



Development of a Controlled Irradiation Device for Photodynamic Therapy

Mariana Hilgert - a65409

Dissertation presented to the School of Technology and Management of Bragança to obtain the Master Degree in Electrical and Computers Engineering, developed under a Double Degree agreement with the Federal University of Technology - Paraná (UTFPR).

Supervised by:

Prof. Dr. José Luís Sousa de Magalhães Lima

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*"To the stars who listen, and the dreams
that are answered"*

– Sarah J. Maas, *A Court of Mist and Fury*

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Abstract

Photodynamic Therapy (PDT) has evolved in recent years, establishing itself as an effective, non-invasive treatment for various oncological and non-oncological diseases. However, the widespread use of this technique faces barriers due to the high cost and architectural rigidity of commercially available equipment, as well as the scarcity of systems capable of compensating for light dosimetry based on the distance between the light source and the target tissue. In this context, this work presents a low-cost modular prototype for PDT applications. The system integrates three LED arrays encapsulated in acrylic structures, which serve both as electrical insulators and physical protective barriers during treatment. The technological difference lies in a control algorithm based on a Lookup Table with bilinear interpolation, which processes distance data from Time-of-Flight (TOF) sensors and adjusts the LED duty cycle (PWM). System management is centralized in a Human-Machine Interface (HMI) with a touchscreen, responsible for communication among all system devices and for enforcing safety limits and barriers during prototype operation. Tests demonstrated the integrity of the communication signals and power lines. Under normal operating conditions, the system's thermal stability was achieved after 6.5 minutes of continuous operation, with a final temperature of 49.2 °C. Based on thermal and optical constraints, the equipment's safe operating range was defined between 40 mm and 130 mm using software. Prototype validation demonstrates technical feasibility, dosimetric precision, and clinical safety.

Keywords: Photodynamic Therapy; Time-of-Flight sensors; Control; Optical dosimetry.

Resumo

A Terapia Fotodinâmica (PDT) evoluiu nos últimos anos para se consolidar como um tratamento eficaz e não invasivo para diversas doenças oncológicas e não oncológicas. No entanto, a ampla utilização desta técnica encontra barreiras no alto custo e na rigidez arquitetônica dos equipamentos disponíveis comercialmente, além da escassez de sistemas capazes de compensar a dosimetria da luz com base na distância entre a fonte luminosa e o tecido alvo. Neste cenário, este trabalho apresenta o desenvolvimento de um protótipo modular de baixo custo para aplicações em PDT. O sistema integra três matrizes de LEDs encapsuladas por estruturas em acrílico, que atua tanto como isolante elétrico, quanto como barreira física de proteção no decorrer do tratamento. O diferencial tecnológico reside num algoritmo de controlo, baseado numa *Lookup Table* com dupla interpolação linear, que processa os dados de distância adquiridos por sensores *Time-of-Flight* (TOF) e ajusta o ciclo de trabalho (PWM) dos LEDs. O gestão do sistema é centralizado numa Interface Homem-Máquina (IHM), com ecrã tátil, responsável pela comunicação de todos os dispositivos do sistema e por impor limites e barreiras de segurança durante a operação do protótipo. Os ensaios realizados demonstraram a integridade dos sinais de comunicação e das linhas de alimentação. Sob condições normais de operação, a estabilidade térmica do sistema foi alcançada após 6,5 minutos de funcionamento contínuo, atingindo 49,2 °C. De acordo com as restrições térmicas e ópticas, a gama de operação segura do equipamento foi delimitada entre 40 mm e 130 mm via *software*. A validação do protótipo demonstra viabilidade técnica com precisão dosimétrica e segurança clínica.

Palavras-chave: Terapia Fotodinâmica; Sensores *Time-of-Flight*; Controlo; Dosimetria Óptica;

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Acronyms

CNC Computer Numeric Control.

DC Direct Current.

FABLAB Fabrication Laboratory.

GND Ground.

GPIO General Purpose Input/Output.

HMI Human-Machine Interface.

I2C Inter-Integrated Circuit.

IC Integrated Circuit.

LED Light Emitting Diode.

MAPE Mean Absolute Percent Error.

PCB Printed Circuit Board.

PDT Photodynamic Therapy.

PS Photosensitizer.

PWM Pulse Width Modulation.

ROS Reactive Oxygen Species.

SCL Serial Clock.

SDA Serial Data.

SPI Serial Peripheral Interface.

VCC Voltage at the Common Collector.

Chapter 1

Introduction

Photodynamic Therapy (PDT) is a non-invasive and painless treatment for various types of cancer and non-oncological diseases. The mechanism of action of PDT involves three components: Photosensitizer (PS), light application, and molecular oxygen [1]. The photosensitizer is applied topically or intravenously to the target tissue and exposed to light at the appropriate wavelength [2]. The combination of these two factors initiates a chain of photochemical and photobiological reactions that generate Reactive Oxygen Species (ROS) and ultimately lead to cell death [3].

PDT applications range from oncological diseases, such as skin, esophageal, and lung cancer, to non-oncological diseases in dermatology, dentistry, ophthalmology, rheumatology, neurology, and orthopedics [2].

Most PDT treatments use light sources with wavelengths within the therapeutic window of 600 nm to 850 nm, since in this spectral region, light penetration into tissues is greater and photon energy is sufficient to activate the photosensitizer [4].

The use of Light Emitting Diodes (LED) as a light source in PDT is advantageous due to their low cost and versatility. LEDs can be easily combined into matrices to cover large treatment areas and can be easily powered by batteries, making the device portable [5]. However, LEDs have lower power than other light sources, such as lasers, requiring a higher-power supply to achieve the desired optical fluence. Furthermore, thermal control of these components is important, as significant temperature variations

can directly affect the treatment's effectiveness and safety [6]. Another issue to consider is that the positioning and proper distance of the light source directly affect the outcome of PDT, since tissues need to receive the correct amount of photons to trigger the expected cellular response [7].

Given this, the overall objective of this work is to develop and manufacture a controlled irradiation device for application in Photodynamic Therapy. To achieve this, a series of specific objectives was established to guide the project's development. First, the system seeks to optimize light dosimetry by controlling optical power. This control is performed in real time based on the distance between the light source and the target tissue, using TOF sensors. In addition, the system aims to integrate an Human-Machine Interface (HMI) coupled to the microcontroller, capable of managing peripheral communication and ensuring safe operational limits. Finally, the work aims to construct a modular acrylic structure to house all the prototype's components, as well as develop Printed Circuit Boards (PCBs) to connect the circuits and ensure the integrity of the communication signals.

The project stages are presented in detail in the four chapters that follow this introduction. Chapter 2 deals with the Literature Review and State of the Art, detailing the theoretical foundation of the PDT application and its three main components, providing an in-depth look at lighting sources, and concluding with a description of available applications and technologies on the market.

Chapter 3, entitled Materials and Methodology, describes the materials used in the project development and the selection criteria adopted for their selection. It also presents the processes of elaborating schematic diagrams, designing and manufacturing PCBs, developing HMI screens and firmware architecture, mechanical structuring, and system calibration.

Chapter 4, Results and Discussions, presents the data from the practical tests performed with the prototype, covering optical calibration and light-dose mapping under Pulse Width Modulation (PWM) control, analysis of communication signals, stability, safety, and navigability of the firmware, and the electrical and mechanical integration of

the system.

Finally, Chapter 5, the Conclusion, consolidates the results, evaluates the achievement of the objectives, identifies the limitations, and offers suggestions and perspectives for future work.

Chapter 2

Bibliography review

2.1 Photodynamic Therapy

Photodynamic therapy (PDT) is a minimally invasive therapeutic approach for the treatment of cancer and other non-oncological diseases [1]. The protocol requires administering a PS, which is subsequently activated by optical irradiation. This triggers a sequence of photochemical and photobiological reactions responsible for the generation of ROS and resulting cellular damage [3].

The therapeutic efficacy of PDT depends directly on the controlled interactions among three fundamental elements: a photosensitizer, light, and molecular oxygen. The PS agent is administered either topically or intravenously, and selectively accumulates in malignant tissues [8]. After an incubation period to allow for this accumulation, the target area is irradiated with light at a specific wavelength corresponding to the PS absorption [9].

