent agreement between simulation results and experimental measurements; both at long focal lengths and short focal lengths, the differences between calculated values and values obtained in practice are negligible. A comparison of simulated and experimental data showed a high degree of correlation. As detailed in Table 3.1, discrepancies were within

a margin of $\pm 2.26\%$, validating the simulation model and confirming the suitability of the selected lenses. Graphical representations in Figures 3.4 through 12 illustrate the convergence of both datasets, reinforcing the accuracy of the optical design.

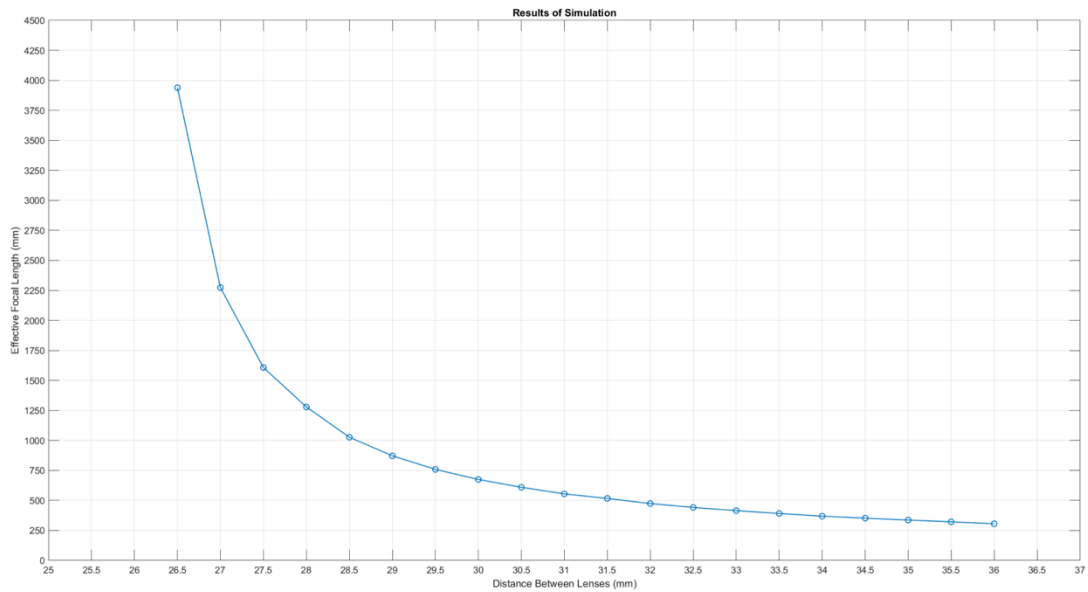


Figure 3.4. Simulation Effective Focal Length vs Distance Between Lenses

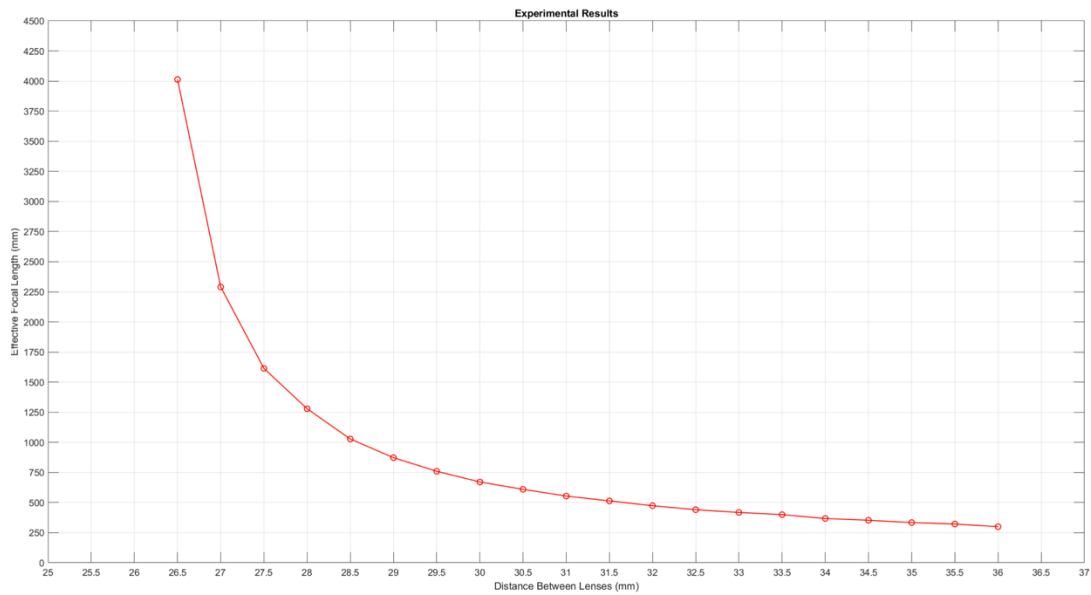


Figure 3.5. Experimental Effective Focal Length vs Distance Between Lenses

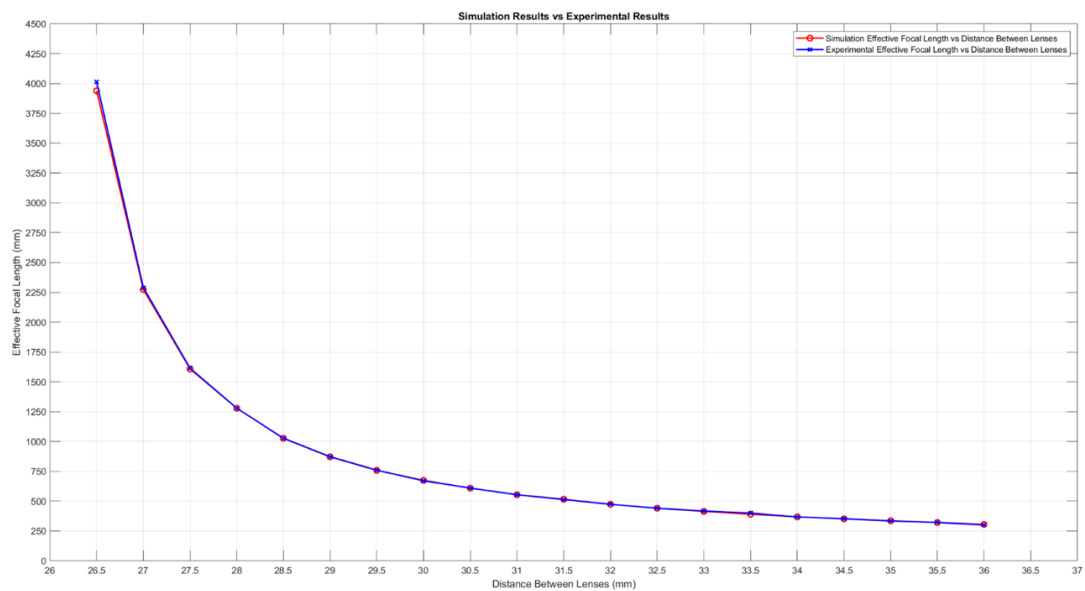


Figure 3.6. Comparison of Simulation Effective Focal Length (mm) vs Distance Between Lenses (mm)

3.5. Experimental Results of Prototype

In order to evaluate the optical performance of the zoom system, the relationship between the interlens distance and the image diameter (magnification) was analyzed through experimental measurements at different target distances.

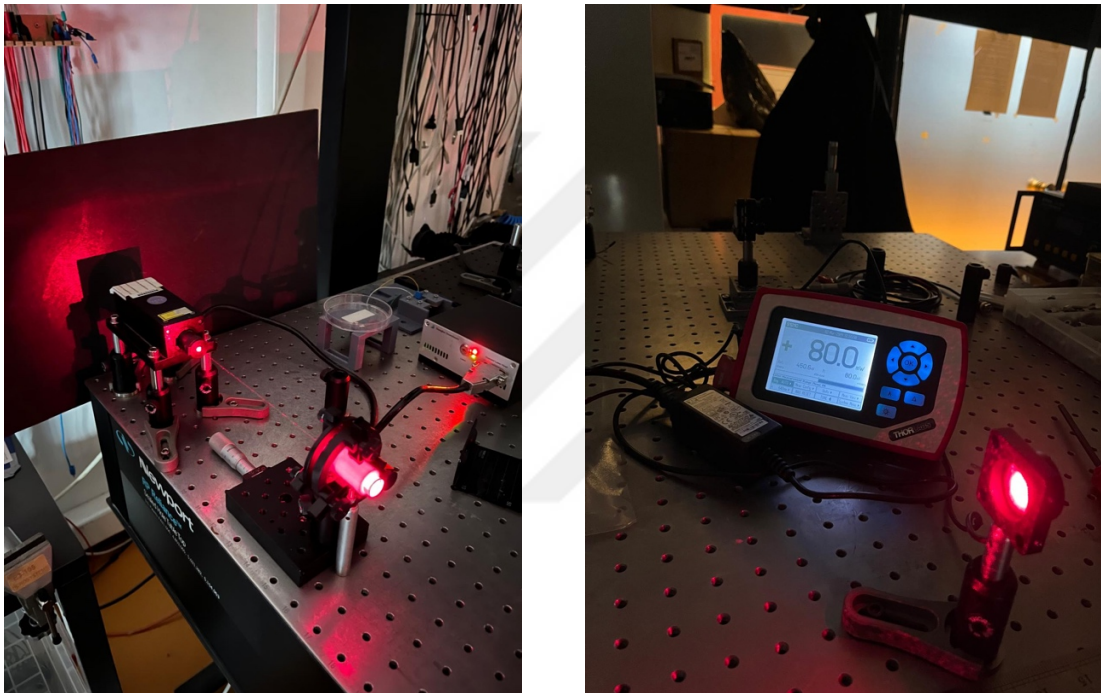


Figure 3.7. An Instance from Measurement Setup for Power of Laser (mW)

The designed experimental setup and measuring process are given in the Figure 3.7. During a series of 10 experiments, each representing a different target distance, the image diameters obtained in response to the interlens distance changed by the movement of the inner cylinder were recorded and presented graphically with the error margins (Figure 3.8).

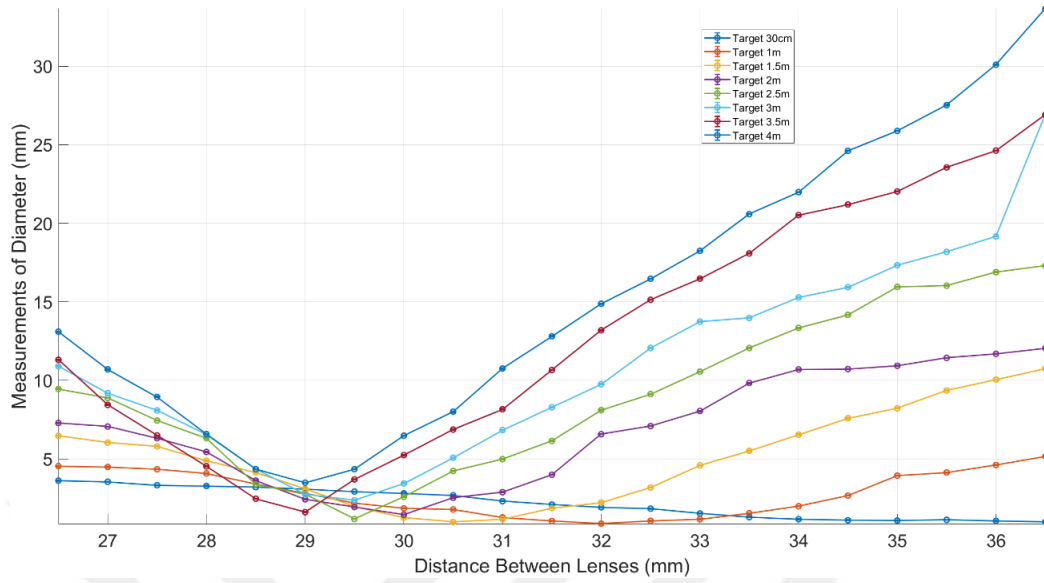


Figure 3.8. Experiments with Error Margins

In the graph, the X-axis represents the distance between the lenses (27–37 mm), and the Y-axis represents the image diameters (mm) measured for different target distances. Each curve shows the magnification characteristics obtained when the system focuses on a specific target distance (30 cm – 4 m). According to the experimental findings, the minimum value of the image diameter for all target distances was approximately 29 mm at the lens distance. This point indicates the position where the system exhibits optimum performance in terms of focusing, and it is predicted that the sharpest image is obtained at this distance. As the focus point is deviated, significant increases in image diameter are observed for both near and far targets. It has been determined that even small lens distance changes cause dramatic magnifications in image size, especially for distant targets such as 3.5 m and 4 m. This situation reveals that the system offers higher magnification for distant targets, but also requires more precise focus adjustment. For medium distance targets (1 m – 1.5 m), the more horizontal magnification curves show that the system operates more stably and tolerantly in this range. This indicates that the system can be optimized especially for medium distance viewing scenarios. The error margins in the graph represent the measurement uncertainties and were observed at wider intervals especially for distant targets. This shows that the system requires higher measurement precision during the focusing process on distant targets. In conclusion, this experimental

analysis confirms that the system can effectively perform dynamic magnification and focus adjustments through the linear movement of the inner cylinder. The obtained data constitute a valuable reference for the design of the optical system and the accuracy of the motor control algorithms.

3.6. Fabricating Optical Lenses with Epoxy Resin

This section presents the steps involved in producing optical-grade resin lenses with optical quality using epoxy resin, based on experimental studies conducted in accordance with methods described in the existing literature. The materials used, the moulding process, curing parameters, and the optical characterisation of the final product are detailed. The aim is to obtain resin lenses suitable for telescopic glasses using a low-cost and reproducible method. In addition, this study presents experimental results comparing the optical properties of the fabricated lenses with those of conventional lenses. Overall, these findings represent a significant advancement in the development of affordable and easily accessible telescopic glasses.

One of the reasons to use epoxy resin is, alongside its chemical structure, its optical behaviour. Designers are particularly interested in light transmittance between 200 nm and approximately 5 μm . Most transparent epoxies exhibit good transmittance between 350 nm and 2.5 μm ; beyond this range, performance varies. The refractive index of cured epoxies typically ranges between 1.50 and 1.65. It can be said that two basic materials are required for lens production: epoxy resin for lenses and silicone moulds to create these lenses.

- Epoxy resin casting; In this study, a two-component epoxy system was used to produce micro-level precision epoxy lenses with optical transparency. The epoxy resin and hardener were mixed in a 2:1 ratio (hardener) in accordance with the manufacturer's recommendations. This ratio was chosen to optimise both the mechanical strength and optical clarity of the system. The resin and hardener components were measured using precise scales and mixed slowly and homogeneously. Mixing at a low speed is crucial to prevent air bubbles from

entering the mixture. The resulting mixture was degassed under vacuum prior to curing to remove any remaining air bubbles, ensuring optical transparency and surface smoothness. This step is critical for preventing the formation of micro-defects on the lens surface and achieving high light transmittance. The key aspects of vacuuming the epoxy resin are as follows:

- Objective: To remove air from the epoxy resin in order to prevent air bubbles from forming on the surface, microscopic voids and deep scratches from forming during the sanding process with low-grit sandpaper.
- Duration and Procedure: Since epoxy resin begins to cure approximately 30 minutes after mixing, the degassing process takes approximately 20-30 minutes. The mixed resin is placed in the desiccator and the vacuum pump is turned on; the vacuum pressure must not exceed 2 bar. The resin is left under vacuum until air bubbles rise and disappear from the surface (bubbles typically disappear approximately 20 minutes after they first appear) followed by an additional approximately 10 minutes to ensure complete purification. Finally, the vacuum is slowly released, and the lid is opened, the resin, as bubble-free as possible, is poured into the mould cavities.

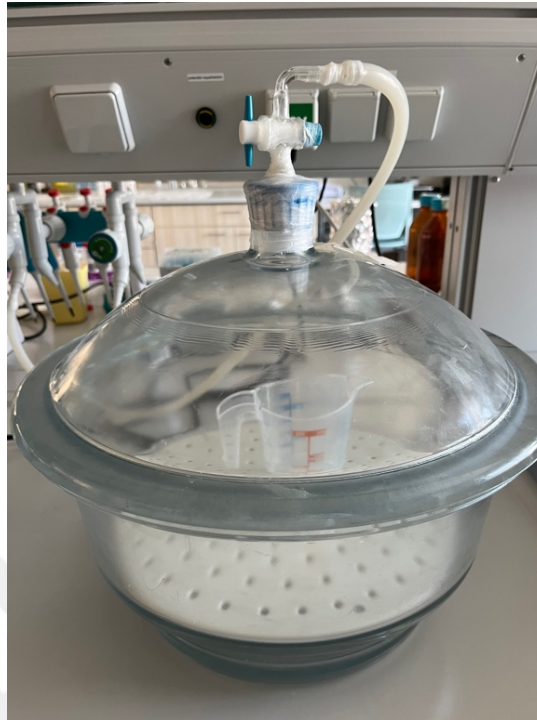


Figure 3.9. Vacuuming to Degass

- Mould Preparation; Two-component silicone (RTV-2) material, which vulcanises at room temperature, was used in the mould production process required for casting epoxy lenses. The production process begins with the preparation of a master mould carrying the negative form of the lens to be produced. Master moulds were obtained using two different methods at different stages of the project: In the first method, moulds of existing optical components were made using achromatic lenses from Thorlabs. In the second method, original lens geometries developed using 3D design software were converted into physical models using SLA 3D printing technology, and these models were used as master moulds. The prepared master mould was placed in a mould box suitable for silicone casting. Then, the RTV-2 silicone system was prepared according to the manufacturer's instructions. This system consists of two components:
 - Base (Component A)
 - Catalyst (Component B) – added at a ratio of 2% in this study.Both components were mixed homogeneously at low speed and degassed in a vacuum desiccator to remove air bubbles from the mixture. This step is critical to

prevent the formation of microscopic voids on the mould surface. The key aspects of degassing the RTV-2 silicone mould mixture are:

- Objective: To eliminate air bubbles formed during mixing and reaction of the silicone.
- Equipments: Desiccator and vacuum pump.
- Duration: 10 minutes (vacuum pressure must not exceed 2 bar or 15 minutes).
- Effect: Silicone volume can expand up to five times, bringing all bubbles to the surface.
- Precautions: Carefully control the volume in the desiccator to prevent overflow and avoid sudden pressure changes.
- Next Step: After gradually releasing the vacuum, transfer the degassed silicone into the mould box and position the object to be cast (the lenses).