Upon light absorption, the PS is promoted to an excited singlet state (1PS), which, in some cases, can transform into a long-lived excited triplet state (3PS). In the 3PS state, the PS participates in two types of photochemical reactions with adjacent molecules [11]:

- Type I Reactions: involve the transfer of electrons from the PS to adjacent molecules, forming free radicals that generate reactive oxygen species (ROS) and induce damage to tumor tissues.

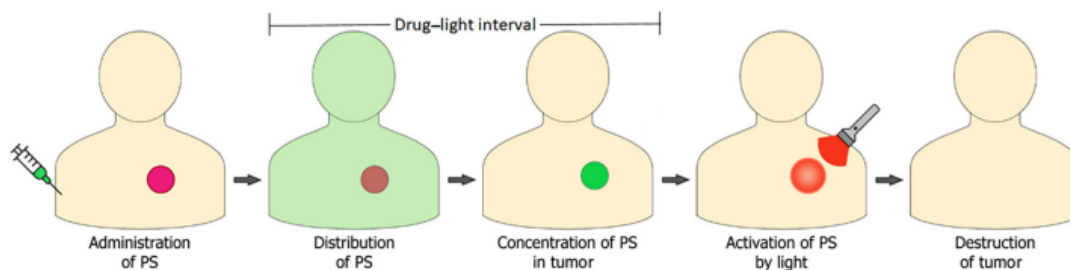


Figure 2.1: Schematic representation of the clinical Photodynamic Therapy (PDT) workflow [10].

- **Type II Reactions:** involve the direct formation of cytotoxic singlet oxygen (1O_2), which induces cell death through an oxidative process. [12]

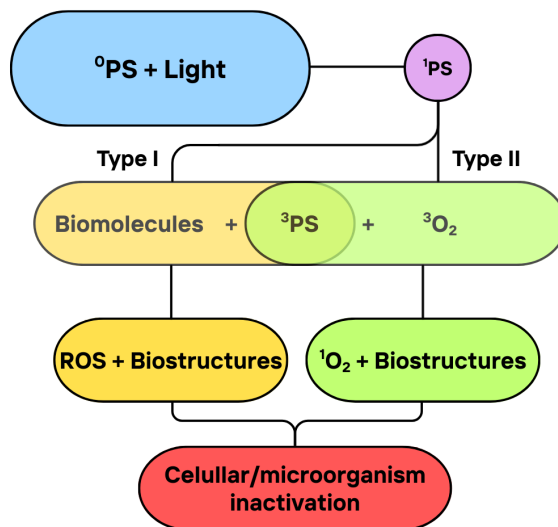


Figure 2.2: Jablonski diagram illustrating the Type I and Type II photochemical reactions during PDT.

Compared with conventional therapeutic approaches such as chemotherapy and radiotherapy, PDT offers several distinct advantages [13]. These include reduced systemic toxicity, minimal invasiveness, the possibility of safe administration in multiple sessions, and high suitability for combination with other therapeutic modalities [14].

Photodynamic therapy has become established as a safe treatment and is widely used across different areas of health care. One of its main applications is in cancer treatment,

encompassing a wide variety of tumors [15] [16] [17]. In addition, numerous studies have examined PDT in dentistry [18] [19] [20]. Furthermore, some studies offer treatments for cardiovascular conditions [21], infections [22], dermatological diseases [23] [24] [25], and diabetes [26] [27].

2.1.1 Photosensitizers

The photosensitizer is the substance that generates the active intermediates responsible for cell death upon exposure to light. The appropriate choice of PS and its response to light are determining factors in PDT efficacy [28].

PSs tend to accumulate more in tumor tissues than in healthy tissues. This selectivity is alleged to be specific to tumor microenvironment characteristics, such as low pH and increased vascular permeability [29].

In early studies related to photosensitizers for PDT, specific criteria were established to define an ideal PS: high toxicity upon light exposure but low toxicity in the dark, high sensitivity to irradiation to maximize ROS generation, and rapid accumulation in tumor cells [30].

In addition, other characteristics are also desirable:

- Accumulation in mitochondria: preferably, ROS should occur in the mitochondria, as this induces cell death via apoptosis [31]. Conversely, PS accumulation in the cell nucleus can lead to tissue necrosis, resulting in an uncontrolled inflammatory response [32].
- Good photostability: when the polymethine chains of the PS are oxidized by singlet oxygen, photobleaching occurs; this process involves decomposition and loss of fluorescence [32].
- Solubility: this characteristic directly influences the mode of PS application and its tissue distribution. More hydrophobic PSs accumulate eight times more in tumor tissues compared to healthy tissues, which is not observed in hydrophilic PSs [31].

Table 2.1: Most commonly used photosensitizers in PDT and their main clinical applications.

Photosensitizer	Activation wavelength	Main applications	References
Photofrin	630 nm	Cancer of esophagus, lungs and bronchi, brain tumors	[33] [34]
5-ALA	630 nm	Brain tumors, skin cancer, actinic keratosis, head and neck cancer	[33] [34] [35]
HAL/Hexvix	380-450 nm	Bladder cancer, skin cancer	[33]
Foscan	652 nm	Head, neck, lung and brain cancer	[33] [34] [35]
Laserphyrin	664 nm	Esophageal and lung cancer, brain tumors, colon and neck tumors	[33] [35]
Redaporfin	749 nm	Cancer of the bile ducts	[33]
Verteporfin	689 nm	Cancer of the bile ducts, ovarian cancer, ophthalmologic	[36] [35]
Methylene Blue	632 nm	Adenocarcinoma, bladder carcinoma, breast cancer, planktonic bacteria	[37] [38]
Curcumin	420-430 nm	Anti-inflammatory, anti-microbial, wound healing	[37] [38]
Toluidine Blue	410 nm	Antibacterial	[38]
Rose Bengal	532 nm	Bacterial inactivation	[38]

Photosensitizers can be categorized into three main classes, defined by type:

- Tetrapyrrolic structures: constitute the largest group and are often referred to as the “pigments of life” due to their natural occurrence in various biomolecules. They are characterized by a high yield of Type II singlet oxygen generation.
- Synthetic dyes: are extensively studied for PDT applications. These compounds are frequently employed in antimicrobial and clinical treatments, as well as in *in vivo* and *in vitro* studies.
- Natural compounds: despite the apparent contradiction of finding highly active photosensitizing molecules in plants that require sunlight for growth, numerous natural products are currently being investigated for use in PDT [39].

2.1.2 Light

The therapeutic application of light dates back to antiquity, with ancient civilizations in Egypt, India, and China reported to have employed sunlight to treat various skin diseases [2]. However, the combined use of light and chemical agents to induce cell death was documented only in the early 20th century in Munich by Herman von Tappeiner and Oscar Raab [40]. Upon observing that the combination of acridine red dye and light caused the death of *Paramecium* species, they concluded that this effect occurred through energy transfer from light to the chemical, a process analogous to photosynthesis [41].

The effectiveness of PDT depends on control of optical dosimetry parameters, particularly fluence, fluence rate, exposure time, and irradiation mode. Fluence is defined as the optical energy delivered per unit area, usually measured in J/cm^2 , whereas fluence rate refers to the power density applied over time, given in W/cm^2 [42]. Proper adjustment of these parameters is essential because different combinations of fluence rate and exposure time can yield distinct biological responses, even when the total delivered fluence remains constant. For instance, delivering $1 \text{ W}/\text{cm}^2$ for 1 second yields the same total energy as $0.001 \text{ W}/\text{cm}^2$ applied for 1000 seconds, yet the outcomes differ significantly [6].

Over the years, various light sources have been developed and evaluated for PDT applications, primarily targeting the optical therapeutic window (600 nm to 850 nm). This term refers to the wavelength range where light penetration into the tissue is maximized while maintaining effective photoactivation [4].

Lasers offer advantages because they provide high power, which reduces treatment time, and ensure greater uniformity in light irradiance. The biggest disadvantage of using lasers as a light source is their limited ability to cover large areas, making them suitable only for treating small areas of the body [43].

In contrast to laser technologies, LEDs are increasingly being used in photodynamic therapy applications due to several advantages, the main ones being their low cost and high versatility [5]. Furthermore, LEDs are compact, lightweight, and energy-efficient [44]. One of the most advantageous aspects of using LEDs in PDT is their safety, as LEDs do not deliver enough energy to damage tissues and do not pose a risk of accidental eye damage, unlike lasers. Finally, LEDs can be combined into arrays of varying sizes and disperse light over a larger area than lasers, resulting in a larger treatment area. [7].