The air bubble-free silicone mixture was carefully poured into the mould box and left to cure at room temperature. After approximately 12–24 hours, the silicone mould is completely cured. The master mould is then carefully removed. This results in a flexible, high-detail negative silicone mould that can be used for lens casting with epoxy resin. The main reasons for choosing RTV-2 silicones are as follows:

- Clear mixing ratios and ease of preparation
- High detail transfer and surface quality
- Flexible structure for easy removal from the mould
- High chemical and thermal resistance
- Ability to produce reusable moulds suitable for multiple castings
- These properties make the RTV-2 silicone system an effective and reliable method for producing moulds for both ready-made optical components and custom-designed lens geometries.

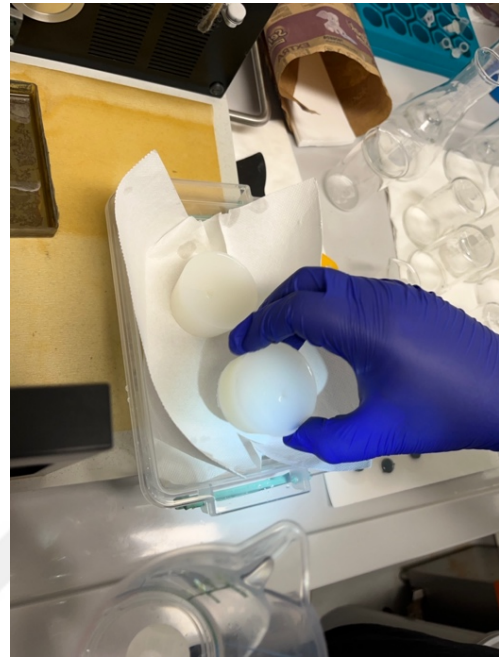


Figure 3.10. Negative Mould Printed with SLA 3D Laser to Mould Designed Lenses

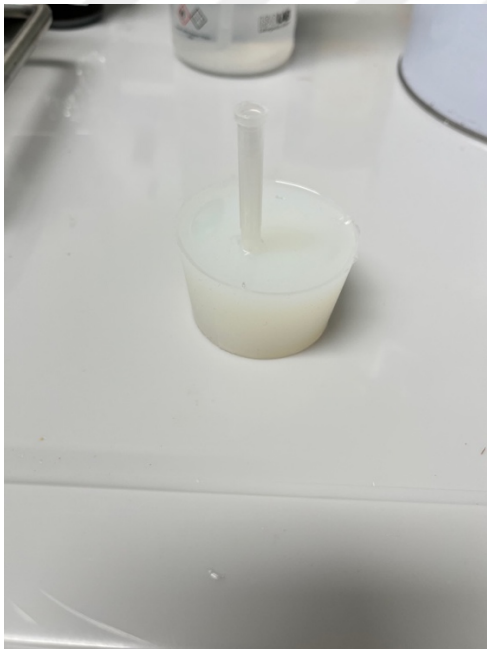


Figure 3.11. Moulding and Cutting Operation of the Lenses

- Casting lenses using silicone molds; After preparing the silicone mould that carries the negative form, the final stage of lens production, the epoxy casting process, begins. In this stage, transparent epoxy resin with optical properties is carefully poured into the mould so that it completely fills the inner cavity. The prepared epoxy mixture was carefully poured into a silicone mould and left to cure at room temperature. Once curing was complete, the hardened lens was carefully removed from the mould. At this stage, any burrs or small defects that may have formed on the surface were removed using the wet sanding method, with sandpaper of gradually increasing grit sizes ranging from 600 to 3000. Subsequently, a polishing process was applied to improve the optical surface quality. The progression of this process is shown in Figure 3.12 an unsanded lens with a completely matte and frosted appearance (a); a lens after the initial sanding stage, with a slight matte finish remaining on the surface (b); a lens after advanced sanding, showing noticeable surface clarity (c); and a fully sanded and polished lens, achieving high optical transparency (d). This method offers an effective solution for the production of low-cost, customisable, and repeatable micro-optical components. This method offers an effective solution for the production of low-cost, customisable, and repeatable micro-optical components.

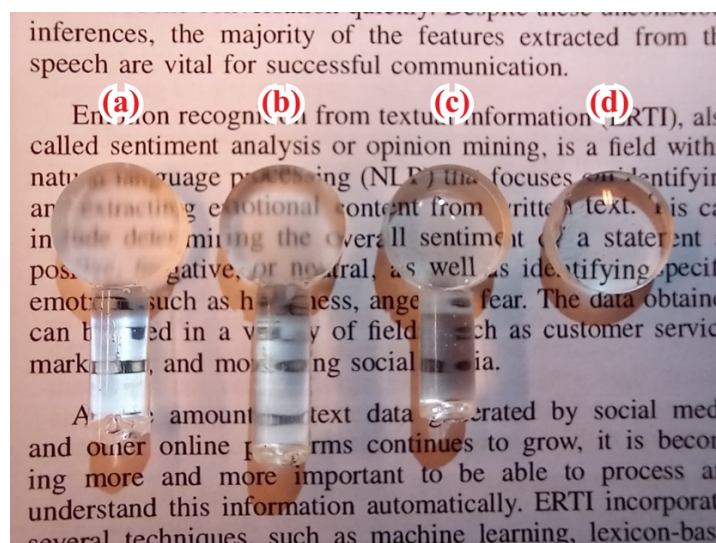


Figure 3.12. Cast Epoxy Plano-Convex Micro-Lenses After Wet-Sand and Polish

After curing, the lens surfaces were sanded with progressively finer abrasives to reduce surface roughness and increase optical clarity (Figure 3.12).

- Points to Consider
 - The epoxy/hardener ratio must be applied correctly. Excess hardener can cause glass-like brittle structures.
 - Degassing of the mixture must not be skipped; otherwise, air bubbles remaining in the lens will adversely affect the optical quality.
 - The mould surface must be clean and smooth; otherwise, surface defects will be directly reflected in the product.
 - The curing time must not be altered; lenses removed too early carry a high risk of deformation.
 - Sanding and polishing processes must not be neglected for surface quality; these steps are essential for achieving high light transmission.

The lens models were designed using Autodesk Fusion 360 software. The initial stage involved sketching the curved profile of the lens according to the required optical parameters, as shown in Figure 3.13.

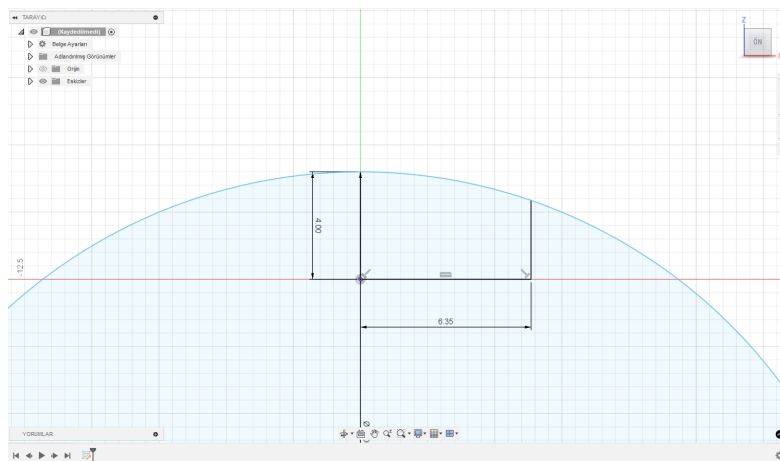


Figure 3.13. Sketch of the Lens Profile with Defined Curvature and Optical Dimensions in Autodesk Fusion 360

To ensure optical properties, only one surface of the lenses is curved, while the other surface is flat. This ‘single flat side’ approach provides sufficient optical focusing performance and is preferred for its suitability for the production process (Figure 3.14).

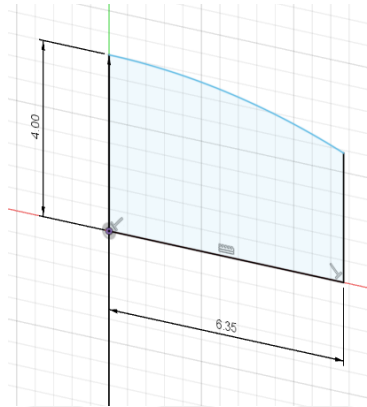


Figure 3.14. Cross-Sectional View of the Lens Showing the Curved and Flat Surfaces for Optical Performance and Manufacturability

Positive models for silicone moulds were produced using 3D printers with SLA technology. The surface quality and precision of models produced using SLA printers are highly suitable for mould production. However, it is generally recommended that at least one surface of the model be flat to ensure proper placement of support structures during production, prevent deformation during printing, and facilitate removal from the mould. A flat surface also ensures that the model adheres more securely to the printer bed. For this reason, lens models are designed with a flat base (Figure 3.15).

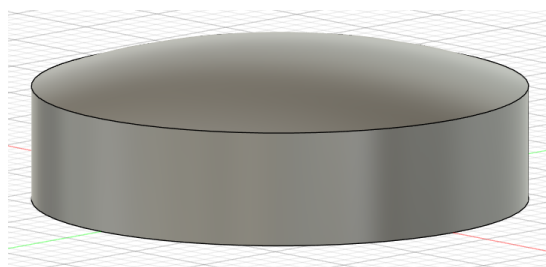


Figure 3.15. Three-Dimensional Model of the Lens Designed with a Flat Base for SLA 3D Printing and Silicone Mould Production

The focal length is determined using the Lens Maker's Equation, and the radius of the curved surface of the lens is calculated based on this focal length:

$$\frac{1}{f} = (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (3.2)$$

where f is the focal length, n is the refractive index of the lens material, R_1 is the radius of the curved entrance surface, and R_2 is the radius of the flat surface (modeled as infinity). In this design, light enters through the curved surface (R_1), and the flat surface ($R_2 = \infty$) remains on the exit side. With this configuration, the equation simplifies to:

$$\frac{1}{f} = \frac{n-1}{R_1} \quad (3.3)$$

indicating that the optical power of the lens is determined solely by the curvature of the entrance surface. The thickness of the lens, while having no direct effect on the focusing function, is set to 4 mm to enhance mechanical durability and structural stability during both printing and use.

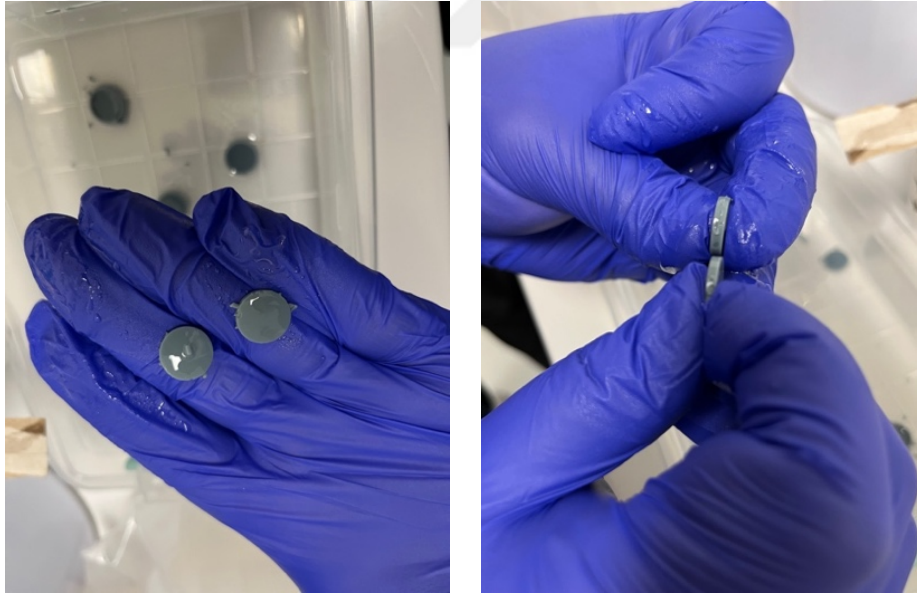


Figure 3.16. Negative Mould Printed with SLA 3D Laser to Mould Designed Lenses

In the subsequent stages of the project, specially manufactured epoxy resin lenses replaced Thorlabs achromatic lenses (ACN127-030-A, Newport PAC028). This change was made to evaluate the optical performance of the elements produced within the project under the same experimental conditions. Prior to integration, the refractive indices and surface profiles of the epoxy resin lenses were characterised to ensure compatibility with the existing optical setup. Two distinct experiments were then performed: (1) measuring the laser beam diameter as a function of inter-lens separation, and (2) measuring transmitted laser power as a function of the same parameter. In both experiments, the lens separation was varied from 25 mm (the nominal/rest position) to 35 mm (maximum separation) in 0.5 mm increments. Each measurement at every increment was repeated five times, and error bars representing the standard deviation were plotted. When beam propagation and focal-spot quality measurements were compared between epoxy resin and Thorlabs achromatic lenses, equivalent performance was observed in terms of aberration correction and light-transmission efficiency—well within experimental uncertainty limits. Moreover, the power-versus-distance experiment validated the diameter-versus-distance results: peaks in transmitted power coincided precisely with the minima in beam diameter, confirming that the focal position produced by the epoxy lenses matched that of the achromats. These results validate that both the power experiment and the diameter experiment confirm the performance of our lens and overall system. In conclusion, these findings demonstrate that the epoxy-based components reliably replicate the optical performance of commercial achromatic lenses, confirming their suitability as cost-effective alternatives for precision optical applications.

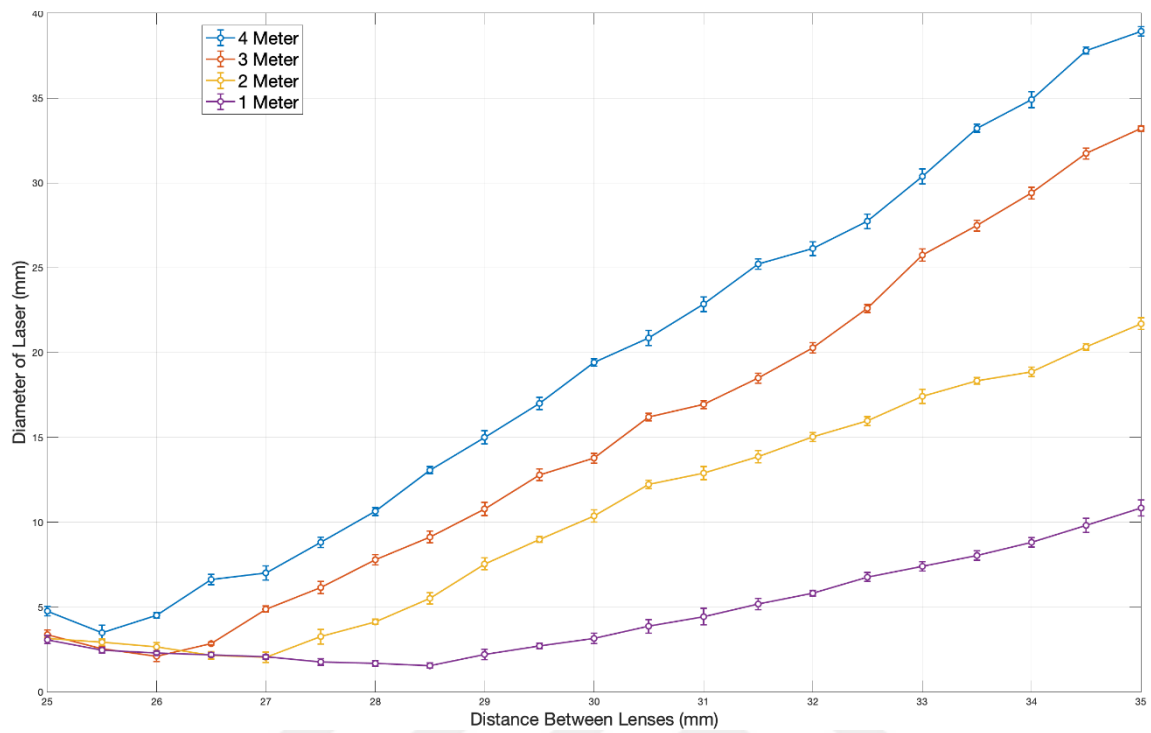


Figure 3.17. Distance Between Lenses vs Diameter of Laser

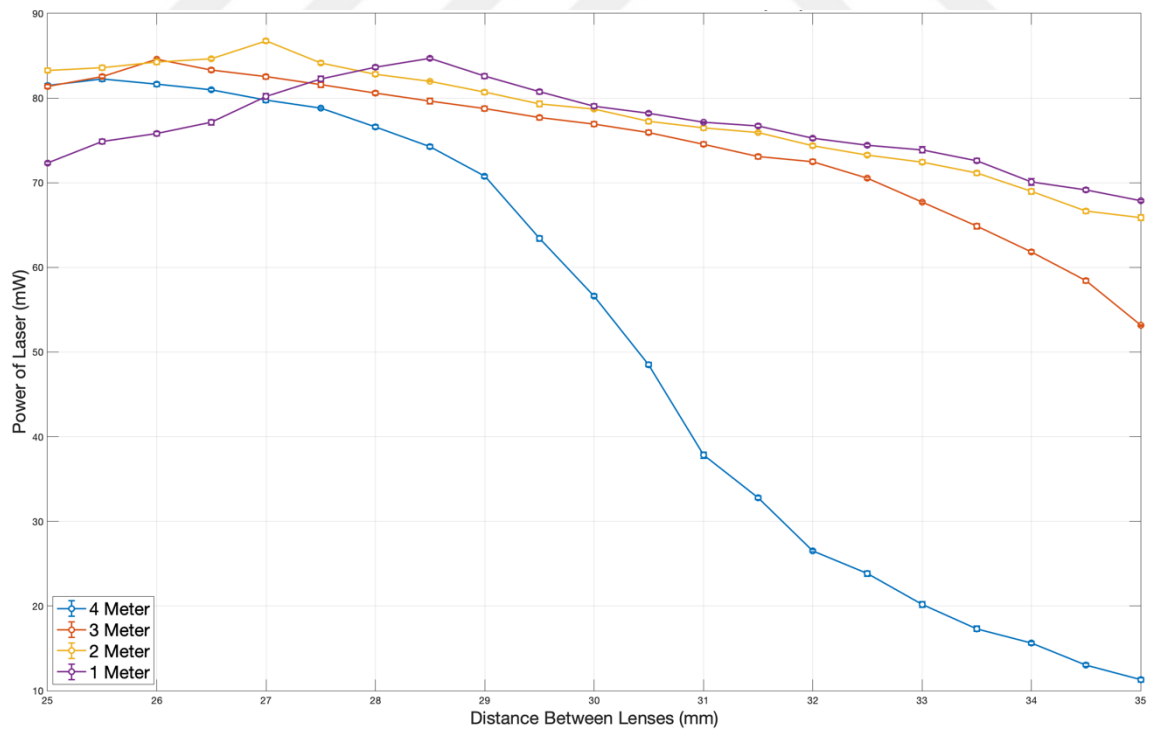


Figure 3.18. Distance Between Lenses vs Power of Laser (mW)

These epoxy resin lenses were manufactured to replace Thorlabs achromatic lenses (ACN127-030-A, Newport PAC028). The lenses were cast from the mould, and then the rough surfaces were sanded and polished for better clarity. You can see the lenses which were cast from epoxy resin by removing the mould in Figures 3.19 and 3.20.