The characteristics of the light source and the concentration of PS play main roles in the extent of induced tissue necrosis. In lesions with excessively high PS concentration, the incident light is mostly absorbed by the superficial tissue layers, preventing the photodynamic effect from reaching deeper regions. Consequently, applying the correct PS dosage and light irradiance is essential to ensure treatment efficacy [45].

Light Fluence

Optical fluence rate is one of the primary factors determining the success of PDT, and its reduction directly compromises treatment effectiveness [46]. A suboptimal light fluence can lead to residual PS accumulation in the treated tissue, necessitating retreatment. In contrast, an excessive light dose may cause thermal tissue damage [47]. Therefore, maintaining the proper distance between the light source and the target tissue is a critical requirement for clinical applications. Because the fluence rate drops rapidly with increasing distance, this physical behavior represents one of the fundamental limitations of the

therapy [48]. This phenomenon is governed by the Inverse-Square Law, which affirms that illuminance is inversely proportional to the square of the distance, as expressed in Equation 2.1 [49].

$$E = \frac{I}{D^2}. \quad (2.1)$$

Where E is the illuminance in lux (lx), I is the luminous intensity in candelas (cd), and D is the distance in meters (m).

One approach to determining the light dose in PDT is to calculate the number of photons absorbed by the PS per unit of tissue volume, which is obtained by multiplying the PS concentration, its extinction coefficient, and the light fluence. This implies that, as the PS concentration changes, the light fluence must be adjusted to compensate [50].

The light fluence rate is linked to the photosensitizer's activation rate and, consequently, to ROS generation. Therefore, the correct determination of the fluence rate in PDT treatment is essential, as characterized by the Inverse Square Law [51]:

2.2 LEDs

Light-emitting diodes (LEDs) are semiconductor p-n junction devices that operate under forward bias, emitting light through electroluminescence, the process of radiative recombination of electrons and holes [52]. This phenomenon was first documented in the 1920s by Oleg Vladimirovich Losev, who observed visible light emission from a zinc oxide-silicon carbide rectifier. By the end of the 1930s, Losev had established the current limit for the onset of light emission, understood the non-thermal nature of the emission, and meticulously documented the voltage-current relationship of the LED [53].

Light emission in an LED is driven by the radiative recombination of electrons in the conduction band with holes in the valence band, typically between the lowest-energy state of the conduction band and the highest-energy state of the valence band. Therefore, the energy of the emitted photon corresponds approximately to the band gap energy of the

semiconductor material. Modifying the composition of the semiconductor alloy allows fine-tuning of the band gap and, consequently, the specific wavelength emitted by the device [54].

This ability to precisely select wavelength emission was crucial for the advancement of PDT. In recent years, LED technology has advanced to the point that its use in PDT is now possible. LEDs offer several advantages for clinical and laboratory applications, such as the ability to emit wavelengths across the visible and invisible spectra, their lower cost compared to lasers, and the versatility of combining LEDs in arrays to increase the treatment area [5]. Another relevant advantage is the low optical power emitted by LEDs, which drastically reduces the possibility of accidental damage to the target tissue [7].

Despite the advantages, it is important to consider the thermal droop effect in LEDs, a decrease in optical power with increasing temperature that can lead to significant suppression of electroluminescence [55]. In addition to optical power, the peak wavelength, spectral width, color temperature, and efficiency of LEDs can also be affected by temperature, with red LEDs being particularly sensitive to these changes [56].

To avoid these variations and ensure the correct dose in PDT, proper LED control becomes fundamental. It is known that the operating parameters of LEDs depend directly on the injected current; therefore, PWM control is one of the most suitable solutions. The reaction time of LEDs to changes in the control signal is very fast, and therefore, high-frequency PWM control is very convenient [57].

2.3 State of Art

Currently, PDT devices can be categorized by both the nature of the light source and the system's physical architecture. Regarding illumination technology, devices are generally based on either lasers or LEDs, and their architecture may be classified as fixed, wearable, or internal.

Although lasers can be used without other components, most applications use optical fibers and lenses to aid light diffusion through tissue [58]. An example of this is the

commercial device used in the study by Lizarelli et al. (2024) [59], which was adapted with different accessories to diffuse light to meet the specificities of the treatments studied. Another device was developed by Usuda et al. (2020) [60], which used a set of optical fibers to facilitate the treatment of lung lesions. Using a set of lenses to direct the laser beam at the desired angle, Obana et al. (2002) [61] applied photodynamic therapy to eye lesions.

Although PDT using LEDs is highly efficient and safe, an implantable photonic approach has been introduced, in which organic light-emitting diodes (OLEDs), small LEDs, or even wireless LED systems are stacked [62]. These approaches are even more beneficial, since (i) they are implantable in various tumor sites, including deep organs, (ii) they allow the emission of a wavelength optimized for photosensitizer sensitization, and (iii) they provide emission control and light intensity precision. [63].

Various LED configurations and types can be used in the construction of PDT application equipment, depending on the treatment for which the device will be used.

Internal devices are those that operate inside the patient's body. These devices can be implanted at the lesion site for an extended period, or inserted only during treatment sessions and removed immediately afterward, with this process repeatable as many times as necessary.

One example of implantable equipment is the cylindrical illumination device studied by Tan et al. (2021) [64], designed for application in non-spherical cavities, which uses an array of LEDs and light diffusers to ensure dosimetry uniformity. Another study was conducted by Zhang et al. (2025) [65], who developed a wireless electronic device composed of a coil, an antenna, and a signal generator, which can be activated by an external source that induces an electromagnetic field in the coil when brought close to the implantation site.

Wearable devices are made from fabrics or flexible materials that adapt to the patient's body structure and maintain uniform illumination at the treatment site. Their most common applications involve skin lesions, whether cancerous or not. For scalp lesions, studies by Vignion-Dewalle et al. [66] and Dubois et al. (2021) [67] tested variations of

helmets made of malleable materials and equipped with LED arrays. Another approach is that adopted by Zhang et al. (2024) [68], who developed an adhesive comprising a light-emitting layer, an energy-conducting layer, and a hydrogel layer loaded with a photosensitizer. This device can be applied to any part of the body.

Finally, there are external, fixed devices that apply light dosimetry at a distance, calculated according to the specifics of the treatment. These represent the majority of the equipment developed and tested, and come in various forms.

Starting with devices for *in vitro* testing, such as that of Théchua et al. (2021) [69], which applies layers of tissue equipped with optical fiber bundles that can be coupled to laser sources, as well as that of Zanzarini et al. (2023) [70], a box with capacity for up to four microwell plates containing LEDs spread uniformly throughout the inside of the equipment.

Moving on to the equipment that applied PDT to humans, the study by Gálvez et al. (2022) [71] developed a portable device composed of three arms, spaced 120° apart from each other, and with LEDs of different colors on each, which allows for a greater variety of possible treatments, as it is capable of emitting light at various wavelengths.

Although the literature presents various light irradiation technologies for application in Photodynamic Therapy, the state of the art indicates that much of the current equipment has significant limitations, such as high cost and limited flexibility, making it inaccessible to small clinics or early-stage research. Furthermore, there is a lack of systems offering dosimetry control capable of compensating in real time for the distance between the light source and the target tissue.

In this context, the present work demonstrates its relevance. The objective of developing a modular device using readily available materials is to offer a low-cost alternative. The great advantage of this prototype lies in its control architecture, equipped with Time-of-Flight sensors and managed by a simple, intuitive interface. This approach ensures the delivery of the necessary light dose throughout the treatment application and establishes physical safety limits that provide protection to the patient.

Chapter 3

Materials and methodology

This work aims to construct a functional prototype capable of controlling the luminous power emitted by LEDs according to user-defined parameters, for later application in Photodynamic Therapy. The work involved the stages of defining electrical circuits, including Printed Circuit Board (PCB) design and production, programming, control, prototyping, and calibration.