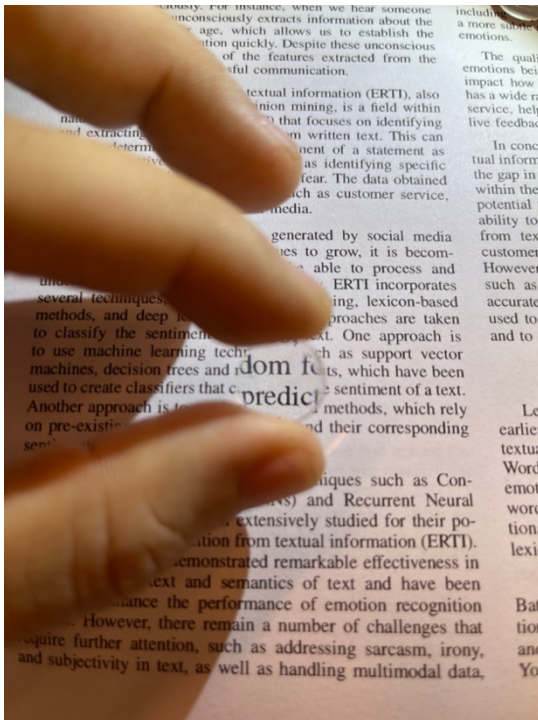


Figure 3.19. PAC Lens

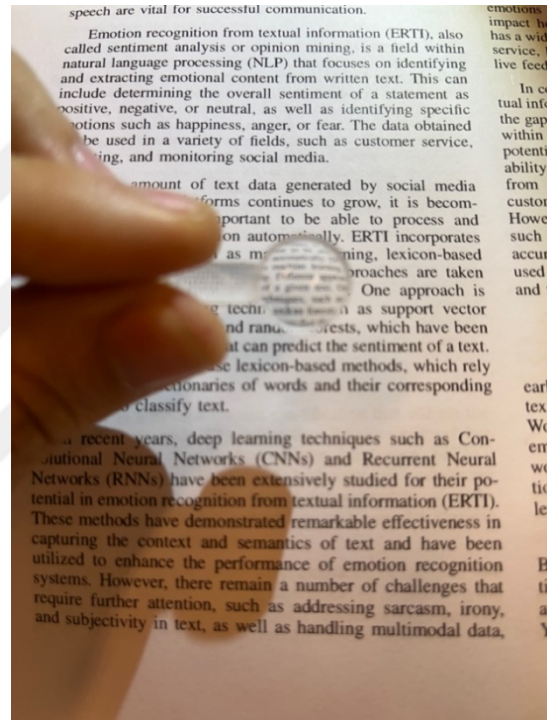


Figure 3.20. ACN Lens

TUBE DESIGN

In order to enable dynamic focal adjustment, the project necessitates a mechanical structure which allows the distance between lenses to be varied precisely. For this purpose, a sliding tube mechanism was designed to house and reposition the optical components in alignment with the Galilean telescope configuration and developed using FDM 3D printing. Focusing and zooming are achieved through a sliding mechanism within the telescopic tubes. A linear stepper motor mounted externally enables precise and rapid horizontal adjustments. This motor was integrated into the system after validating the design in the experimental phase.

4.1. Design Iteration and Conceptual Development

Initially, a gear-based telescoping mechanism was conceptualized. However, early studies from literature revealed that the gear spacing was too wide, resulting in insufficient positional resolution and poor control over lens separation. The initial gear pitch of 0.42 mm was determined to be below manufacturable limits, based on the fact that FDM 3D printer has manufacturing limits. This 0.42 mm value itself was derived by dividing a desired 10 mm lens-separation range into 24 gear teeth ($10 \text{ mm} / 24 \approx 0.42 \text{ mm}$ per tooth) because in the optical system the maximum adjustment range between lenses was determined to be approximately 10 mm (the difference between 25.5 mm for long focal length and 35 mm for short focal length $\approx 10 \text{ mm}$). However, FDM printers typically require a minimum tooth thickness of around 0.5–0.6 mm—given a 0.4 mm nozzle and standard layer settings—so a 0.42 mm pitch would not print reliably. Consequently, the gear-based approach was abandoned in favor of a more practical solution.

4.2. Tube Architecture

The primal design utilizes a dual-tube sliding mechanism consisting of an inner and an outer tube. This configuration allows one tube to slide within the other, thereby adjusting the inter-lens distance. The inner tube measures 21.2 mm in length, while the outer tube extends to 40 mm. The motion of the tubes enables an adjustable focal distance ranging from 26.5 mm to 36 mm between the lenses—matching the focal requirements established in the optical simulations.

Each tube incorporates custom-designed lens holders to securely position the optical elements while minimizing misalignment. The lens mounts include stabilizing rectangular prisms on both the front and rear faces to prevent lateral or rotational movement. These blocks measure 1 mm (W) $\times$ 1.4 mm (L) $\times$ 1 mm (H) and are strategically positioned to ensure optical stability during usage.

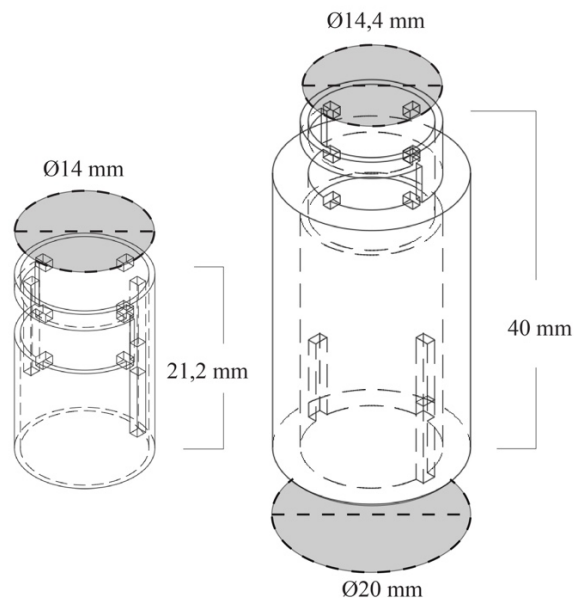


Figure 4.1. Technical Drawings of Inner and Outer Tubes

4.3. Structural Details and Fabrication

The inner tube features an internal ring of 12.8 mm diameter and an outer ring of 14 mm diameter. Its full length extends to 19.2 mm, including a 2 mm rear support thickness. Additionally, three evenly spaced alignment blocks (each 1 mm × 1.4 mm × 11 mm) are placed around its exterior to stabilize motion within the outer tube.

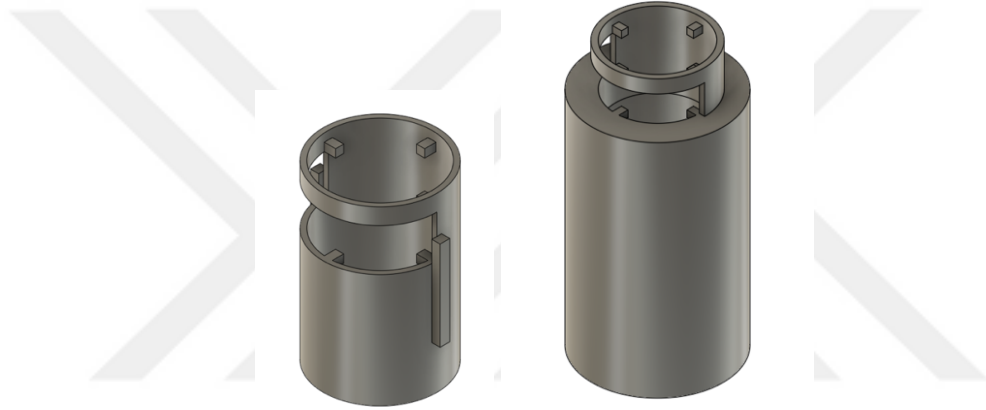


Figure 4.2. 3D Models of Inner and Outer Tubes

The outer tube, on the other hand, consists of concentric rings measuring 14.4 mm and 20 mm in diameter. It includes lens stops and supports, a 4.45 mm lens holding section, and three vertical guide channels (1 mm × 1.6 mm × 9.5 mm) that align with the inner tube's external blocks. These channels enable smooth linear translation while preventing unwanted rotation or misalignment.

Both components were designed using 3D CAD modeling tools and fabricated via FDM-based 3D printing using the Bambulab A1 printer. The print speed was reduced to one-third of the nominal rate to enhance dimensional accuracy. The resulting parts, shown in Figure 4.2, demonstrated tight tolerances and excellent fit, validating the sliding mechanism's design.

4.4. Final Tube Design: Sliding Mechanism

In the final design, this system comprises two concentric cylinders—a fixed inner (smaller) tube and a movable outer (larger) tube. The inner tube contains longitudinal channels carved into its exterior surface, and matching protrusions on the inner surface of the outer tube engage these channels to ensure smooth and guided sliding motion. The lenses are securely mounted inside each tube, and their relative movement adjusts the distance between the lenses, thereby modifying the system’s focal length. To attach the linear motor, specialized mounting brackets were incorporated on the exterior of the moving outer tube, and a square prism-shaped support piece was positioned between the motor and the tube to stabilize the motor and reduce vibration during operation.

As detailed in the experiments described above, the existing tube model was modified: the inner (small) tube was extended by 5 mm toward the rear, and mounting fixtures for the linear motor were added on top of it. Additionally, a square-prism-shaped support piece was placed between two mounting rods to stabilize the motor during operation. As in the first prototype, the newly modified tube was printed using an FDM 3D printer and fixed to the test bench. The same experimental procedures as before were repeated for this tube, but with two distinct measurements: one measuring laser beam diameter versus lens separation, and the other measuring laser power versus lens separation. For both experiments, data collection began at 25 mm (the “rest” position) and increased in 0.5 mm increments up to 35 mm (maximum separation). Each experiment was repeated five times, and error-bar graphs were plotted for both sets of results. As seen from the outcomes, the power experiment confirmed the diameter experiment: the points at which laser power peaked corresponded exactly to the points where beam diameter reached its minimum. These results validate that both the power experiment and the diameter experiment confirm the performance of our lens and overall system.

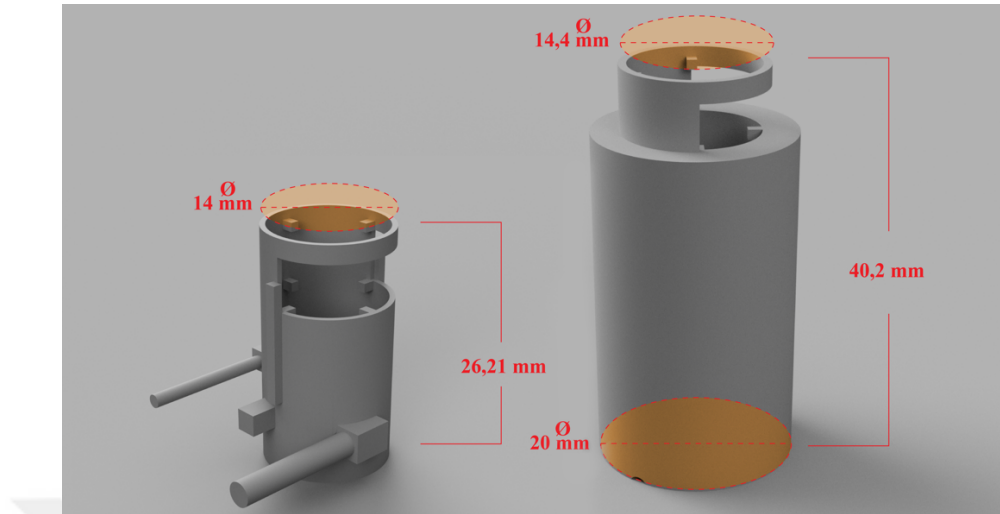


Figure 4.3. Final 3D Renders of Inner (on the Left) and Outer (on the Right) Tube Designs

4.4.1. Extended Outer Tube Design for Battery and PCB Integration

An additional outer tube variant has been developed to enable the full integration of the battery and the custom-designed printed circuit board (PCB) into the system. In this expanded design, the dimensions, internal structure, and lens placement of the original outer tube have been preserved; only a dedicated compartment has been added to its exterior to accommodate the battery and the electronic control board. This ensures that both the mechanical sliding mechanism and the optical system's focal length adjustment are fully preserved. The inner tube has not been modified and continues to be used in its original form from the first prototype.

The new outer tube design, illustrated in Figure 4.4, demonstrates the positioning of the battery and the printed circuit board relative to the optical assembly. This configuration enables compact integration while enhancing the overall structural integrity of the system.

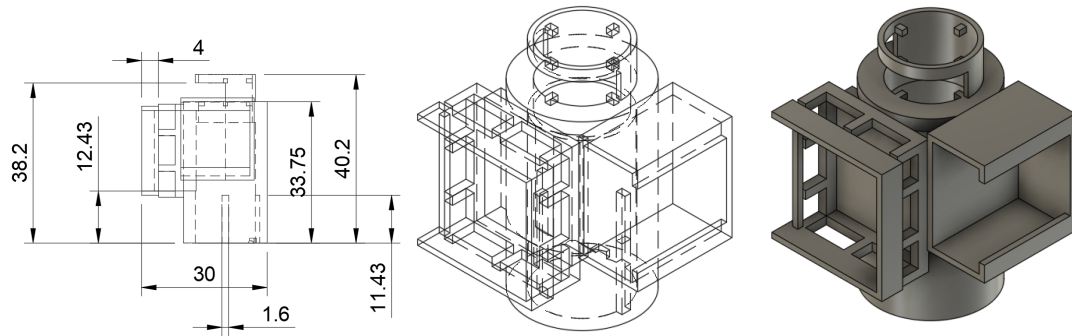


Figure 4.4. Dimensional Drawing and 3D Model of the Extended Outer Tube for Battery and PCB Integration

4.5. Functional Range and Assembly

The sliding tube system allows the lens spacing to vary between a minimum of 25 mm and a maximum of 35 mm. These distances correspond to the lens separations that were found, through simulation and experimentation, to deliver the required range of focal lengths for effective vision enhancement. Figure 4.5 illustrates cross-sectional views of the assembled tubes, showing the minimum and maximum positions achievable by the sliding mechanism.

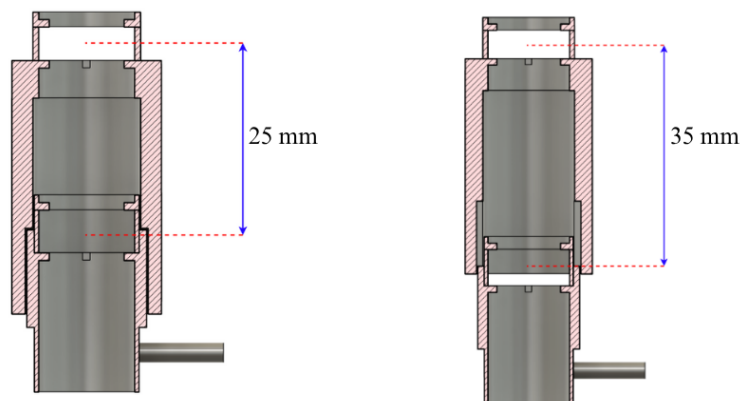


Figure 4.5. Sliding-Tube Lens Spacing Mechanism (25 mm – 35 mm)

To fabricate the tubes, the BambuLab a1 printer was used with adjusted settings that emphasized printing precision over speed. Specifically, the print speed was reduced to one-third of the standard setting to minimize mechanical inaccuracies and layer misalignment. PLA filament was selected for its rigidity and ease of post-processing. After fabrication, the components were manually assembled, and the lenses were inserted into their respective holders. The image shows the assembled prototype where the telescopic tube is mounted onto the glasses, demonstrating the intended real-world application.



Figure 4.6. Integrated Look of Tube and Glasses

5. ELECTRONICS AND MECHANICS SYSTEM DESIGN

5.1. Motor and Microcontroller Selection

In this study, a suitable motor was initially selected to enable the movement of the optical tube, followed by the identification of the need for a processing unit to drive and control the motor. Instead of utilizing development boards such as Arduino or ESP32, a custom embedded board was designed specifically to meet the project requirements. This approach allowed for optimisation in both size and cost, while also enabling the customisation of motor speed control, communication protocols, and power management features tailored to the specific needs of the application. Two motor technologies were evaluated to provide linear motion for the optical tube. First, a PCB-based motor—with stator coils directly integrated into a printed circuit board—was designed and tested. Second, a commercially available mini linear step motor was considered. In the following sections, we will describe the PCB motor's operating principle in detail and then explain why, based on time-efficiency and cost considerations, the linear step motor was ultimately chosen.

5.2. Design and Operating Principle of the PCB Motor

A PCB motor is a motor architecture in which the stator is implemented directly on a printed circuit board (PCB), serving as an alternative to conventional wound-stator designs. In this approach, the motor windings and the control electronics coexist on the same multi-layer PCB. Instead of using separate copper wire coils for the stator, the required windings are realized as copper traces etched into the PCB layers. As a result, PCB motors achieve an extremely compact form factor and a high degree of integration between mechanical and electronic components.

Stator Structure and Coil Arrangement

- The stator section of the PCB motor is designed to have a three-phase BLDC coil configuration. For example, in a single-layer PCB, three separate spiral or circular copper traces are arranged to form each phase coil. When using a multi-layer PCB, the coils are arranged in parallel or series layers to increase the conductive cross-section and optimise the magnetic flux paths. The coil windings are insulated by interlayer dielectric material (FR-4, polyimide, etc.).

Rotor and Magnetic Assembly

- The rotor consists of neodymium magnets (N and S poles) fixed to a thin shaft. The polarity arrangement of the magnets is determined to match the number of magnetic poles of the stator coils (e.g., a 4-pole rotor with 6 coil layers, etc.). The rotor is positioned at a distance of only 0.2–0.5 mm from the stator surface (air gap). This positioning maximises magnetic flux transfer and thus enables higher torque density.

Based on the aforementioned working principles and supported by the literature [32][33], a custom-designed 6-layer FR-4 based PCB motor was developed in this study. The motor follows a three-phase BLDC topology, with each phase coil distributed across two copper layers in a symmetrical configuration. The coil traces follow a concentric circular pattern, optimized for flux symmetry and minimal cogging torque. Each layer contains finely routed copper spirals with a trace width of 0.25 mm and inter-trace spacing of 0.2 mm, ensuring both electrical efficiency and manufacturability.

The stator windings are interconnected through 0.3 mm plated vias, strategically placed to minimize resistance and thermal hotspots. The dielectric material used between copper layers is standard FR-4, providing both mechanical support and insulation. The rotor is designed to house four neodymium magnetic poles, matched precisely to the stator geometry. The rotor-stator air gap was maintained at 0.3 mm, as suggested by prior studies, to maximize magnetic coupling while preserving mechanical clearance.

This multi-layered approach enables increased current handling per phase and improved thermal dissipation, making the motor suitable for compact applications where traditional wound-core motors would be impractical. The PCB layout and geometrical parameters were adapted and refined from [32,33], with modifications made to better align with our specific torque and footprint requirements.

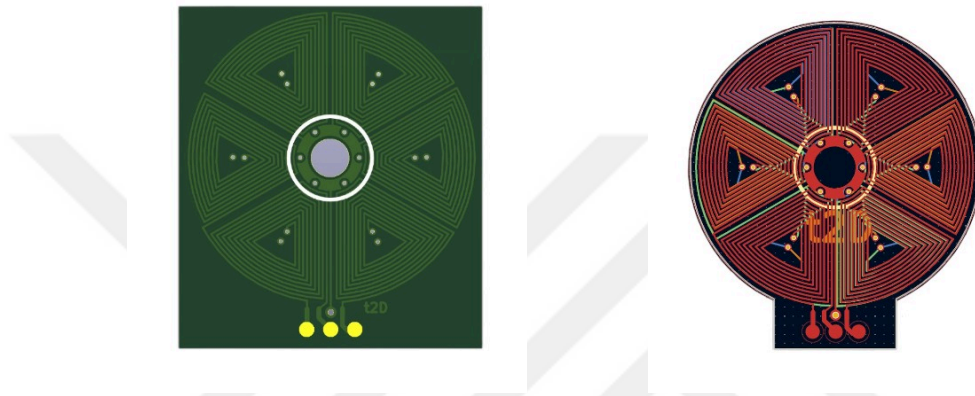


Figure 5.1. Geometrical and Coil Arrangement of the PCB Motor

In summary, although the conceptually designed PCB motor offers chip-level driver integration and a compact design advantage in the prototype stage, it has been a limiting option in terms of low-volume production costs and torque/weight optimisation, thereby restricting the prototype development pace.

5.3. Selection Rationale and Operating Principle of the Stepper Motor

Stepper motors operate using magnetic fields and electromagnetic principles. Their structure consists of a rotor, stator, and bearings. The stator is the stationary part that usually consists of windings that generate a magnetic field. The rotor is the rotating part, which is usually made of a magnet or magnetisable multipolar material. Bearings allow the shaft connected to the rotor to move freely. The stator has multiple poles; the number of poles varies from motor to motor but is typically eight. The polarity of the poles is

continuously changed via electronic switches. The magnetism of the rotor is either created by a permanent magnet or through external excitation techniques.

The operating principle of a stepper motor is that energy is supplied to the coils via electronic switches, causing the rotor to stop when it passes opposite the coil that is energised. The number of pulses sent to the coils determines how much the motor rotates. The current applied to the stator windings affects the rotor's magnetic field, causing the rotor to begin rotating under the influence of the stator's magnetic field. The frequency of the current controls the motor's rotational speed, while the duration of the current controls the motor's step-by-step movement. Stepper motors are devices that can change angular coordinates in steps. They are commonly used in applications such as CNC machines, 3D printers, laser cutting machines, and robots.

A driver is required to control stepper motors. The basic function of the driver is to receive these low-power control signals and provide the motor windings with the necessary power (voltage and current) to move the motor. In other words, the driver ensures that the control signals are supplied to the motor windings in the correct sequence and at the correct timing. Leveraging this sequential energisation, the rotor rotates step by step under the influence of the stator's magnetic field. The driver can control the motor's step count, direction, speed, and even torque. Different driver types exist, and not all drivers are suitable for all motors, so driver selection is important. To achieve this level of precision and control, effective drivers such as the A4988 are preferred. It was selected the A4988 stepper driver for its combination of precise control, built-in logic, robust protection, and cost-effectiveness. Its microstepping capability divides each full step into smaller increments, yielding higher positioning accuracy, smoother motion, and reduced noise—essential for our optical tube's fine movements. The onboard translator handles all the complex phase-sequencing internally, so our controller needs only simple STEP and DIR pulses to drive the motor, significantly simplifying the control circuitry. Integrated protection features—such as overcurrent protection, thermal shutdown with hysteresis, low-voltage lockout, and cross-current protection—safeguard both the driver and the motor against electrical faults, enhancing system reliability and longevity. Moreover, the A4988 can supply sufficient current to energize typical two-phase stepper windings,

ensuring dependable torque under load. Finally, its widespread availability and low unit cost make it an economical choice compared to alternative drivers or motion-control solutions, which is why it became our preferred component.

5.3.1. Micro Stepper Motor Technical Specifications and Mechanical Parameters

The selected motor is a 2-phase, 4-wire stepper motor. The body diameter is 4.3 mm and the total height is 8.3 mm. The fine-threaded mechanism integrated into the motor shaft creates a linear slide movement, with an effective stroke (stroke) of 8 mm. To complete this linear stroke, the motor must produce a total of 1,750 steps (pulses); therefore, each step signal provides approximately 0.0046 mm of movement along the slide axis (8 mm / 1,750 steps).

The super-miniature ball bearing located at the top of the slide minimises friction, enabling high-precision movement and contributing to long-lasting performance. The motor phase resistance is specified as 10 Ω for each phase. At a supply voltage of 5 V, the short-circuit current is approximately 390 mA.

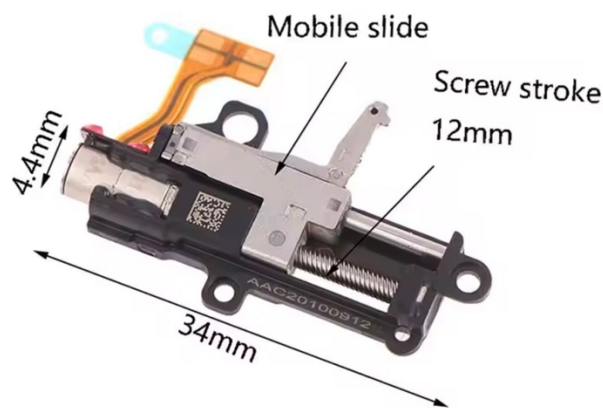


Figure 5.2. Measures of Linear Step Motor

These values indicate that the motor can be used under low power conditions and can be easily driven with microstep driver circuits (e.g., A4988). Considering the phase

resistance and current values, the motor's operational safety and thermal stability can be ensured when a current limiting function is used in the driver circuit.

5.3.2. Performance and Application

The motor's total weight is only 3 grams, making it ideal for portable applications such as telescopic glasses that require minimal space. The 8 mm linear stroke and 0.0046 mm resolution provide sufficient accuracy for optical systems and adjustable lens applications requiring micron-level positioning. The miniature ball bearing minimises friction, ensuring repeatable linear motion and reducing system instability. When combined with low power consumption, these features enable long-lasting and reliable performance in applications such as wearable devices and mobile optical platforms.

$$Resolution = \frac{8 \text{ mm}}{1750 \text{ step}} = 0.004571 \text{ mm/step}$$

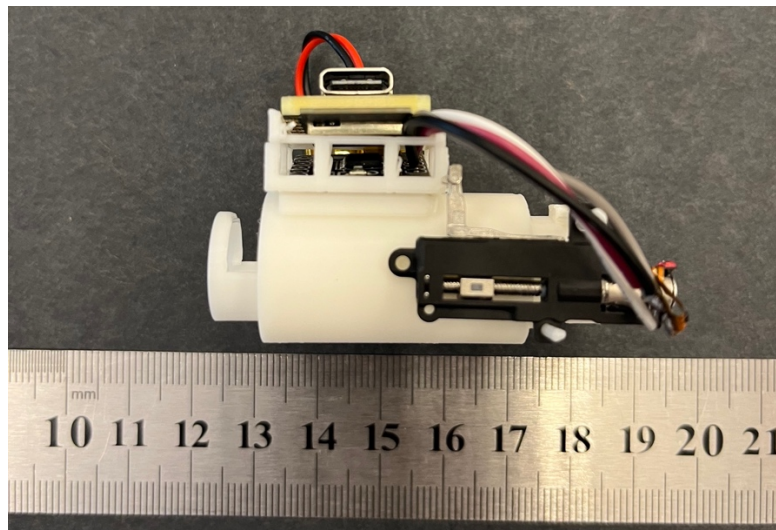


Figure 5.3. Actual Visual for Stepper Motor Replaced on the Tube Along with a Ruler

5.3.3. PID (Proportional-Integral-Derivative)

In the initial phase of system development, discrete Hall-effect sensors were employed to determine the mechanical zero and end positions of the linear actuator. These calibration experiments were repeated multiple times under varying conditions to ensure mechanical consistency and to verify the repeatability of boundary detection. A custom PID (Proportional-Integral-Derivative) controller was implemented during this phase to fine-tune the actuator's movement and dynamically correct any overshoot or lag observed near the stroke limits.

Through extensive experimentation, it was observed that the miniature stepper motor used in the system—owing to its compact size and internal metal gear construction—exhibited negligible backlash and no observable step loss under nominal load conditions. Even in scenarios involving minor perturbations or missed steps, the combination of position feedback during the initial calibration phase and the real-time correction enabled by the PID algorithm effectively compensated for positional drift. Thus, once the stroke endpoints were reliably characterized, sensorless step counting became viable for continuous position control during normal operation.

To further simplify the hardware architecture and reduce power consumption during runtime, it was later decided to phase out discrete Hall sensors and instead leverage the integrated BNO085 sensor, specifically its magnetometer module, for subsequent soft-limit calibration. The approach involves detecting unique and stable magnetic field signatures positioned at the mechanical boundaries of the actuator stroke. This eliminates the need for external sensors and facilitates a more compact and cost-efficient design.

However, magnetometers are inherently susceptible to environmental electromagnetic interference and often provide lower spatial resolution than discrete sensors. To address these limitations, a combination of signal conditioning techniques was employed:

Hysteresis thresholds were applied to distinguish true magnetic signatures from noise-induced fluctuations.

Low-pass digital filtering was used to suppress high-frequency disturbances.

A state machine was designed to validate magnetic field transitions, ensuring soft-limit detection only under consistent and stable readings.

While the BNO085's magnetometer cannot replace precise closed-loop encoders in high-precision systems, its integration with the existing control algorithm and PID-based correction strategy proved sufficient for periodic recalibration. This hybrid approach ensures long-term reliability while maintaining minimal hardware complexity and power consumption—critical for space- and energy-constrained applications such as wearable optical systems.

PID equation is as follows:

$$u(t) = K_p \cdot e(t) + K_i \cdot \sum_{i=0}^n e(i) \cdot T + K_d \frac{e(t) - e(t-1)}{T} \quad (5.1)$$

Here;

- $u(t)$: Output (Number of steps)
- $e(t) = r(t) - y(t)$: Difference between target and measurement (error)
- T : Sampling period
- K_p, K_i, K_d : Proportional, integral and derivative gain, respectively

Table 5.1. System Parameters

Parameter	Value	Explanation
s_{res}	0.0046 mm/step	Resolution of step motor
d_{stroke}	8 mm	Distance of total linear movement
T	20 ms	PID sampling period
m	3 g	Load (Optical tube and lens)
F_{load}	~0.05 N	Typical friction load
v_{target}	1 mm/s	Target speed (Baseline scenario)

$$K_p = 2.0, K_i = 0.5, K_d = 0.1$$

- Logic of Application (Positioning of Step Motor)

The system operates as follows according to the specified target position:

1. Target position x_r is compared with current position x
2. Error: $e(t) = x_r - x$
3. Output is produced by algorithm of PID control
4. This output determines how many steps forward or backward the motor needs to move.

- Discrete-Time PID Equation (Euler Approach)

Discrete form is used due to digital control in real systems:

$$u[k] = K_p \cdot e[k] + K_i \cdot T_s \cdot \sum_{i=0}^k e[i] + K_d \frac{e[k] - e[k-1]}{T_s} \quad (5.2)$$

Or with more compact form:

$$u[k] = u[k-1] + K_1 \cdot e[k] + K_2 \cdot e[k-1] + K_3 \cdot e[k-2] \quad (5.3)$$

Here:

- $K_1 = K_p + K_i \cdot T_s + \frac{K_d}{T_s}$
- $K_2 = -K_p - 2 \frac{K_d}{T_s}$
- $K_3 = \frac{K_d}{T_s}$

- Formulation of Position Update (for step motor)

The step motor position is updated as follows with the given step amount:

$$x[k+1] = x[k] + u[k] \cdot s_r \quad (5.4)$$

Here, $u[k]$ is generally rounded to the nearest whole number since step motor can not move with rational number.

Example: Numeric Application

Let's assume

$$K_p = 2.0, K_i = 1.0, K_d = 0.05$$

$$T_s = 0.02 \text{ s}$$

$$s_r = 0.0046 \text{ mm/step}$$

Initial error: $e[0] = 1.0 \text{ mm}$ -> System needs to move 1mm

$$u[0] = 2.0 \cdot 1.0 + 1.0 \cdot 0.02 \cdot 1.0 + 0.05 \cdot \frac{1.0-0}{0.02} = 2 + 0.02 + 2.5 = 4.52 \Rightarrow$$

$$u[0] = 5 \text{ steps}$$

$$x[1] = x[0] + 5 \cdot 0.0046 = 0.023 \text{ mm}$$

- PID Controller Transfer Function (Z-Domain)

As already derived above:

$$G_{PID}(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 - z^{-1}} \quad (5.5)$$

Constants (with parameters):

$$K_p = 2.0, K_i = 1.0, K_d = 0.05, T_s = 0.02 \text{ s}$$

$$b_0 = K_p + K_i \cdot T_s + \frac{K_d}{T_s} = 2.0 + 0.02 + 2.5 = 4.52$$

$$b_1 = -K_p - 2 \frac{K_d}{T_s} = -2.0 - 5.0 = -7.0$$

$$b_2 = \frac{K_d}{T_s} = 2.5$$

$$G_{PID}(z) = \frac{4.52 - 7z^{-1} + 2.5z^{-2}}{1 - z^{-1}} \quad (5.6)$$

- Transfer function of closed loop system

Whole system is modelled as below:

$$G_{closed}(z) = \frac{G_{PID}(z).G_{motor}(z)}{1 + G_{PID}(z).G_{motor}(z)} \quad (5.7)$$

First, open loop transfer function is written as

$$G_{open}(z) = G_{PID}(z).G_{motor}(z) = \left(\frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 - z^{-1}} \right) \cdot \left(\frac{s_r}{1 - z^{-1}} \right) \quad (5.8)$$

$$G_{open}(z) = \frac{s_r (b_0 + b_1 z^{-1} + b_2 z^{-2})}{(1 - z^{-1})^2} \quad (5.9)$$

And closed loop transfer function is derived as below:

$$G_{closed}(z) = \frac{s_r (b_0 + b_1 z^{-1} + b_2 z^{-2})}{(1 - z^{-1})^2 + s_r (b_0 + b_1 z^{-1} + b_2 z^{-2})} \quad (5.10)$$

Example: Numeric Transfer Function

Resolution of step motor: $s_r = 0.0046$ mm/step

$$G_{open}(z) = \frac{0.0046(4.52 - 7z^{-1} + 2.5z^{-2})}{(1 - z^{-1})^2} = \frac{0.0208 - 0.0322z^{-1} + 0.0115z^{-2}}{(1 - z^{-1})^2}$$

$$G_{closed}(z) = \frac{0.0208 - 0.0322z^{-1} + 0.0115z^{-2}}{(1 - z^{-1})^2 + 0.0208 - 0.0322z^{-1} + 0.0115z^{-2}}$$

5.3.4. Cost and Functionality Balance

From a cost perspective, this micro stepper motor, priced at approximately 0.6 USD per unit, is directly suited for prototype or small-scale production requirements. The 8 mm linear stroke, micron-level step resolution, and low power requirement it offers in terms of functionality make it cost-effective, especially in budget-constrained projects. The motor's availability in the market and low unit cost provide cost-effectiveness in both research and development processes and in the final product. Therefore, when its technical parameters and economic value are evaluated together, the motor is fully capable of meeting the precise focusing and low production cost objectives of the telescopic glasses project.

The importance of using mini linear step motors in telescopic eyeglass designs is directly related to the prototype's ability to precisely adjust the lens distance. The main reasons for choosing step motors include their ability to position with high precision, suitability for continuous motion, and energy efficiency.

Step motors, which move in specific step sizes, offer an ideal solution for achieving clarity and focus by adjusting the distance between the lenses in the glasses at the micron level [34]. The customisable features of step motors, which can be configured according to application requirements, provide a significant advantage in the project.

In particular, various control methods can be applied to optimise the time and precision required to adjust the position of the lenses, thereby enhancing the practicality of the design [35]. The high torque and instantaneous control capability of the motors enable the glasses to adapt quickly to different optical conditions [36].

Additionally, the robust feedback mechanisms provided by stepper motors enhance accuracy and stability. This contributes to the overall performance of the application and improves the user experience of the glasses prototype. When used in conjunction with advanced control algorithms, mini linear stepper motors simplify the complexity of lens positioning systems and make them more user-friendly [36].