3.1 Materials

3.1.1 Microcontroller and HMI

To integrate the microcontroller and the HMI, this project employs the WT32-SC01 development board. The selection of this component was driven by its integration of a capacitive touch display along with the microcontroller. This architecture minimizes the need for external wiring and simplifies the HMI development process. Furthermore, the embedded ESP32-WROVER-B module offers inherent advantages, including low cost, high market availability, and extensive documentation within the engineering community. Alongside these features, the board includes two expansion buses for connecting external peripherals.

The board-integrated microcontroller controls the touch display, which consists of two

main parts: the display and the touchscreen. The first one operates at up to 80 MHz and uses the Serial Peripheral Interface (SPI) protocol for communication, while the touchscreen communicates via Inter-Integrated Circuit (I2C) [72].

3.1.2 LEDs and Driver

This design incorporates 3 W LEDs with a 620 nm wavelength to meet the needs of photodynamic therapy, as presented in the previous chapter. This power rating provides sufficient luminous power for PDT applications, and the selected wavelength falls within the optical window of greatest absorption in human skin. Furthermore, the system is divided into three groups of six LEDs each, totaling 18 LEDs and 54 W of power. This architecture allows the device to be flexible, as it can illuminate in different directions and also cover larger areas.

The LED driver, based on the P9813 Integrated Circuit (IC) [73], features three independent output channels originally intended for RGB (Red, Green, Blue) LED control. In this design, each channel manages its own LED group independently. Furthermore, the module includes three D472 MOSFETs [74] capable of handling up to 72 Watts (6 A). The driver receives power through two isolated networks: the P9813 IC is powered at 5 V to handle the internal logic, whereas the power circuit hosting the MOSFETs can be supplied with up to 12 V. For the physical implementation of this prototype, this power line is operated as 5.5 V to match the nominal requirements of the LED modules, a selection further detailed during the circuit sizing calculations.

The communication between the microcontroller and the driver uses a two-wire synchronous serial protocol, with the CIN wire providing the clock signal and the DIN wire carrying the data payload. The P9813 IC receives a 32-bit data message with the intensity configuration for the three independent channels. Subsequently, the IC translates this value into a high-frequency PWM signal, adjusting the duty cycle applied to the MOSFET gates. Consequently, the MOSFETs switch the 5.5 V power line, controlling the average forward current delivered to the LEDs. The IC's high-frequency (over 1 kHz)

ensures linear dimming of the optical output and prevents flickering.

3.1.3 Time-of-Flight Sensors

TOF sensors are contactless distance-measuring devices, and their operating principle is based on the emission of a signal and the processing of the reflected signal's time of flight [75]. TOF sensors operate by emitting a pulse of infrared light that travels to the object and returns to the sensor, and the distance is given by the time of flight to the object multiplied by the speed of light, represented by the Equation 3.1, where d is the distance, t is the time of flight and c is the constant value for the speed of light [76].

$$d = ct. \tag{3.1}$$

TOF sensors perform very well at long distances (above 50 meters), and their mechanism is simple; however, at shorter distances, the device must account for factors that interfere with the measurement, such as the pulse shape and the temporal overlap of the outgoing and return pulses. Therefore, autocorrelation algorithms and photon-counting techniques are used to ensure measurement accuracy [77].

The TOF sensors chosen for this project are the VL53L0X [78], which operate at 3.3 V and use the I2C communication protocol. Three units were used in total, one for each arm of the equipment, and the measurement results are directly used in the calculation of the PWM that controls the power delivered to the LEDs.

Table 3.1 summarizes the main electronic components and modules integrated into the system, along with their manufacturers and primary functions in the prototype.

3.1.4 Bench Instrumentation and Power Supply

The system was powered using a Keithley 2231A-30-3, presented on Figure 3.1, manufactured by Tektronix and available in the IPB laboratories for student use. The power

Table 3.1: Main electronic components and modules utilized in the prototype.

Component/Module	Model/Reference	Description	Manufacturer
Microcontroller and HMI	WT32-SC01	Processing logic and user interface	Wireless-Tag Technology
Time-of-Flight Sensors	VL53L0X	Real-time distance measurement	STMicroelectronics
LEDs	3 W / 620 nm	Light source for PDT irradiation	-
LED Strip Driver	P9813 IC / AOD472 MOSFETs	PWM signal and power switching for LEDs	DIY More
Voltage Regulator Module	XL4005	Power management and voltage stabilization	XLSEMI

supply features two channels capable of providing up to 30 V and 3 A, and one channel capable of supplying up to 5 V and 3 A. In addition to the standard configuration, the equipment allows the first two channels to be connected in series or parallel, increasing the voltage or current supply capacity as required by the application [79].

The validation of the circuit's logic and power supply signals was performed using a Tektronix TBS 1052B-EDU Digital Oscilloscope, shown in Figure 3.2, also manufactured by Tektronix and available in the IPB laboratories for student use. The equipment has two analog channels, a 50 MHz bandwidth, and a real-time sampling rate of up to 1 GS/s. In addition to standard configurations, the model integrates tools for capturing and analyzing high-speed waveforms, making it ideal for validating the communication signals of the developed prototype [80].

Optical calibration and validations were performed using a TES-1334 lux meter available at IPB. The equipment is integrated with a photodiode sensor with a correction filter, a cosine correction for angular light incidence, and multiple reading scales [81].

Surface temperature of the LEDs was registered during thermal stability tests using a non-contact infrared digital thermometer. This instrument was used to record the LED's



Figure 3.1: Keithley 2231A-30-3 benchtop power supply used to energize the system during experimental tests.



Figure 3.2: Tektronix TBS 1052B-EDU digital oscilloscope used for signal validation and communication analysis.

temperature progress during calibration tests to analyze the circuit's thermal stability.

3.2 Electric Circuit development

This section details the project's electrical characteristics, focusing on component selection, sizing, and distribution, as well as the design of required PCBs.

3.2.1 Power calculations and component sizing

In this context, a fundamental aspect of the hardware development involves power calculation and component sizing. These procedures are necessary to guarantee system protection, separate power supply networks, and ensure adequate heat dissipation.

Resistance calculations

Starting with the LED matrix topology, the design divides the 18 LEDs into three groups, arranged into 3 parallel branches, each containing 2 LEDs in series. This configuration will limit the voltage and current required to power the LEDs. Since each LED drops approximately 2.4 V, placing too many LEDs in series would raise the total voltage required to power the circuit, whereas connecting all six LEDs in parallel would increase the forward current per channel. This topology successfully balances the optical output and electrical efficiency.

Given that LEDs with a wavelength of 620 nm (red) have a voltage drop of approximately 2.4 V and a maximum rated current of 700 mA, the circuit's total voltage is 4.8 V. For the sizing of the LED circuit components, the design adopts a 5.5V supply voltage, accounting for the 4.8V required by the LEDs and a 0.7V safety margin. Equation 3.2 determines the resistance value.

$$R = \frac{V_{in} - V_l}{I_n}. \quad (3.2)$$

Where $V_{in} = 5.5\text{ V}$, $V_l = 4.8\text{ V}$ and $I_n = 0.7\text{ A}$. Thus:

$$R = 1\ \Omega. \quad (3.3)$$

The equation 3.4 provides the power dissipated by this resistor.

$$P_r = (V_{in} - V_l)I_n \quad (3.4)$$

Applying the previously established values:

$$P_r = 0.49\text{ W}. \quad (3.5)$$

Adding a safety margin and searching for commercially available values, a resistance of $1\ \Omega$ and a power of 1 W were adopted for each circuit branch.

Power and Current supply

Given the circuit topology, with three parallel branches of LEDs, the total circuit current is described by equation 3.6.

$$I_c = 3I_n \quad (3.6)$$

Given that the nominal current of the LEDs (I_n) is 0.7 A , we have that:

$$I_c = 2.1\text{ A}. \quad (3.7)$$

Since the project involves three circuits identical to the one designed, the total current of these circuits is given by the equation 3.8:

$$I_t = 3I_c \quad (3.8)$$

Resulting:

$$I_t = 6.3 \text{ A}. \quad (3.9)$$

Therefore, to ensure a robust hardware design and prevent thermal stress, the components and PCB traces were dimensioned to safely support the maximum load of 6.3 A. However, as will be detailed in the experimental validation, the nominal operating current is much lower. This operational margin ensures high reliability, minimizes heat dissipation and extends the lifespan of the LED modules.