In conclusion, the preference for mini linear step motors in telescopic eyeglass designs is supported by both the technical advantages they offer and their practical application ease. These motors significantly improve the performance of eyeglass prototypes and positively impact the user experience by offering high precision, reliability, and energy efficiency.

5.4. Embedded System Design

As in this project, processor selection is critical in energy-constrained applications, especially those powered by batteries, in terms of both hardware architecture and wireless protocol support. Within the scope of this study, a custom PCB was designed to integrate all essential components required for controlling and operating the system, including the microcontroller, power regulation units, and peripheral interfaces. Rather than relying on off-the-shelf development boards such as Arduino or ESP32 modules, a dedicated board was developed to meet the application's specific constraints in terms of physical size, power efficiency, and connectivity. This approach enables tighter system integration, a reduced form factor, lower weight, and a hardware architecture optimized for the system's communication and power management needs. The PCB designed for this project is configured as follows: First, the card can be powered both via the LiPo battery connector and via the USB-C port. The USB-C port is not only used as a power source but also for reprogramming the card and charging the battery. On the power management side, the

BQ24232 battery management integrated circuit forms the heart of the circuit. This IC enables dynamic power-path control, allowing the battery to be charged while the system is running and enabling direct use of USB power for high-priority loads when needed. Focusing on the card's sensor platform, the VCNL4040 light and proximity sensor has been directly integrated into the circuit. This enables ambient light measurement and detection of objects up to 20 cm away. In this project, the BNO085 motion sensor was also placed on the PCB to enable motion tracking and more accurate position information. The BNO085 enables the use of sensor fusion algorithms by supporting them at the hardware level via its built-in 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer. This enables direct measurement of angular parameters such as roll, pitch, and yaw, as well as real-time monitoring of motion status detection, personal activity estimation, linear acceleration, and step counting. The ESP32-C6 Mini microcontroller board was used as the communication and processing unit. The ESP32-C6 Mini's low power consumption and support for multiple communication protocols (Wi-Fi, Bluetooth LE, and Zigbee compatibility) provided significant advantages for the project's applications. The circuit traces required to power the microcontroller peripherals and communicate with the external world were carefully placed on the board. Particular attention was paid to minimising interference between digital and analogue sections by distributing power lines and grounding across layers. The aim was to block high-frequency noise from sensors while ensuring uninterrupted Bluetooth signal transmission. The PCB layout features a four-layer structure: The first layer contains signal traces, the second layer power distribution (VCC, battery, and SYS paths), the third layer the ground (GND) layer, and the fourth layer signal traces again. This layering isolates the power path of the BQ24232 and ensures high accuracy in sensor ADC (Analog-to-Digital Converter) readings. Additionally, by directly connecting the analog reference lines (AREF) of the VCNL4040 and BNO085 sensors to the GND layer, ADC sensitivity is maximised. For battery protection, the necessary SMD resistors and MOSFET arrangements have been added to the PCB. Using the I²C communication of the BQ24232 integrated circuit, the charge status, battery voltage, and temperature data can be monitored in real-time via the microcontroller.

With the integration of the embedded power management logic implemented in the software layer, the system automatically transitions into a power-saving mode when the battery level drops below a predefined threshold. Prior to disabling any critical sensor or processing units, a warning is issued, ensuring a controlled and predictable shutdown process. The BNO085 sensor provides access to full 9-axis raw data, from which sensor fusion outputs—such as Euler angles and linear acceleration—can be derived in real time.

The data were collected using a task-oriented system architecture capable of entering low-power sleep modes when required. This architectural approach enhances overall energy efficiency and contributes to extended battery life, even in applications that demand continuous sensing and processing. Furthermore, the mechanical dimensions of the PCB were optimised to minimise spatial footprint, in alignment with the form factor constraints defined in this study.

To this end, all SMD components were meticulously selected, and their layout was optimized to ensure that the PCB retained a compact square form factor measuring 1.85×1.85 cm. This compact design can be easily used in wearable robotic prototypes or mobile research platforms. Additionally, necessary test points and programming headers (SWD and UART) were predefined to facilitate PCB surface mounting. As a result, the PCB designed in this research process successfully integrates a robust power management system (BQ24232), precise light/distance measurement (VCNL4040), advanced motion detection (BNO085), a powerful processor module (ESP32-C6 Mini), and an optimised four-layer PCB layer structure, enabling it to operate successfully in applications requiring both low power consumption and high accuracy, and is hereafter referred to as t2D. This design demonstrates qualities suitable for academic applications and may inform future work in robotic and portable wearable system development.

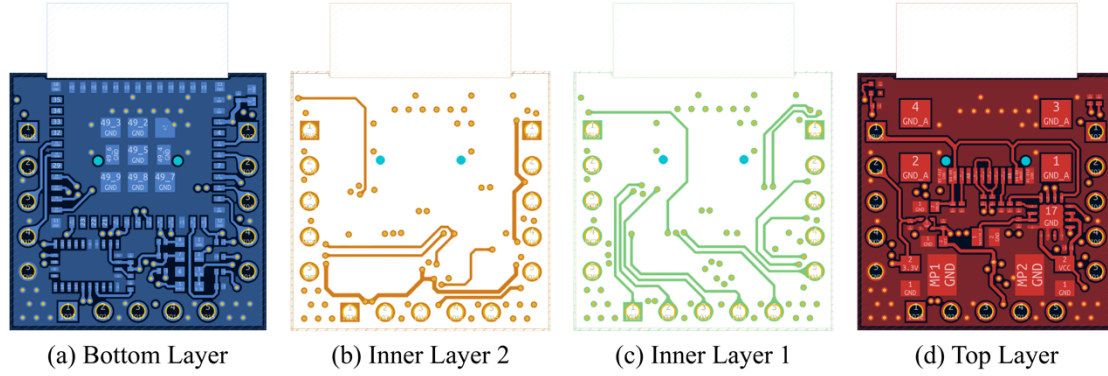


Figure 5.4. Layer-by-Layer Structure of the t2D Four-Layer PCB

The t2D board developed in this study was designed with a four-layer printed circuit board (PCB) architecture centered around the ESP32-C6-MINI-1 module. The board consists of four signal layers arranged from bottom to top as a) Bottom Layer, b) Inner Layer 2, c) Inner Layer 1, and d) Top Layer (Figure 5.4). All signal traces for the I/O pins are routed through c) Inner Layer 1, while power distribution and I²C bus lines are routed through b) Inner Layer 2 using dedicated traces. To reduce manufacturing costs and minimize the expense of plated through-holes in high-density layouts, vias have been optimized with a 0.20 mm drill size and a 0.45 mm copper annular ring. All layers function as signal layers, and both power and data lines are distributed across multiple layers to increase routing flexibility. The system offers a total of 10 GPIO outputs (GPIO2, GPIO3, GPIO4, GPIO5, GPIO14, GPIO15, GPIO18, GPIO19, GPIO21, GPIO22) which are depicted in Figure 5.5, two of which (GPIO2, IO3) provide ADC (analog input) functionality. Additionally, GPIO18 (SCL) and GPIO19 (SDA) are designated as the I²C bus lines. GPIO31 (TXD0) and GPIO30 (RXD0) are assigned for UART communication and routed to the programming and debugging header. While the system primarily supports over-the-air (OTA) updates via Bluetooth through a mobile application, these UART lines remain available for initial firmware flashing, debugging, and fallback programming when necessary. This architecture provides high routing capability and systematic signal integrity for sensor and motor control applications.

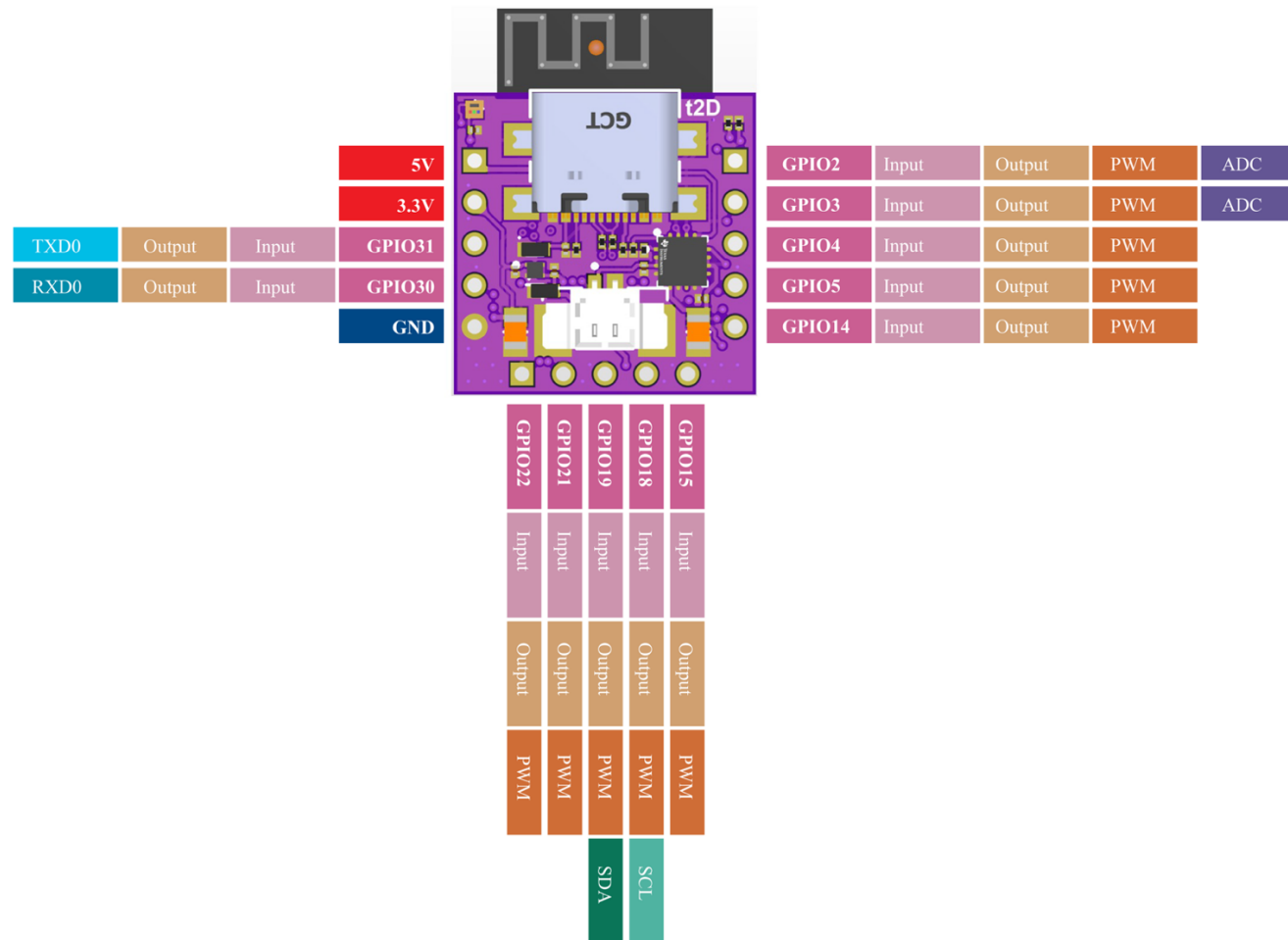


Figure 5.5. Pinout Diagram of t2D

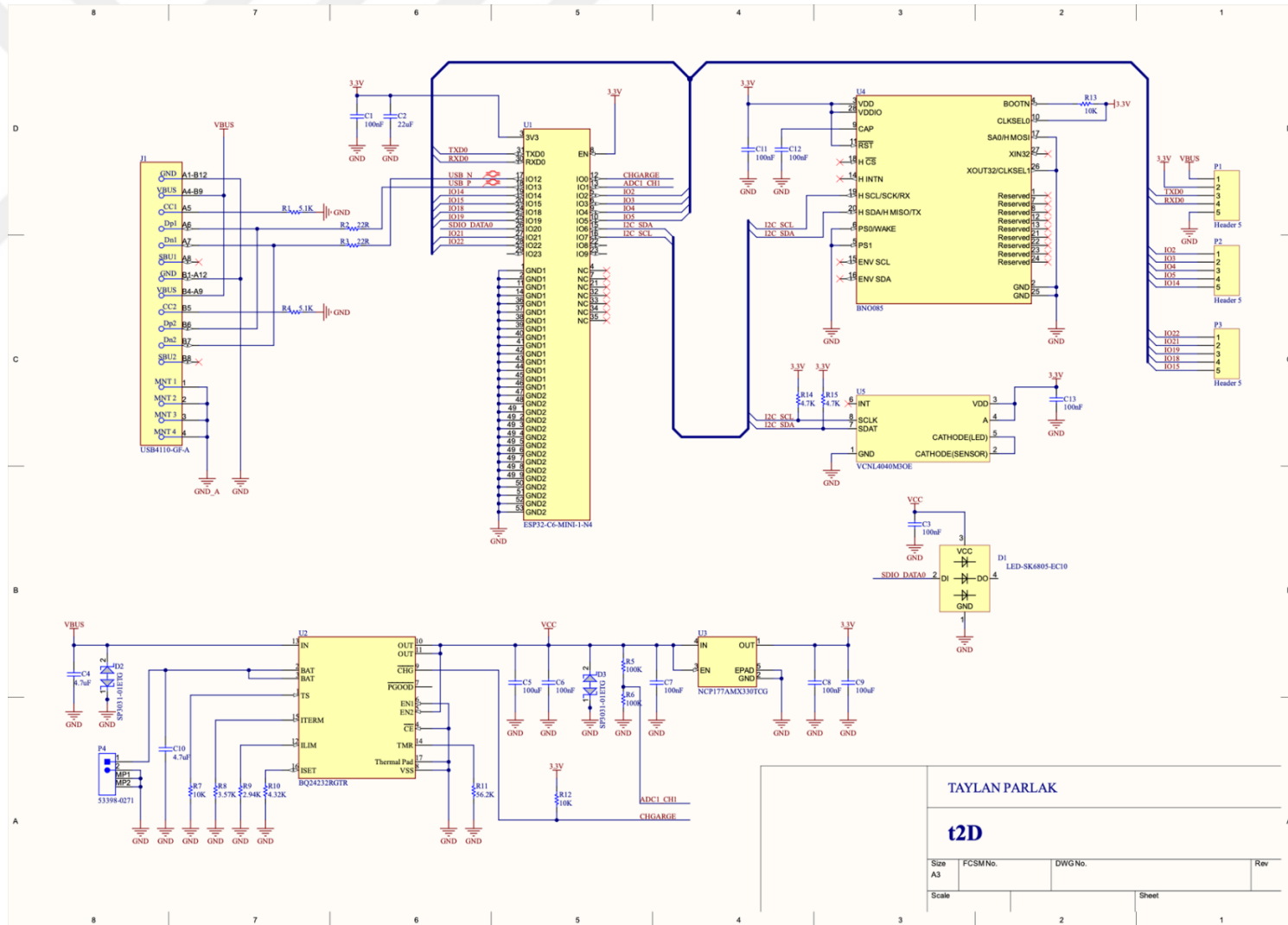


Figure 5.6. Schematic of t2D

5.4.1. Key Components in the Hardware Design

- **t2D-C6-MINI-1**
 - 32-bit RISC-V, 160 MHz
 - Powered via 3.3 V LDO (NCP177AMX330TCG LDO used here)
 - In active mode (Wi-Fi/BLE enabled, running code) ≈ 70 mA @ 3.3 V (datasheet typical)
 - In Deep-Sleep mode (RTC + minimal units enabled) ≈ 2.5 μ A @ 3.3 V (module level; may be around 14 μ A with additional circuits on the board)
- **BQ24232RGTR (Battery Management)**
 - 1S Li-Po CC/CV charge controller and power-path (SYS) output
 - Charge current programmable up to 1 A via the PROG pin (by selecting R_PROG)
 - Provides power to both the ESP32-C6 and the motor driven by the boost converter via the SYS (load output)
 - The ‘System Discharge’ (charging) current from the SYS output can support up to 2 A depending on thermal conditions.
- **NCP177AMX330TCG (3.3 V LDO Regulator)**
 - SYS (varies between approx. 3.7 V–4.2 V) $\rightarrow$ 3.3 V regulation
 - Efficiency (η_{LDO}) for mixed loads (ESP32-C6 + sensors) is assumed to be approximately 90%
- **BNO085 (9-Axis IMU Sensor)**
 - Typical operating current (active, all sensors on) ≈ 12 mA @ 3.3 V (nominal ≈ 12 mA according to datasheet)
 - When in low-power mode (suspend ≈ 2 μ A), but here 12 mA during ‘active’ times and ≈ 2 μ A during ‘sleep’ times will be taken.
- **VCNL4040M3OE (Proximity + Ambient Light Sensor)**
 - Typical ‘proximity measurement’ current ≈ 200 μ A @ 3.3 V (active)
 - Standby (before individual ‘proximity/light’ readings) ≈ 0.5 μ A.

- Here, it is assumed that it will operate at 200 μA in ‘active mode’ and 0.5 μA in ‘sleep mode’.
- **Other Passive on t2D /LED/PCB Draws**
 - Several LEDs (charge status, power LED), I²C drivers, pull-up/pull-down resistors, etc., on the board.
 - These passive extras will be accounted for as an additional $\approx 5\text{--}8\text{ mA}$ in active mode and an additional $\approx 5\text{--}10\text{ }\mu\text{A}$ in sleep mode.