The system was designed to operate at a nominal 5.5 V, chosen to match the LED modules' operating requirements. By adopting a 5.5 V supply, the PWM control safely operates over its full range.

To ensure the stability of the prototype's power lines, isolate sensitive components from electrical fluctuations, and allow the system to be adapted to a higher voltage than the 5.5 V adopted here, a DC-Direct Current (DC) step-down module based on the XL4005 integrated circuit was added to the circuit. This device operates with high efficiency and can supply up to 5 A of output current [82]. The module was set to lower and stabilize the input voltage to 5.05 V, a safe operating voltage for the microcontroller and the driver IC, with a small safety margin above 5 V.

Table 3.2: Discrete electronic components utilized in the custom hardware design.

Component	Specification	Package/Model	Function	Quantity
Capacitor	1000 μ F, 25 V	Electrolytic (10 mm)	Filter	1
Capacitor	100 nF, 3.3 V	Ceramic (5.08 mm)	Decoupling	3
Capacitor	100 nF, 5 V	Ceramic (5.08 mm)	Decoupling	1
Power Resistor	1 Ω , 1 W	Metal Film (10 mm)	LED limiting	9
Schottky Diode	40 V, 3 A	1N5822	Microcontroller protection	1

Printed Circuit Boards

In order to centralize all the project components, simplify the prototype assembly, and ensure circuit safety, this project features two different PCB designs: one to group the LEDs and the distance sensor, which the device replicates three times, and one to centralize the microcontroller, driver, power supply, and other connections and components. Both PCBs are designed as single-sided boards for simplicity and with a ground plane (GND) to ensure good heat dissipation from the components. Furthermore, the component layout avoids communication noise and interference by physically separating the power and signal circuits on the boards.

The calculation of PCB track widths followed Abbott's methodology and the guidelines of the IPC-2221 [83] standard, as described by equation 3.10, where k is the layer constant, ΔT is the temperature variation relative to ambient temperature, b is the temperature variation factor, A is the cross-sectional area of the track, and c is the track geometry factor. Table 3.3 lists all the trace dimensions used for the design and production of the PCBs. Finally, Figure 3.3 presents the schematic diagrams of the project, showing the connections between the microcontroller, control driver, sensors, LEDs, and other components. Figure 3.4 shows the PCB layout, including component placement and track routing, aiming to separate logic and power circuits, optimize space, and enable

efficient heat dissipation.

$$I = k\Delta T^b A^c. \quad (3.10)$$

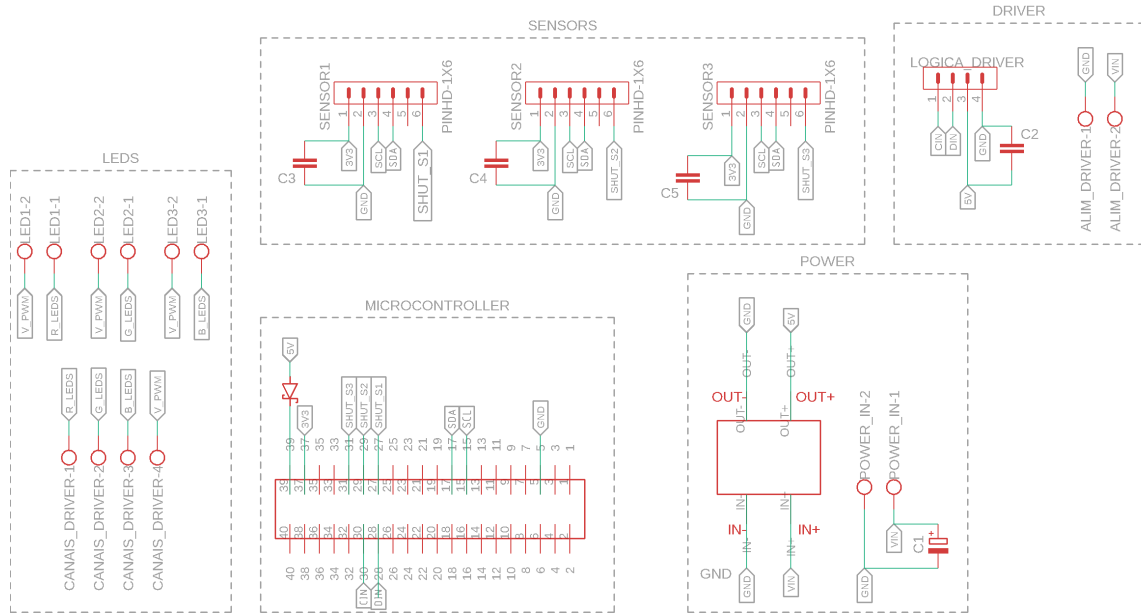
Table 3.3: Technical specifications and dimensional parameters of the designed PCB traces.

Name	Current (A)	Width (mm)
VCC_LED	2.1	1.12
GND_LED	2.1	1.27
GND	2.1	1.12
R_LED, G_LED, B_LED	2.1	1.27
V_IN	6.3	4
5V	0.5	1.02
3V3	0.125	0.81
ALIM_ESP	0.4	1.02
SHUT_S1, SHUT_S2, SHUT_S3	-	0.16
DIN, CIN, SDA, SCL	-	0.16

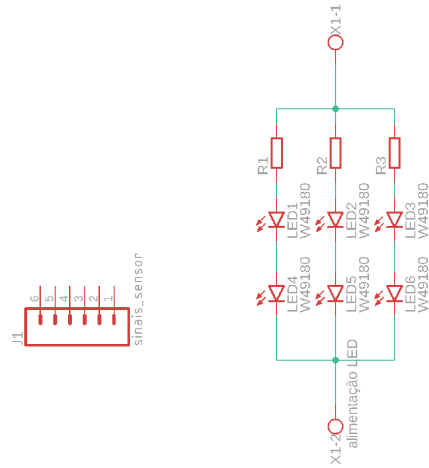
It should be noted that the diagrams presented correspond to the final version and incorporate all the corrections, refinements, and optimizations made during the construction of the prototype. The entire process of creating the electrical circuit and designing the PCBs was carried out using Autodesk Fusion 360 under a student license.

3.3 Programming and control

The device software was developed in C++, using the PlatformIO platform integrated with Microsoft Visual Studio Code. The software architecture modularizes the code into three subsystems: HMI, sensors, and power driver.



(a)



(b)

Figure 3.3: Schematic diagram of (a) the device's main control and power driver circuit, and (b) the LED array and Time-of-Flight sensor module.

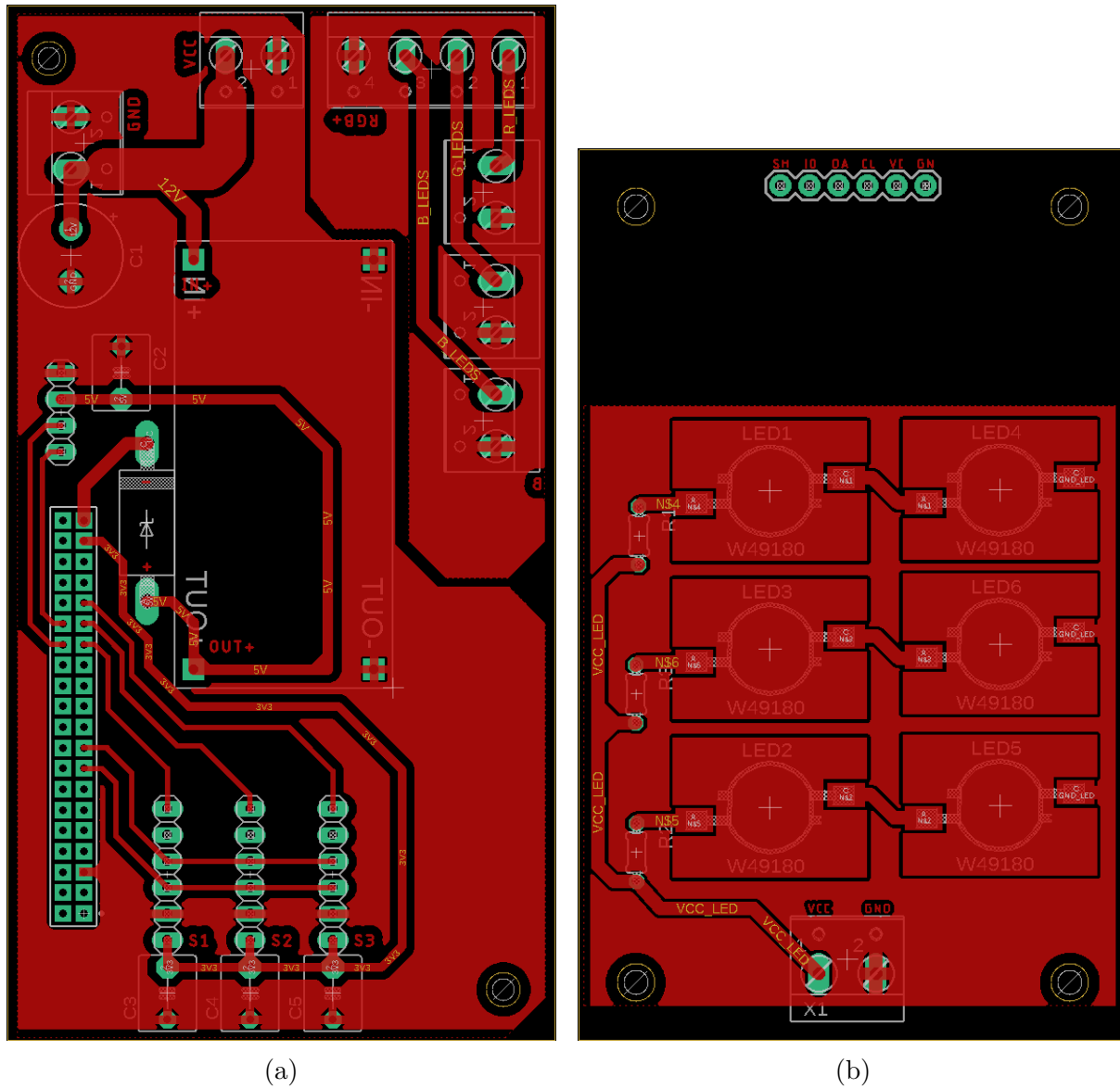


Figure 3.4: Printed Circuit Board (PCB) routing and component placement layout: (a) main control and power supply board, and (b) LED array and sensor module.

3.3.1 Sensors

The device integrates three VL53L0X TOF sensors that communicate over a single I2C bus. To make this possible, an initialization routine was applied using the native Wire.h library: the sensors are initially deactivated, then activated separately so that different I2C addresses are assigned to each (0x30, 0x31, and 0x32).

The microcontroller acquires readings using the VL53L0X library, maintained by Pololu Corporation, and analyzes the data to ensure it falls within the equipment's efficient and safe operating range. Readings outside this range are discarded and considered as 0.

3.3.2 Power driver

A closed-loop PWM controls the power driver for the LEDs: the user sets the treatment power, and the software sets the PWM signal's limits accordingly. I.e, the average power applied to the LEDs is calculated in real time based on the distance measured by the sensors, ensuring that the light dose remains constant even if the equipment's position changes.

This control relies on the FastLED library, developed by Daniel Garcia and Mark Kriegsman, and widely recognized as one of the main libraries for LED and driver control.

However, a safety protocol has been implemented to ensure the equipment remains within its safe operating limits. If the calculated power exceeds the system's capacity, the firmware turns off the LEDs and indicates that the distance is outside the operating range. This mechanism prevents the application of a sub-therapeutic dose of light during treatment, reinforces hardware safety, and visually alerts the operator to adjust the patient's positioning.

3.3.3 HMI

For HMI development, the system relies on the open-source LovyanGFX library, which provides low-level hardware control and reduces the microcontroller's memory usage.

However, it makes screen rendering more complex.

The interface code implements the screen design by directly drawing components and controlling text cursors. On screens requiring a specific value, the display presents a numeric keypad that uses loops to calculate the x and y coordinates of a 3x3 matrix that fits within the 320x480 pixel screen.

A dedicated routine monitors touch events by processing touchscreen data: the code identifies the touch, captures and converts the coordinates to the screen's coordinate system, and then compares with the button positions to determine the decision defined by the user. To prevent double touches, the code imposes a 250 ms screen lock after a touch event.

A key part of HMI operation is input limit control. The firmware validates the user-entered values on the numeric keypad and, if the value is outside the operating range, replaces it with the nearest valid limit. The value is displayed on the next screen for operator confirmation before treatment begins.

A finite-state machine orchestrates navigation between screens, while a flag identifies the machine's state and displays the appropriate screen to the user.

- State 0: Welcome screen, with a button to start the process.
- State 1: Displays the numeric keypad and prompts for the desired power for the treatment.
- State 2: Keeps the numeric keypad and prompts for the treatment duration.
- State 3: Displays the parameters registered by the operator, with a button to start the treatment and another to cancel.
- State 4: Active treatment screen, displays the timer and the power delivered by the LEDs. It has a button that cancels the treatment immediately.
- State 5: Completion screen, displays a message for a few seconds and returns to the initial screen.

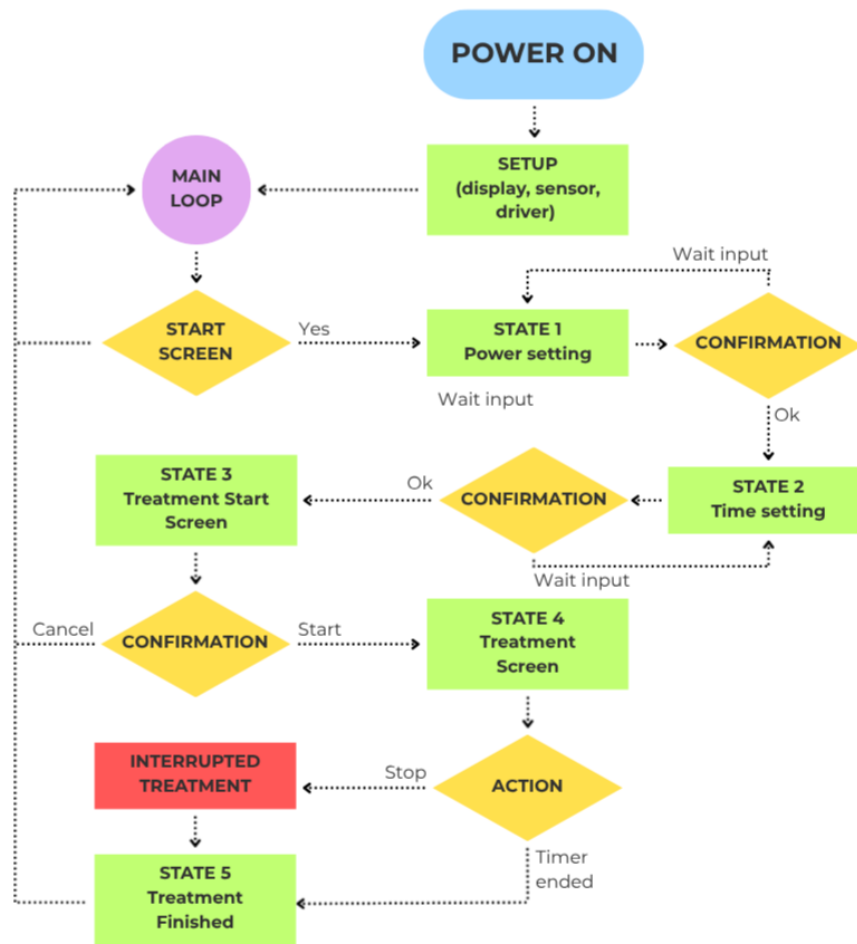
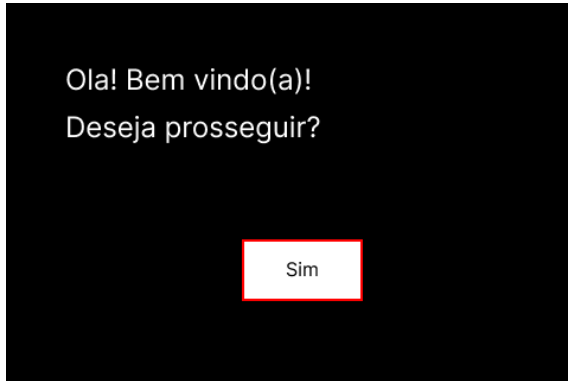


Figure 3.5: Finite-state machine flowchart illustrating the HMI navigation and the active treatment control loop.