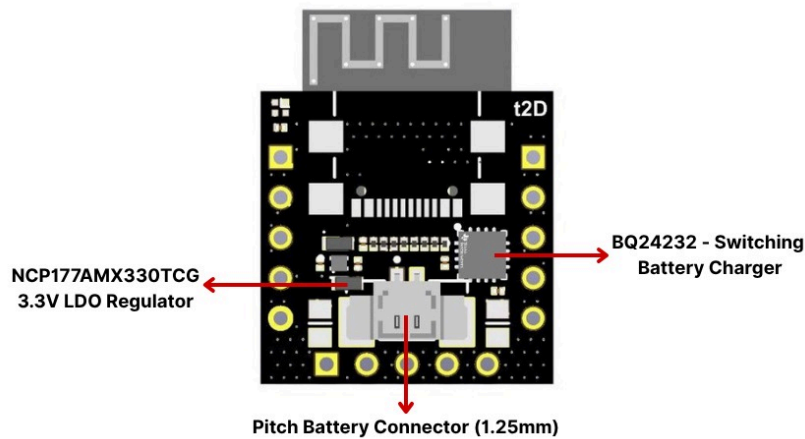


Figure 5.7. Main Components of t2D (Front)

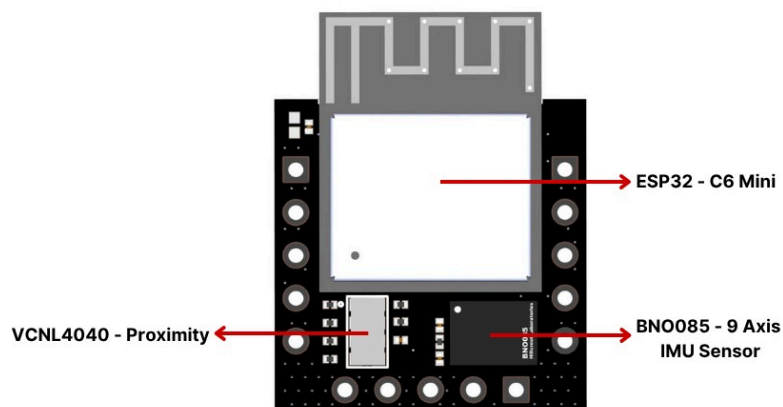


Figure 5.8. Main Components of t2D (Back)

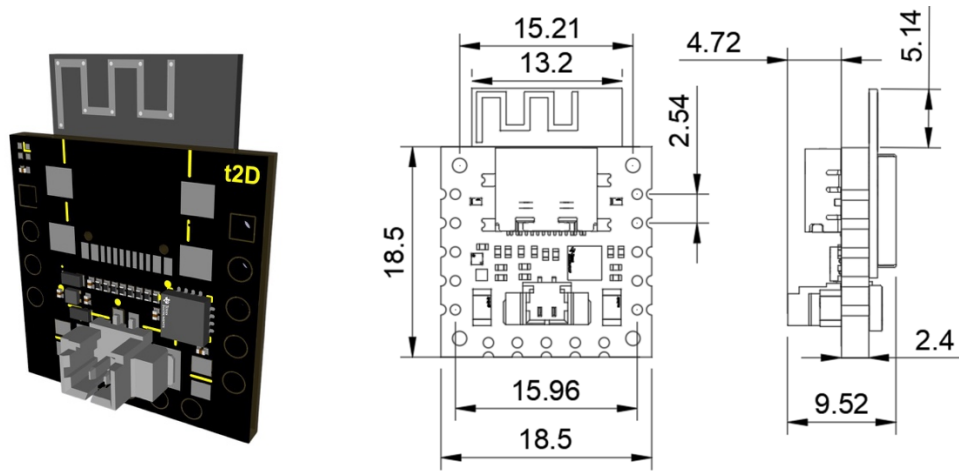


Figure 5.9. 3D Visual of t2D and Measures

The images above show the 3D model and physical dimensions of the designed t2D PCB. The images below display the actual fabricated PCB without its electronic components, placed next to a 1 Turkish Lira (TL) coin for scale. This visual comparison highlights the compactness and real-world size of the board.

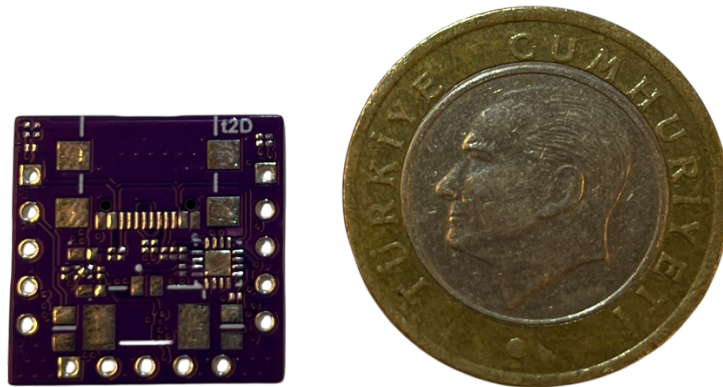


Figure 5.10. Real PCB without Components, Compared with 1 TL

5.5. System Hardware Architecture

5.5.1. Component Selection and Rationale

- **ESP32-C6-MINI-1** 32-bit RISC-V core, operating at 160 MHz, this module was selected for its low power consumption and support for Wi-Fi 6 and BLE 5. In active mode, it draws approximately 70 mA at 3.3 V, which is sufficiently low for embedded applications; in deep-sleep mode, the module draws approximately 2.5 μ A (approximately 14 μ A with additional circuitry on the board), enabling it to remain in standby for months. The SMT package size ($13.2 \times 16.6 \times 2.4$ mm) allows for easy integration into compact designs such as eyewear.
- **BQ24232RGTR (Battery Management)** A single-cell (1S) Li-Po battery can be charged up to 1 A using the CC/CV method, and this chip supplies power to both the battery and the load (ESP32 and motor from the boost module) via the ‘power-path’ output (SYS). The charge current, programmable via the PROG pin, protects the battery while the system is active; it can provide continuous ‘system discharge’ up to 2 A via the SYS output as long as thermal conditions permit. This design ensures both a long battery life for the device and safe handling of sudden high current requirements (motor driving) situations.
- **NCP177AMX330TCG (3.3 V LDO Regulator)** reliably reduces the SYS voltage from the BQ24232, which is approximately 3.7–4.2 V, to 3.3 V. With approximately 90% efficiency, it minimises power loss while powering both the ESP32-C6 and I²C sensors (BNO085, VCNL4040). It is preferred for portable devices like glasses because it eliminates the need for an additional voltage converter and features a compact SOT-23 package size.
- **BNO085 (9-Axis IMU Sensor)** This sensor integrates an accelerometer, gyroscope, magnetometer, and AI processor, making it ideal for motion detection and directional sensing. In active mode, it draws approximately 12 mA at 3.3 V, and in low-power mode, it draws approximately 2 μ A, extending battery life in wearable applications while maintaining high accuracy. This is made possible by the dual-core sensor processor, which enables complex motion algorithms to run

quickly on the device, providing a significant advantage for automatic position adjustment and stabilisation in wearable applications.

- **VCNL4040M3OE (Proximity + Ambient Light Sensor)** This I²C -based sensor detects both proximity and ambient light, drawing $\approx 200 \mu\text{A}/3.3 \text{ V}$ in active mode and $\approx 0.5 \mu\text{A}$ in standby mode. It has been selected for eyewear applications to provide automatic brightness adjustment based on the user's movement or proximity-based functions (e.g., control via hand gestures). Low power modes ensure long battery life for the eyewear in standby mode.
- **Bluetooth Low Energy (LE)** support is preferred in situations that require low-power communication over short distances. Bluetooth LE communication with low power consumption is used to control motor movements (zoom in, zoom out, focus adjustment, position presets) by connecting the glasses to a smartphone, tablet or remote control device. The long-range ‘Coded PHY (LE Coded)’ mode offered by BLE 5 provides a relatively wider coverage area even with the limited power of the small antenna mounted on the glasses. Additionally, an iOS or Android-based app enables remote adjustment while preserving battery life.

The t2D system is a compact, low-power wearable control unit built around the ESP32-C6-MINI-1, which enables Bluetooth communication with a mobile app or controller to drive a linear stepper motor that adjusts the position of a telescopic optical tube. Commands received over BLE allow the tube to move forward or backward with micron-level precision. For motion sensing and event-based, the system integrates the BNO085 IMU, which not only calibrates the motor’s position at startup but also continuously monitors for sudden movements such as falls. In such cases, the system can automatically send an alert—along with real-time location data—to a predefined contact via the mobile app. To enhance reliability, the VCNL4040 proximity and light sensor enables a touchless “reset” mechanism: if an e.g., a hand is brought within approximately 1–2 cm of the sensor and held steady for about 3 seconds, the system interprets this as a reset gesture and returns the motor to its default home position. Power is efficiently managed via the BQ24232RGTR battery management IC, which handles both charging and power delivery

using a single-cell Li-Po battery, and the NCP177AMX330TCG LDO regulator, which steps down the system voltage to 3.3 V for the ESP32 and I²C sensors. This architecture ensures a compact form factor and long standby time (drawing as low as 14 μ A), making the t2D ideally suited for smart wearable applications such as motorized telescopic glasses.

5.5.1.1. Low Power Consumption and Energy Efficiency

In battery-powered embedded sensor applications, the primary goal is to maximise battery life. The ESP32-C6-Mini-1 stands out in this context with the following features:

- **Ultra-low power modes**
 - **Deep Sleep:** When all major memory units and peripherals are turned off, the module's current consumption drops to approximately 2.5 μ A. Only the RTC (Real-Time Clock) circuit and a small portion of low-power (LP) SRAM remain active. Within the scope of this project, the system is programmed to wake at scheduled intervals to perform sensor readings and data transmissions, then return to deep sleep. This approach significantly extends battery life, potentially lasting for several months or years depending on usage frequency.
 - **Light Sleep:** Small peripheral circuits other than the RTC can remain on; wireless wake-up (wake-on-WiFi or wake-on-BLE) functions can be used. This mode offers a low-power but fast-response sleep solution for short standby periods.

Battery voltage depletion during wireless communication periods. Flexible Supply Voltage The module is compatible with operating voltages between 3.0 V and 3.6 V; it is typically powered through a 3.3 V LDO voltage regulator. The low voltage tolerance eliminates the need for additional voltage converters when using Li-Po or Li-Ion batteries, simplifying power management circuits. This also provides space and cost savings on the PCB. the cost ranges approximately between 3–5 \$.

5.6. Power Source and Consumption Estimation

The system designed for this project must be lightweight and compact as it will be integrated into a pair of glasses. For this reason, we selected a small 170mAh LiPo battery with the following specifications: The 170 mAh 20C LiPo battery measures $23 \times 17.5 \times 8.7$ mm and weighs 4.6 grams. It has a cable with a 1.25 mm female connector, which can be plugged directly into the connector on the card. The physical size of the device is approximately the size of a penny, making it easy to use in projects where weight and size are critical.

- Stepper Motor
 - *Battery $\rightarrow$ Boost $\rightarrow$ Motor: 0.587 A ($3.7\text{ V} \rightarrow 5\text{ V}$, $\eta_{\text{boost}} = 0.90$)*
- ESP32-C6 Active
 - $3.3\text{ V} \times 0.07\text{ A} = 0.231\text{ W}$
 - *LDO efficiency 0.90 $\rightarrow$ from battery: $0.231\text{ W} / 0.90 \simeq 0.257\text{ W}$*
 - *Battery current: $0.257\text{ W} / 3.7\text{ V} \simeq 0.069\text{ A}$*
- BNO085 Active
 - $3.3\text{ V} \times 0.012\text{ A} = 0.0396\text{ W}$
 - *LDO efficiency 0.90 $\rightarrow$ from battery: $0.0396\text{ W} / 0.90 \simeq 0.044\text{ W}$*
 - *Battery current: $0.044\text{ W} / 3.7\text{ V} \simeq 0.012\text{ A}$*
- VCNL4040 Active
 - $3.3\text{ V} \times 0.0002\text{ A} = 0.00066\text{ W}$

- LDO efficiency 0.90 $\rightarrow$ from battery: $0.00066 \text{ W} / 0.90 \simeq 0.00073 \text{ W}$
- Battery current: $0.00073 \text{ W} / 3.7 \text{ V} \simeq 0.0002 \text{ A} (\approx 0.2 \text{ mA})$
- Other Passive/LED (Active)
 - $3.3 \text{ V} \times 0.006 \text{ A} = 0.0198 \text{ W}$
 - LDO efficiency 0.90 $\rightarrow$ from battery: $0.0198 \text{ W} / 0.90 \simeq 0.022 \text{ W}$
 - Battery current: $0.022 \text{ W} / 3.7 \text{ V} \simeq 0.006 \text{ A}$

Table 5.2. Currents of Active and Deep-Sleep Modes of Components

Componet	Batary Current	Componet	Batary Current
Motor (5 V stall)	0,587 A	Motor (5 V off)	0 A
ESP32-C6 (active)	0,069 A	ESP32-C6 (deep sleep)	14 μA
BNO085 (active)	0,012 A	BNO085 (low power)	2 μA
VCNL4040 (active)	0,0002 A	VCNL4040 (shutdown)	0.5 μA
Diğer Pasif/LED (active)	0,006 A	Diğer Pasif/LED (sleep)	1 μA
Total	$\approx 0,674 \text{ A}$	Total	$\approx 26,5 \mu\text{A}$.

5.6.1. Active mode Consumption;

$$I_{battery,motor} = \frac{V_{motor} \times I_{motor,5V}}{\eta_{boost} \times V_{battery}}, I_{battery,t2D} = \frac{V_{reg_out} \times I_{t2D}}{\eta_{reg} \times V_{battery}} \quad (5.11)$$

Then by adding these,

$$t = \frac{\text{Battery Capacity (mAh)}}{I_{\text{battery,total}}(\text{mA})} \quad (5.12)$$

$$I_{\text{battery,motor}} = \frac{5V \times 0,39A}{0,90 \times 3,7V} \approx 0,587A.$$

Total current (worst case): 0.674 A

Active time: 3 s

Coulomb (A s) → mAh conversion:

$$\begin{aligned} Q_{\text{per activation}} &= 0,674 A \times 3 s = 2,022 A \cdot s = \frac{2,022}{3600} Ah \approx 0,00056 Ah \\ &= 0,56 mAh. \end{aligned}$$

5.6.2. “Sleep” Mode Consumption;

$$I_{\text{sleep}} = 14\mu A + 2\mu A + 0,5\mu A + 10\mu A = 26,5\mu A.$$

5.6.3. Daily mAh Based on “50 Activations per Day” Scenario

Active Consumption (50 activations × 0.56 mAh):

$$50 \times 0,56 mAh = 28 mAh /day$$

Sleep Consumption (≈ 26.5 μA for 23.993 hours):

$$\text{Sleep duration} \approx 24 h - 50 \times 3 s = 86\,400 s - 150 s = 86\,250 s \approx 23.958 h$$

Converting sleep current to mAh:

$$Q_{sleep/day} = I_{sleep} \times duration (h) = 0,0265 mA \times 23,993 h \\ \simeq \frac{0,635 mAh}{day}.$$

$$Q_{total/day} = 28 mAh + 0,635 mAh = 28,635 mAh / day.$$

Battery Life (170mAh 28,635 mAh)

With 170 mAh battery

Daily worst case consumption: 28,635 mAh

$$Battery\ life = \frac{170 mAh}{28,635 mAh/day} \approx 5,93\ days$$

With 50 activations per day, the t2D board consumes approximately 28.635 mAh/day. Using a 170 mAh Li-Po battery, the system will operate for approximately 5.9 days (~6 days) under full load conditions (stepper motor running at stall for 3 seconds per activation).

5.6.4. Expected Daily Consumption

In real-life stepper motor drives, the motor does not always operate under full load (stall current). Especially in scenarios such as microstepping or low-speed movement, the motor current is controlled by the driver according to instantaneous requirements. In this case:

- Acceleration and deceleration phases have low instantaneous current.
- Mechanical load is often limited (e.g., a lightweight telescopic tube).
- Most of the motor's time is spent 'idling' or at low torque.

Therefore, to estimate the system's energy consumption more realistically, an 'average use' scenario is used. In this scenario, it is assumed that the motor draws an average current of around 250 mA during each operation (instead of the full load of 587 mA). In A4988 or similar drivers, the current supplied to stepper motors is typically limited to a

range of 0.2–0.5 A. The 250 mA value represents the average power drawn by the system during normal operation, which is reasonable given that the motor is not continuously active but only operates in short intervals (e.g., 3 seconds at time). 250 mA is the estimated current that the motor will draw in a typical practical usage scenario. This value is chosen as a balance point where the system will use energy efficiently without causing overheating or excessive battery consumption.

$$Q_{per\ activation} = \frac{0,250\ A \times 3\ s}{3600\ s} \times 1000 \approx 0,208\ mAh.$$

$$50 \times 0.208 = 10.42\ mAh/day$$

Sleep Consumption ($\approx 26.5\ \mu A$ for 23.958 h):

$$Q_{sleep/day} = I_{sleep} \times duration\ (h) = 0,0265\ mA \times 23,993\ h \\ \approx \frac{0,635\ mAh}{day}.$$

$$Q_{\frac{total}{day}} = 10,42\ mAh + 0,635\ mAh = 11,055\ mAh / day.$$

$$Battery\ life = \frac{170\ mAh}{11,055\ mAh/day} \approx 15,4\ days$$

The Stall Current scenario represents the worst-case scenario where the motor operates continuously at maximum load. The Average Use scenario represents a more realistic situation where the motor draws an average current during typical use. Considering these results, the actual system life will be between these two scenarios; it may vary depending on the load, motor type, and driving profile.

$$Average\ Consumption = \frac{T_{stall} + T_{average}}{2} = \frac{28,635\ mAh + 11,055\ mAh}{2} \\ \approx 19,845\ days$$

$$\text{Average Battery Life} = \frac{P_{stall} + P_{average}}{2} = \frac{5,93 \text{ days} + 15,4 \text{ days}}{2} \approx 10,67 \text{ days}$$

5.7. System Software Architecture

The t2D is a low-power, wearable device that controls a telescopic tube by moving it forward and backward using a linear stepper motor. The system's central unit is the ESP32-C6-MINI-1 module, which supports BLE (Bluetooth Low Energy) and can be controlled via various input methods. Below, the main user control methods are mapped to corresponding hardware modules described in Section 5.5.

5.7.1. Control via iOS App (via BLE)

This mode operates through the “BLEManager” class in the Communication Layer, with high-level logic coordinated by the “MainController”. The user connects to the t2D device via an iOS app using BLE. The app interface provides a continuous slider (0–100%) and several predefined position buttons, which send commands such as “MOVE_TO:x” (where x represents the target motor position) to the device. These commands are processed by the “MainController” and forwarded to the “MotorDriver,” which executes precise stepper motor movement via the “moveToPosition(x)” function.

Simultaneously, the “IMUSensor” module in the Sensor Layer constantly evaluates device orientation. In case of abnormal movement, such as a fall, the “IMUSensor” triggers an interrupt. The system then uses “BLEManager” to dispatch an emergency BLE message (e.g., “FALL_DETECTED@Location”), optionally augmented with real-time location information if the iPhone app provides access to GPS services.

5.7.2. Control via Another t2D or via a Joystick (Master-Slave BLE)

In this configuration, the controlling t2D device or an external joystick module functions as a BLE Master, while the target t2D behaves as a BLE Slave. BLE communication is again managed through the “BLEManager”. Joystick actions are interpreted by the controlling unit’s “MainController” and translated into directional commands (e.g., "FORWARD", "BACKWARD"). These are sent over BLE and received by the target device, which processes them through its own “MainController” and actuates the motor accordingly using the “MotorDriver” interface.