The flowchart in Figure 3.5 shows how the developed state machine works.

Figure 3.6 displays the sequence of screens rendered on the device's display during operation. This interface translates the implemented state machine into an intuitive workflow, allowing the user to configure the treatment power and duration, confirm the parameters, and monitor the real-time distance and power adjustments during the active session.



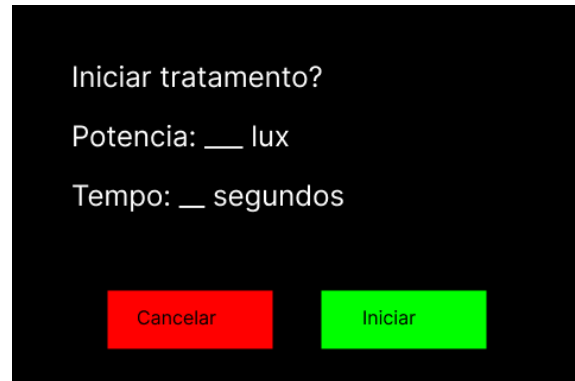
(a)



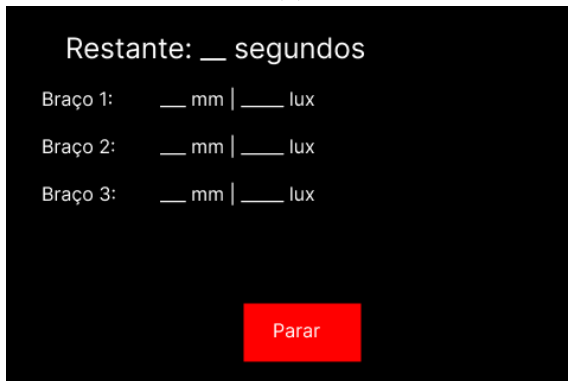
(b)



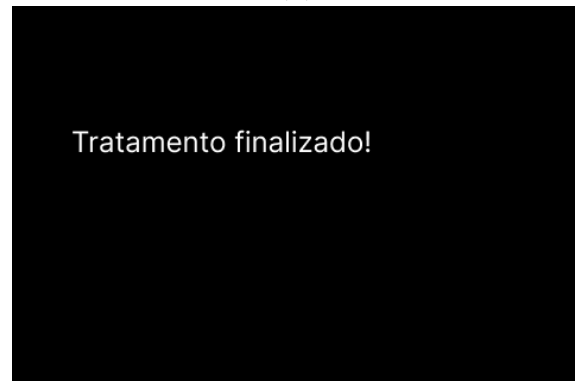
(c)



(d)



(e)



(f)

Figure 3.6: Human-Machine Interface (HMI) screen sequence during operation: (a) welcome screen, (b) treatment power configuration, (c) treatment duration configuration, (d) parameter confirmation screen, (e) active treatment interface with time and dosimetry variables, and (f) treatment finalization screen.

3.3.4 PWM Control

The PWM control that adjusts the light dosimetry delivered by the equipment uses a dynamic compensation algorithm that adjusts the PWM based on the defined illuminance setpoint and the distance measured by the TOF sensors. Since light propagation is non-linear and the system suffers losses due to the Thermal Droop effect, the modeling was performed empirically. The firmware was fed with data from the equipment's calibration matrix (Lookup Table), which contains illuminance values for different duty cycles and distances, employing the bilinear interpolation technique to infer intermediate values.

The processing occurs in two consecutive linear interpolation steps. First, the algorithm receives the distance data read by the sensor (d) and frames it between the two closest known physical limits in the calibration matrix (d_{min} and d_{max}). To estimate the exact system value at this point, the firmware creates a virtual vector with approximate illuminance values for that distance, calculating each element from Equation 3.11.

$$L_v = \frac{(d - d_{min})(L_2 - L_1)}{d_{max} - d_{min}} + L_1 \quad (3.11)$$

where L_v is the vector of illuminances calculated for that distance, and L_1 and L_2 are the illuminances recorded at the limit distances for the same PWM step.

The second step seeks to fit the user-desired illuminance value (L_t) within the previously calculated vector. It scans to find the closest lower and upper limits among the calculated values (L_{v1} and L_{v2}) that encompass the target. From this, a second interpolation is performed, described by Equation 3.12, which determines the PWM value associated with the target illuminance compensated for the distance.

$$PWM = \frac{(L_t - L_{v1})(P_2 - P_1)}{L_{v2} - L_{v1}} + P_1 \quad (3.12)$$

where P_1 and P_2 are the PWM values from the calibration tables that define the range found for L_t , and PWM is the value that will be transmitted to the driver to control the LEDs.

The primary advantage of this technique is the fast processing, since it does not use complex polynomial regressions, without having to give up the physical compensations necessary to guarantee precision in the control.

3.4 Prototyping

This section addresses the device's mechanical structure. It aims to ensure the safety of operators and users, the integrity of electronic components, and the flexibility of positioning the light sources.

For the structure, the project uses acrylic, a durable material with good electrical insulation and easy handling and machining.

To create the 2D vector drawing of the prototype, the design workflow employed the open-source software Inkscape, while IPB's Fabrication Laboratory (FABLAB) handled the cutting and assembly. For this reason, the acrylic chosen for the structure was 3 mm-thick transparent extruded acrylic, which was available in stock at the laboratory.

To accommodate flexibility in light-source positioning during treatment, the engineering features a modular structure that allows the operator to adjust it for each use. Therefore, the project separates the designs into two different blocks: control/HMI and lighting.

3.4.1 Control and HMI structure

This part is a central box that houses the driver and the display with an integrated microcontroller. It is a central component of the equipment, since the power and signal cables that connect to the other parts will originate here. This structure incorporates sides with holes for power supply and cable routing, a bottom, a top with an opening exactly the size of the LCD (Liquid Crystal Display) used in the project, and an inner layer that serves as a support for fitting, positioning, and securing the display.

The sides are attached to the top and bottom pieces by finger joints, a pattern of protrusions on the sides that fits into a pattern of holes in the pieces where they are fixed.

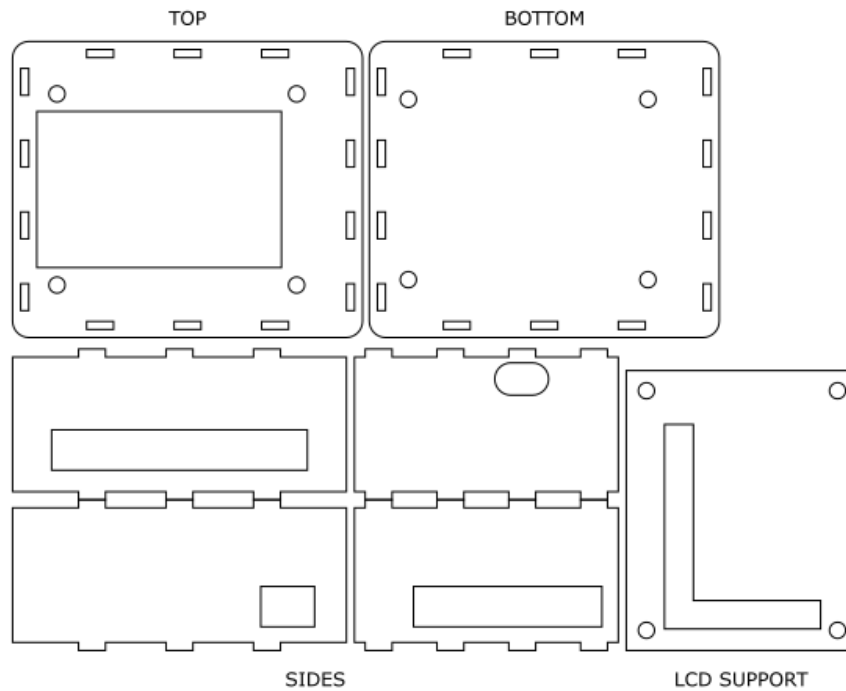


Figure 3.7: 2D vector blueprint of the main control and HMI acrylic enclosure.

In addition, to ensure greater stability and safety, the top and bottom pieces also have 5 mm round holes for screws. Figure 3.7 shows the 2D drawing of this box.