In addition to joystick-based control, the motor can also be controlled using the integrated 9-axis IMU sensor (BNO085) embedded in the t2D. In this alternative method, when the t2D is held in hand and gently tilted forward, the motor moves forward; when tilted backward, the motor moves in reverse. This enables intuitive and effortless control through natural hand movements, eliminating the need for an external joystick.

Consisting solely of the custom-designed t2D board and a LiPo battery, the compact structure of the t2D allows for easy handheld operation (Figure 5.11).

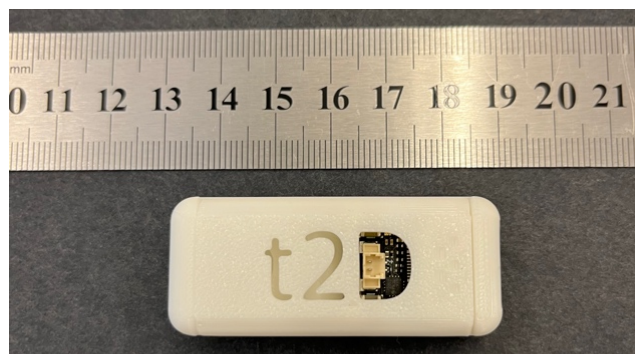


Figure 5.11. Designed and Produced Gesture-Controlled Gadget

5.7.3. Touchless Proximity Control (Failsafe / Reset)

In scenarios where BLE communication is unavailable or user input is limited, the “ProximitySensor” module (based on VCNL4040) provides a redundant failsafe mechanism. If a user's hand is brought within approximately 1–2 cm of the device and held for a defined duration (e.g., 3 seconds), the “ProximitySensor” registers the gesture as a soft reset event. This information is passed to the “MainController”, which in turn calls “MotorDriver.resetPosition()” to return the stepper motor to its calibrated zero position. This proximity-based interaction ensures that the device remains operable under impaired input conditions, offering robustness to the overall system design.

5.7.4. IMU-Supported Safety and Location Information

The “IMUSensor” (BNO085), residing in the Sensor Layer, is responsible for high-fidelity motion and orientation tracking. The sensor operates continuously in active mode, using embedded processing to detect events such as falls or abnormal tilting. Upon detecting a fall, the system generates an emergency signal that is handled by the “MainController”. If BLE is active and an iOS device is connected, the “BLEManager” module sends a "FALL_DETECTED@Location" message, optionally enriched with real-time positional data provided by the phone's geolocation services. This safety mechanism is critical for applications in assisted living, wearables, and mobility-enhancing systems.

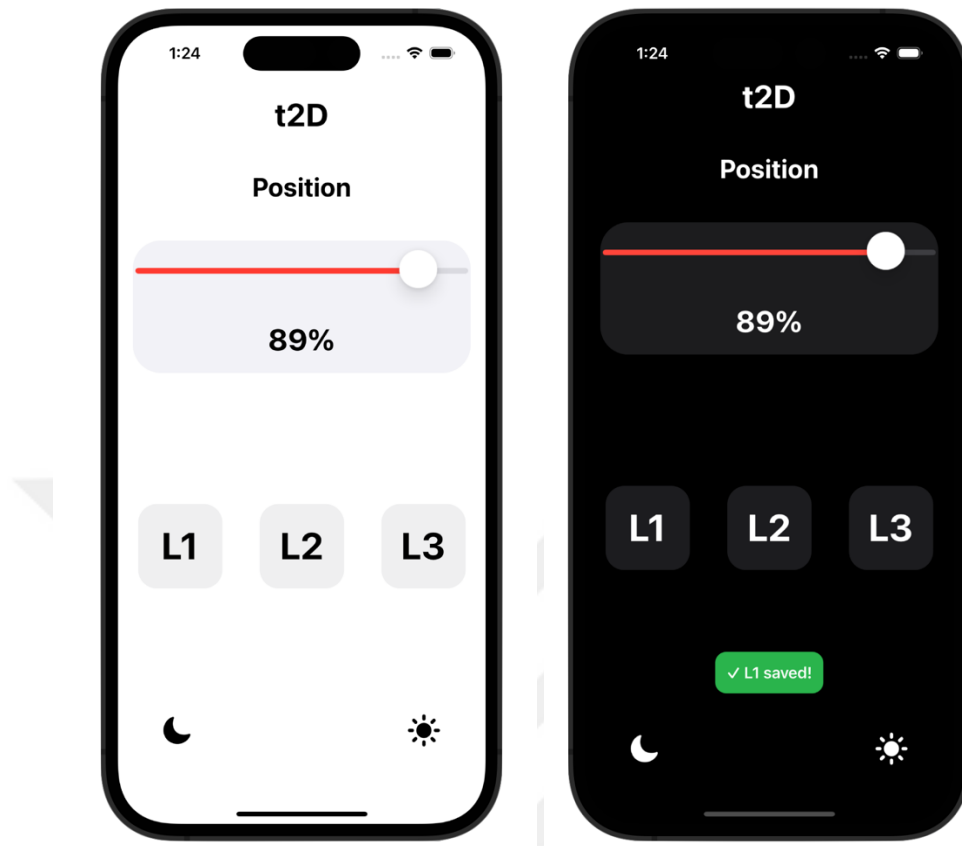


Figure 5.12. Mobile App for Glasses Control with Different Modes

The graphical user interface (GUI) of the t2D iOS application is deliberately designed with accessibility in mind, targeting individuals with low vision or visual impairments. The enlarged UI elements and minimalistic structure reflect a user-centered approach focused on clarity, contrast, and ease of interaction.

Large Visual Elements for Enhanced Visibility

- The slider used for motor position control is rendered with bold outlines, a thick progress bar, and a large circular thumb, making it easier to detect and operate even with limited visual acuity.
- The percentage indicator (“89%”) is placed prominently and sized appropriately to ensure legibility without requiring fine focus, addressing common challenges faced by users with reduced central or peripheral vision.

Oversized Preset Buttons (L1–L3)

- The L1, L2, L3 memory buttons are intentionally large and spaced out, allowing users to quickly save or recall predefined positions without precise finger targeting.
- This layout reduces the risk of accidental touches, which is crucial for users with hand tremors or impaired depth perception.

Dual Theme Support (Light & Dark Mode)

- The inclusion of light and dark modes is not purely aesthetic; it serves to accommodate different contrast preferences and lighting sensitivities.
 - Dark mode reduces glare and is particularly helpful for photophobic users.
 - Light mode maximizes contrast for users who prefer brighter visuals or who use screen magnification.

Confirmation Feedback

- The application provides immediate visual confirmation (e.g., "✓ L1 saved!") after interactions, offering reassurance and usability to users who may not perceive subtle UI state changes.

The program allows users to save custom motor positions using the L1, L2, and L3 buttons. When any of these buttons is held down for 3 seconds, the current motor position is saved to the relevant memory location. The saved position remains active in memory until the user overwrites it by repeating the same process. This feature provides quick and intuitive access to frequently used positions, offering ease of use, especially for users with low vision.

In addition, if a predefined emergency contact has been specified via the mobile app, the system can automatically send the user's real-time location and a fall notification to this person when a fall is detected. A fall detection system is of vital importance for individuals with low vision because vision loss makes it difficult to perceive environmental hazards and increases the risk of falling. When a person falls, they may need assistance but may delay calling for help because they cannot see their surroundings or determine their location. Therefore, the system's ability to detect a fall and automatically send location and alert information enables rapid response and enhances user safety.

6. EXPERIMENTAL RESULTS AND MULTIDIMENSIONAL IMPACT ANALYSIS

6.1. Findings

This study has focused on designing and developing a low-cost, lightweight, and adaptable telescopic lens system specifically intended for individuals with advanced visual impairments. Traditional telescopic eyewear, while offering some optical aid, presents significant limitations including excessive cost, considerable weight, lack of adjustability, and limited accessibility. These factors collectively restrict their adoption and practical use by those who need them most.

Through an in-depth review of existing optical systems, the Galilean telescope model was selected as the core architecture for the proposed design due to its simplicity, upright image output, and suitability for compact integration. The project then proceeded with the selection of specific glass lenses, guided by the need to meet a defined range of focal lengths suitable for daily use (approximately 30 cm to 4 meters). Optical simulations using ZEMAX validated that the proposed configuration could meet these constraints.

To corroborate the simulation results, an experimental setup was assembled on an optical bench. The physical system showed a high degree of agreement with the modeled predictions, with deviation margins remaining under 3%, which is acceptable for this class of application. Following this, a mechanical tube system was designed and fabricated using 3D printing technology. This structure allows variable lens distances through a sliding mechanism, enabling dynamic adjustment of focal points in response to different viewing scenarios.

Within the scope of this study, a low-power, wearable, and Bluetooth-controlled motorised telescopic optical system has been successfully developed. The system uses a linear stepper motor to move a sliding tube mechanism forward and backward, enabling precise adjustment of the distance between lenses. This movement is motorised, meaning

it can be controlled without manual intervention, via a specially designed control board called t2D. With BLE connectivity, users can control the position in real time via a mobile app or a Bluetooth controller.

In an important phase of the project, epoxy-based polymer lenses were produced to replace traditional glass lenses. For this purpose, epoxy resins with suitable optical properties were selected; the casting method was applied using silicone moulds, and the lens surfaces were polished to achieve the required optical clarity. This process not only provided the advantages of low cost and light weight, but also ensured that the system was easy to manufacture. The polymer lenses produced were tested in the existing mechanical and optical setup and demonstrated satisfactory focus performance.

As a result, the system now operates fully integrated both mechanically and optically; users can control the tube movement via an application or a Bluetooth controller in a motorised and wireless manner and easily adjust the desired focus positions. In this form, the t2D platform offers an innovative, low-cost, and user-friendly solution for smart wearable systems developed specifically for visually impaired individuals. In Table 6.1, the initially targeted values for each characteristic of the designed motorised telescopic glasses are presented in black, while the actual results achieved from the fully integrated motorised telescopic glasses are shown in green within parentheses in the same cell. The comparison clearly demonstrates that the final results meet or surpass the initial targets, proving the efficacy of the proposed glasses.

Table 6.1. Project Baseline Objectives and Final Outcomes in Relation to Key Determinants

Length (mm)	Volume (mm^3)	Weight (gr)	Dynamic range (mm)	Dynamic range change speed (sec)	Cost
					
< 70 mm (50.6 mm)	< 15 cm^3 (6.34 cm^3)	< 25gr (21gr)	Min 30cm Max 400cm	<6 sec (2 sec)	<20 \$ (14 \$)

6.2. Social Impact

The proposed telescopic lens system is not only a technical innovation but also a socially impactful project that addresses a vital accessibility gap in vision aid technology. Individuals who suffer from severe visual impairment, due to conditions such as age-related macular degeneration, albinism, or congenital ocular disorders, often find themselves excluded from educational and professional opportunities due to their inability to afford or physically manage traditional telescopic eyewear.

By significantly reducing the cost—targeting a price point between \$15 and \$20—and designing for minimal weight, the project dramatically increases the accessibility of optical aids. This makes it feasible for broader use in developing countries, underserved communities, or public health systems. Furthermore, the adaptability of the system’s focal length allows it to be used in varied contexts—reading, identifying distant objects, or navigating environments—all of which contribute to greater independence and inclusion of visually impaired individuals.

The anticipated outcome of the project is not just a tool but a catalyst for reintegration—empowering users to participate more actively in social, educational, and professional spheres. In doing so, it contributes directly to UN Sustainable Development Goals related to health, education, and reduced inequalities.

6.3. Economic Impact

From an economic standpoint, the project proposes a transformative approach to manufacturing assistive optical devices. Commercial telescopic eyewear is often priced between \$1,500 and \$5,000, due in part to the use of precision-ground glass optics and complex mechanical housing. These high prices not only limit accessibility for individuals but also reinforce monopolistic practices within a relatively small and specialized industry.

By substituting costly materials and processes with accessible alternatives—such as 3D-printed mechanical parts and polymer optics—the project opens the door to decentralized, scalable production models. These systems could be fabricated in local workshops, universities, or small-scale manufacturing centers, reducing the need for imports and expanding local technical capacity.

If scaled effectively, the design could serve as a foundational platform for startup ventures or government-funded initiatives aiming to distribute affordable vision aids. This would both stimulate local economies and challenge the current market structure dominated by a few high-end suppliers.

6.4. Environmental Impact

Environmental sustainability has been a core consideration throughout the design and development of this project. Traditional optical device production often involves energy-intensive glass grinding and machining, alongside significant material waste. In contrast, this project utilizes additive manufacturing (3D printing), which allows for minimal material use and precision production without excess waste.

Additionally, the filament materials used for 3D printing—such as PLA—are often recyclable or biodegradable. The lens material, anticipated to be a clear epoxy resin, will be selected based on its compatibility with green manufacturing principles. Wherever possible, recyclable polymers will be prioritized.

Furthermore, the small form factor and low energy requirements of the system (especially in its electronic configuration) make it environmentally friendly in terms of use-phase emissions and power consumption. These choices align with global trends toward sustainable, low-impact product design.

6.5. Standards Compliance

To ensure that the proposed design meets the regulatory and performance expectations for ophthalmic and mechanical products, several international and regional standards have been reviewed and incorporated into the design process:

- **TS EN ISO 14489** – Specifies power variation tolerances for ophthalmic lenses.
- **TS EN ISO 8980-2** – Defines measurement procedures and requirements for variable power lenses.
- **ISO 262, ISO 68-1, ISO 261** – These mechanical standards define the sizing and tolerances of threads, screws, and metric fasteners, which are critical for designing the modular housing and tube interfaces.

Adherence to these standards enhances the potential for certification and ensures safe, interoperable use in future medical or assistive applications.

6.6. Cost Analysis

An overview of the project's current cost structure is provided below. These values represent initial prototyping and development costs and may decrease significantly in mass production scenarios.

Table 6.2. Estimated Cost Breakdown for the Motorized Telescopic Glasses Prototype

Category	Estimated Cost (TRY)	Notes
Consumables	2,500	Includes 3D printing filament, resin for lens casting, adhesives
Mechanical Components	4,500	Includes motors, gears, structural components,pcb
Service Procurement	5,000	Optical lab usage fees, clean room access for lens casting
Software & Licenses	10,000	Zemax license, MATLAB usage, CAD software
Total Estimated Cost	22,000	Based on prototyping; scalable reduction possible post-validation

7. CONCLUSION

Within the scope of this thesis, a low-cost, lightweight, and adaptable motorised telescopic eyeglass system was designed and developed to enhance the visual independence of individuals with advanced vision loss in their daily lives. The primary aim of the study was to provide a user-friendly alternative to traditional telescopic glasses by addressing common drawbacks such as high cost, excessive weight, limited adjustability, and lack of accessibility.

The system design was based on the Galilean telescope configuration, incorporating both optical simulations and experimental prototyping. The developed mechanical tube structure, which was fabricated using 3D printing technology, was integrated with a motorised linear motion mechanism, enabling precise control over the distance between lenses. In addition, a BLE-based electronic circuit (t2D) was developed to allow wireless control, and the system was configured for seamless operation with an iOS application. Low-cost polymer lenses were also successfully fabricated using epoxy resin, and their optical performance was experimentally validated.

The system was designed with attention to its social, economic, and environmental impacts. Detailed assessments were conducted regarding cost analysis, standards compliance, and energy consumption scenarios. The proposed solution represents not only a technical innovation but also delivers strong contributions in terms of accessibility, sustainability, and local manufacturing potential.

As a result, this thesis has successfully developed an accessible, low-cost, and user-oriented telescopic visual aid system for individuals with low vision. Future work may focus on further miniaturisation of the system and the integration of advanced features to enhance the user experience. In particular, natural visual responses—such as the involuntary narrowing of the eyelids when trying to focus on distant objects (a common squinting reflex), and changes in pupil diameter (pupillary response)—could be tracked to enable automatic adjustment of the focal distance. By analysing these subtle

physiological cues through artificial intelligence algorithms, the system could intuitively respond to the user's visual intent, dynamically adjusting its focus without requiring any deliberate physical input. Furthermore, it is recommended that the product be further refined and clinically validated through user testing to broaden its practical applicability.

Designing assistive technologies is not merely a technical challenge but a human one, ensuring that individuals with vision loss regain a sense of autonomy in daily life. Reimagining familiar tools through affordable, adaptable innovation opens new paths, yielding dignity, independence, and a renewed confidence for those long underserved. Accessible solutions must not remain theoretical—they must be built, shared, and lived.

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APPENDICES

Appendix A. Volume and Mass Calculations of the Dual-Tube Assembly

The final mechanical design consists of two concentric hollow cylinders:

- an outer tube (movable)
- and an inner tube (fixed).

These components enable precise adjustment of the distance between the lenses, which directly determines the focal length of the optical system.

Outer tube:

- Outer diameter: 20 mm
- Inner diameter: 14.4 mm
- Length: 40.2 mm
- Inner tube:
 - Outer diameter: 14 mm
 - Inner diameter: 12.8 mm
 - Length: 26.3 mm

When assembled, the tubes overlap by approximately 15.9 mm, which is subtracted from the total volume to avoid double-counting.

Volume Calculation:

The material volume V of each hollow cylinder is calculated as:

$$V = \pi \times h(r_{outer}^2 - r_{inner}^2)$$

- Outer Tube Volume

$$V_1 = \pi \times 40.2(10^2 - 7.2^2) = 7253.78mm^3$$

- Inner Tube Volume

$$V_2 = \pi \times 26.3(7^2 - 6.4^2) = 1926.95mm^3$$

- Overlap correction

$$V_{Overlap} = \pi \times 15.9(7^2 - 6.4^2) = 835.82mm^3$$

- Total theoretical volume

$$V_{Total} = V_1 + V_2 - V_{Overlap} = 7253.78 + 1926.95 - 835.82 = 8344.91mm^3$$

- Actual volume measured from CAD:

The presence of design-specific features such as lens holders, screw holes, and motor mounting recesses leads to additional material reductions that are not considered in the theoretical volume calculation. Therefore, the actual material volume obtained from the CAD model is lower and is calculated to be approximately $6.34cm^3$.

Implications for Weight Estimation:

Using the known density of PLA ($\rho=1.24 \text{ g/cm}^3$):

$$6.34cm^3 \times 1.24g/cm^3 = 7.80g$$

Measured real weight: 8g

The close agreement between these values validates both the computational model and the physical production process.

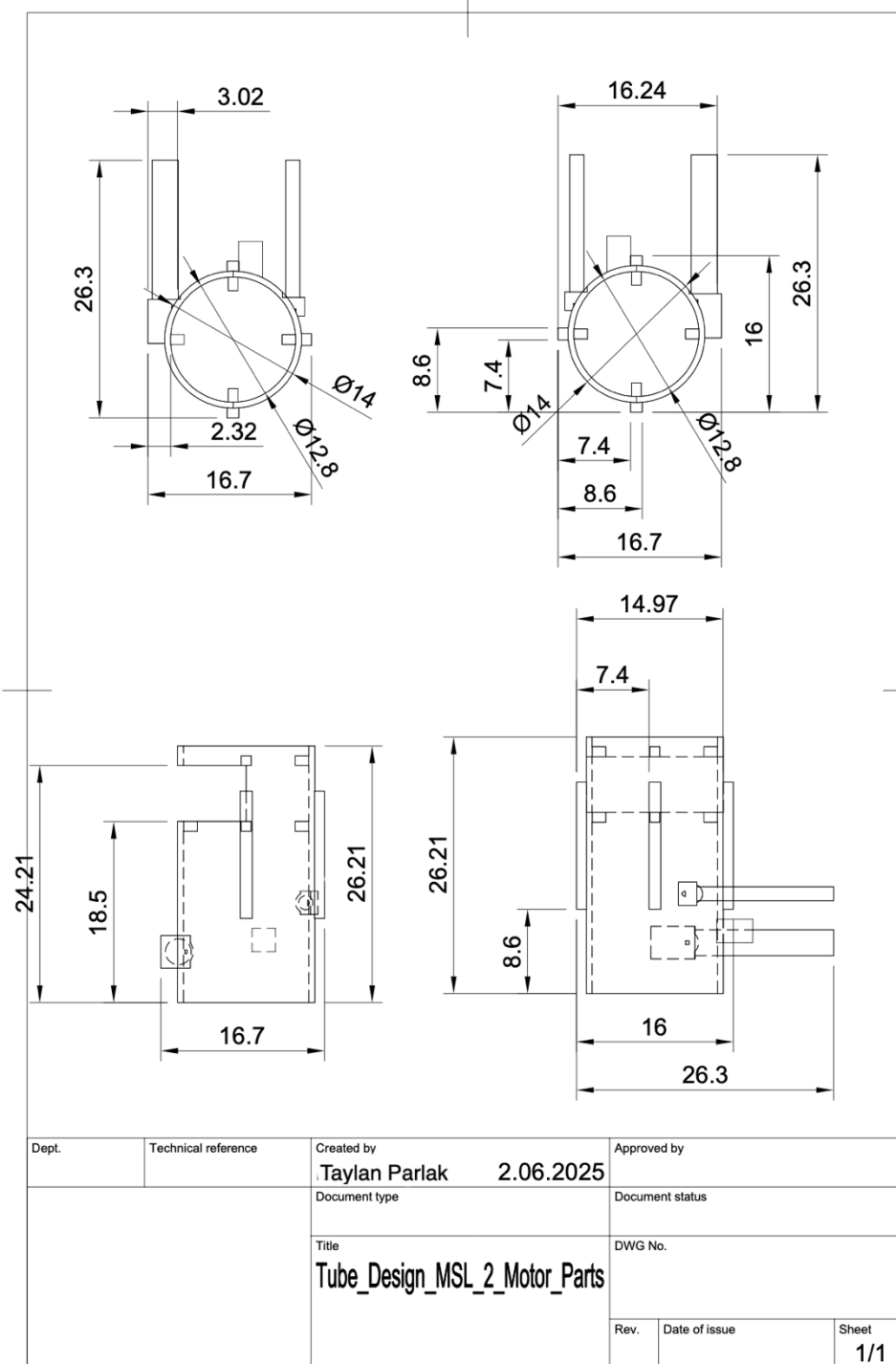


Figure A.1 Inner Tube Design

Appendix B. Experiments Setup and Measurements

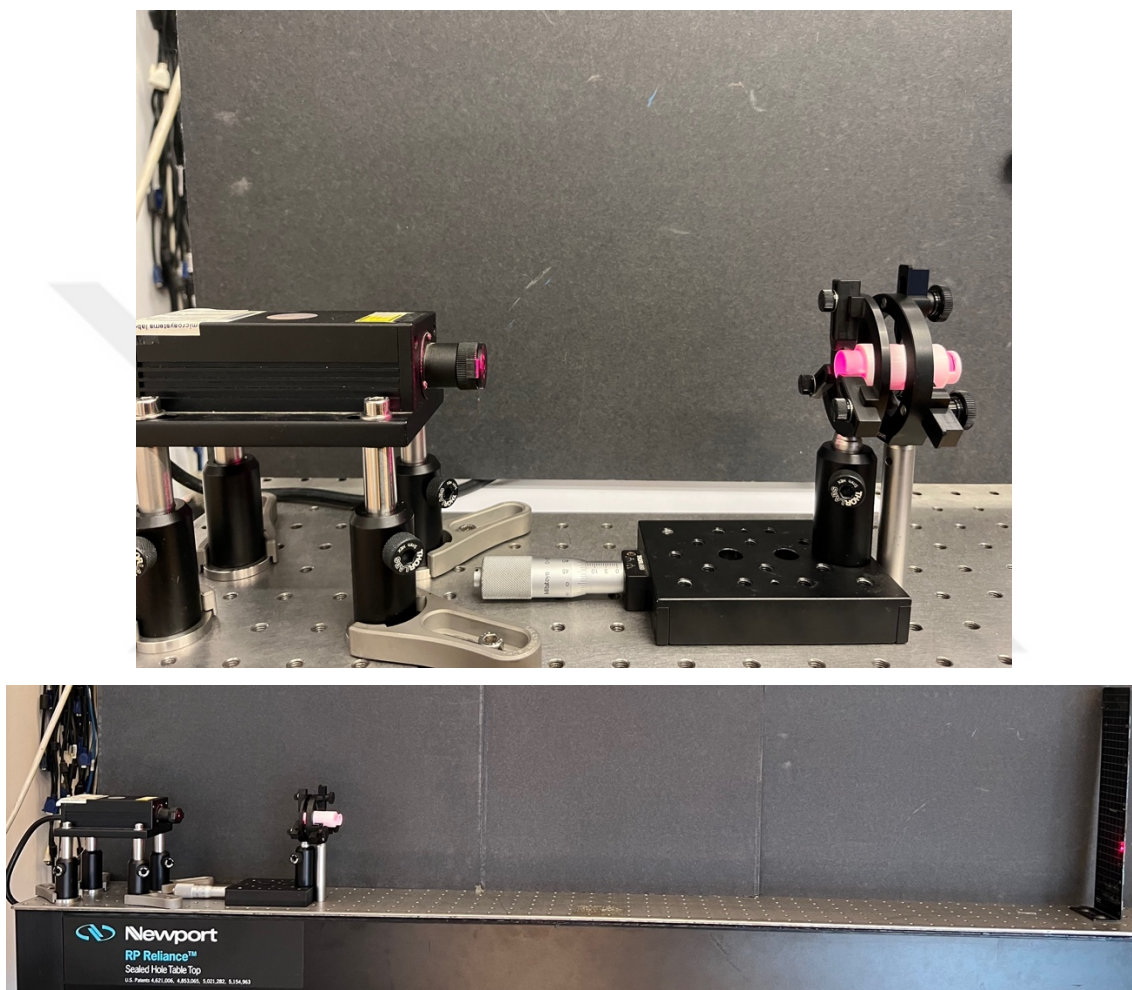


Figure B.1. Experimental Setup



Figure B.2. Measurement of Laser Diameter (Left: 10.2mm, Right: 9.35mm)

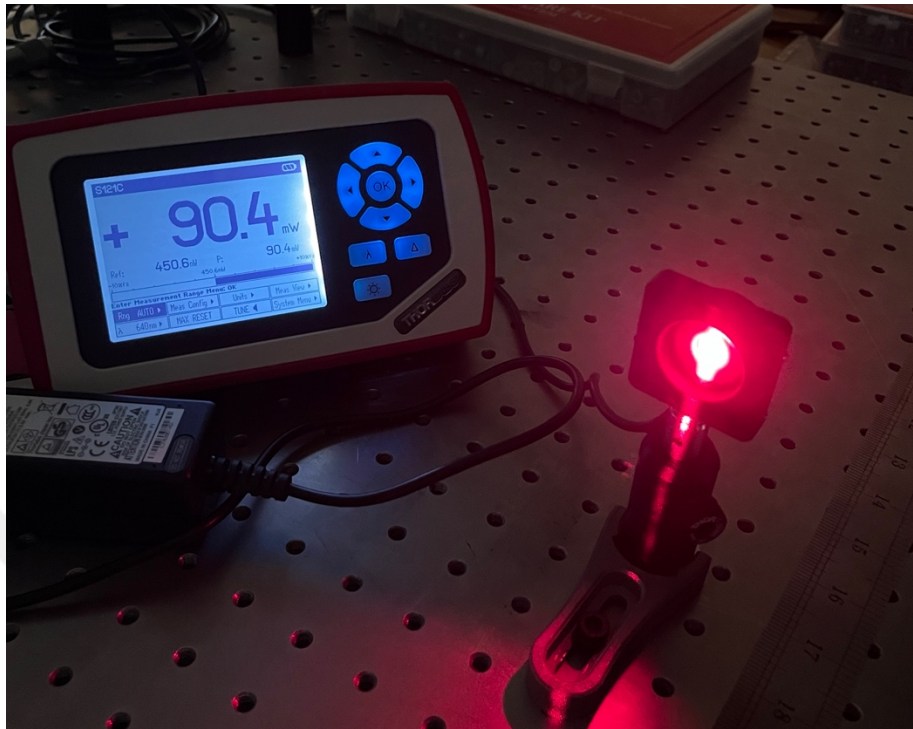


Figure B.3. Measurement of the Pure Laser Power

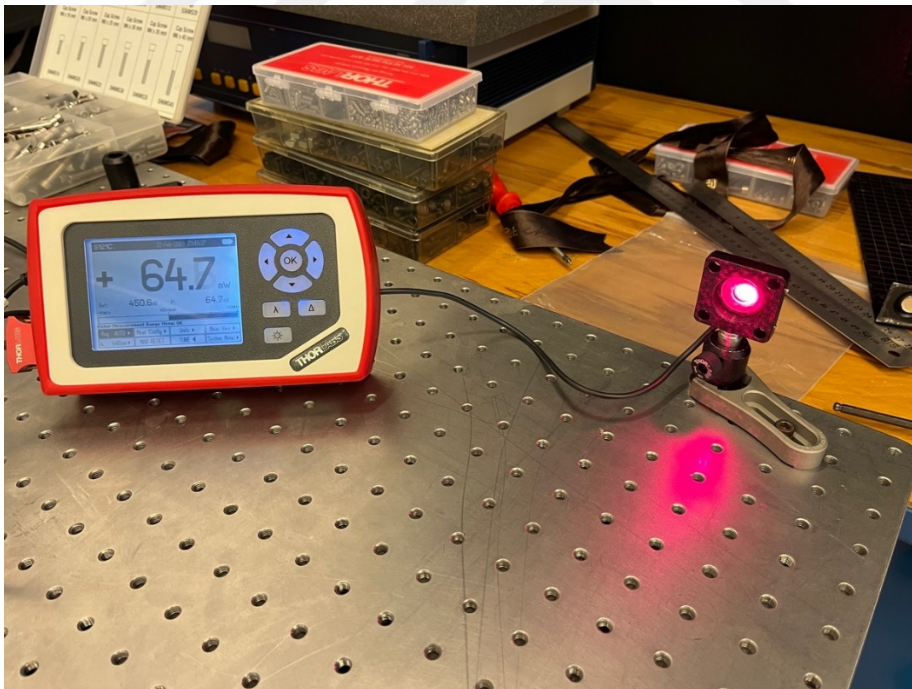


Figure B.4. Measurement of the Different Laser Powers

Appendix C. Lens Design

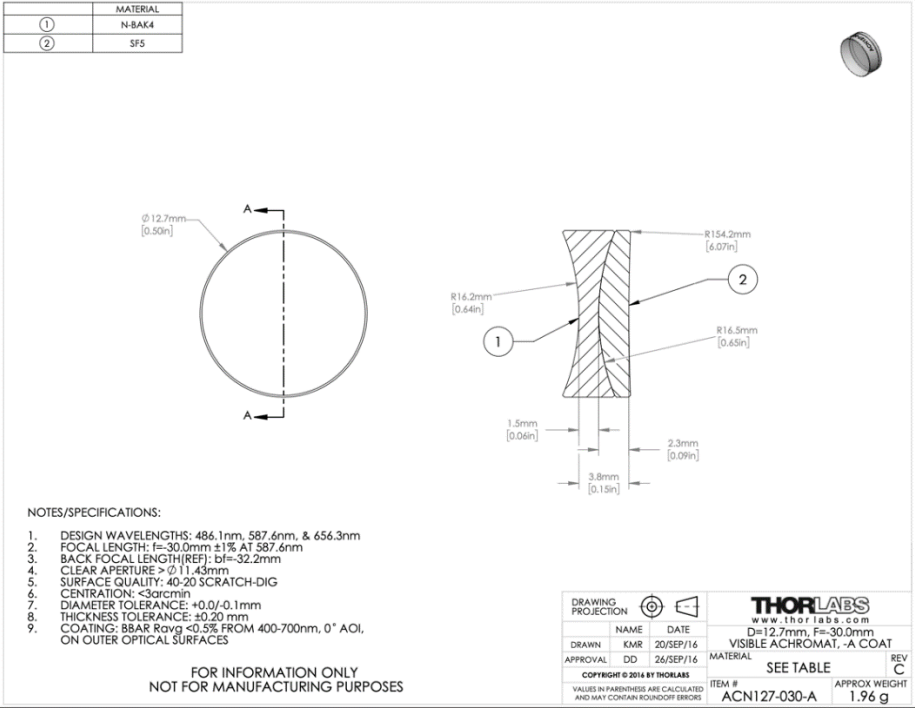
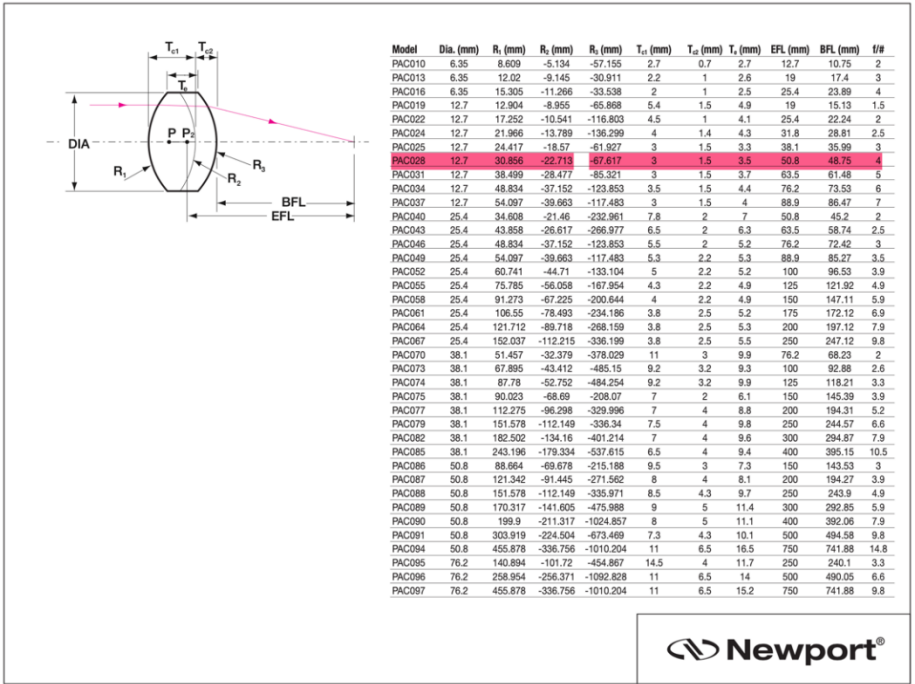


Figure C.1. ACN127-030-A Datasheet



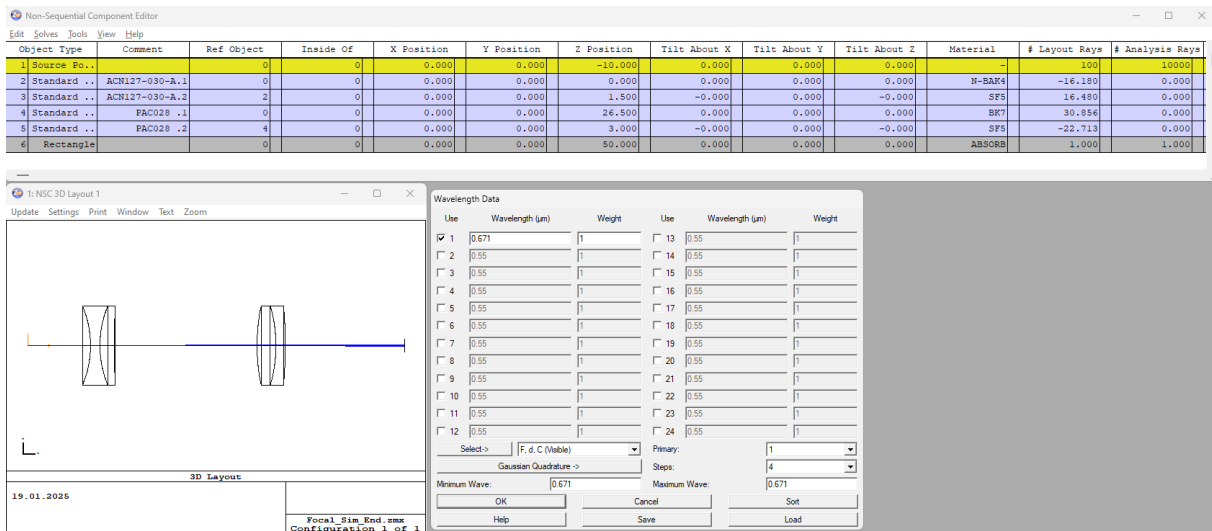


Figure C.3. ZEMAX Simulation Parameters



Figure C.4. Measures of Actual Lenses