3.4.2 Illumination structure

The lighting section consists of three small, identical boxes, completely separate from each other, each containing a single LED PCB.

The case consists of a bottom with ventilation openings, sides with openings for powering the circuit, a top with an opening and holes for positioning and securing the PCB, and a protective layer on top of the latter to protect users of the equipment and ensure the integrity of the electronic components.

The sides are fitted together at the bottom and top with finger joints, and to ensure greater stability, the bottom and top pieces have 5 mm diameter holes for securing the structure with screws and nuts. The 2D drawing of this box is shown in Figure 3.8.

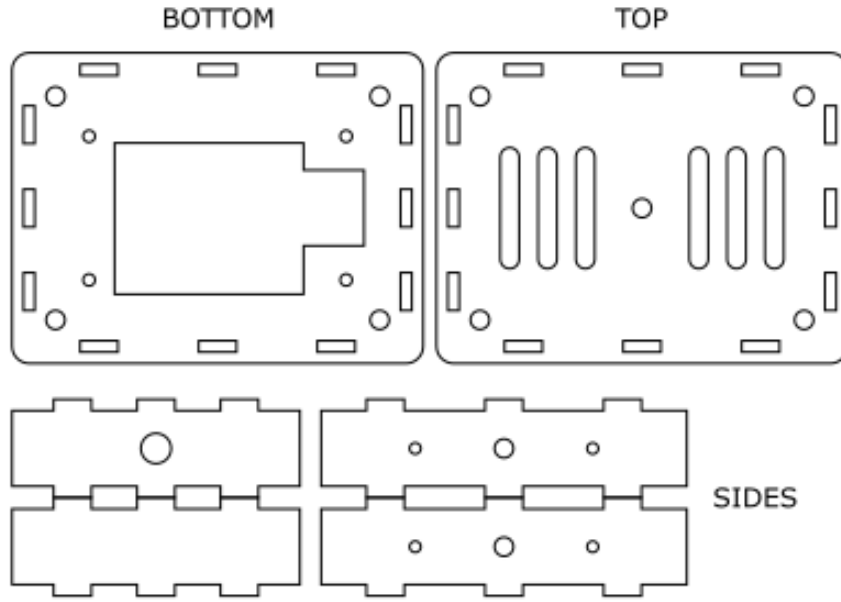


Figure 3.8: 2D vector blueprint of the modular LED illumination acrylic enclosure.

3.5 Calibration

The correlation between the power emitted by the LEDs and the PWM applied to the driver channels ensures the system’s reliability. For this, equipment calibration is of paramount importance.

The first step in this test was to position the lux meter and the equipment on the laboratory bench. The prototype was programmed to ignore the sensor readings, and fixed PWM values were sent to the driver to control one of the lighting panels. The adopted values were 55, 95, 135, 175, 215, and 255. The system was powered by a fixed 5.5 V from a Keithley 2231A-30-3 power supply. Measurements were collected at different distance intervals (4 cm, 7 cm, 11 cm, and 16.5 cm) using a tape measure, and the structure was positioned on the fixed bench and moved vertically.

To avoid reading errors caused by thermal droop in the LEDs, each measurement lasted 6.5 minutes, with values registered every 30 seconds. This methodology afforded sufficient time for the LEDs to reach thermal equilibrium and, consequently, maintain stable illuminance.

For detailed raw data, the complete calibration tables mapping the illuminance variation across all tested distances and PWM levels can be found in Appendix A.

Chapter 4

Results and discussions

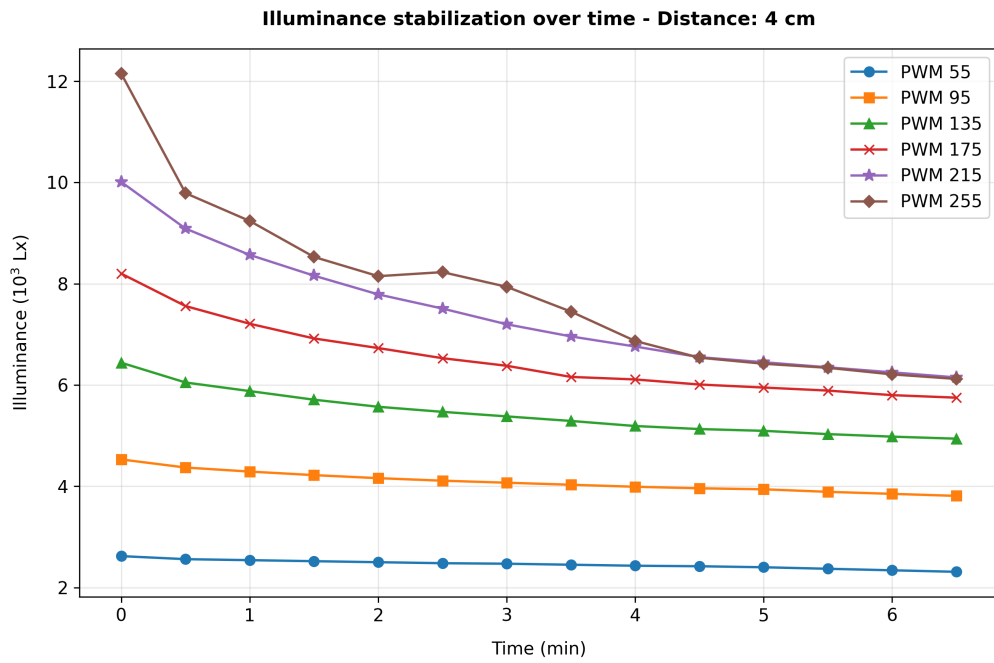
4.1 Optical calibration and dosimetric mapping

The optical calibration tests established the design parameters for the control variables and the equipment's safety limits. Based on the measurements and results, it was possible to determine the system's optical behavior, an essential condition for the development and implementation of PWM control.

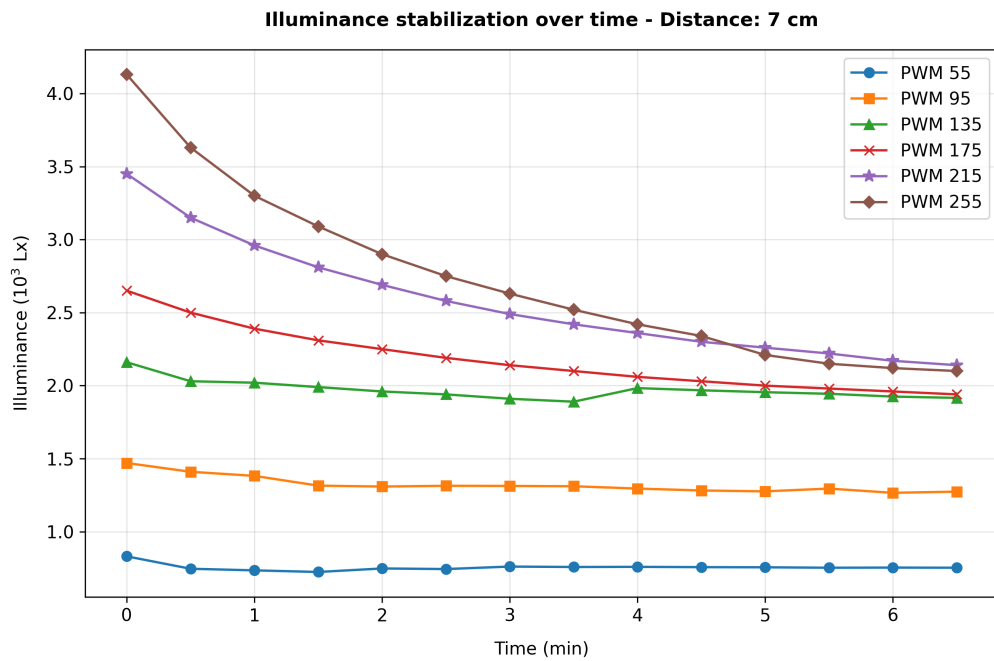
Based on the test results, it was possible to investigate and describe several characteristics and behaviors of the system. The following subsections detail the thermal stabilization of the LED modules, the spatial illuminance distribution, the correlation between distance and PWM modulation, the validation of the Inverse Square Law, and, finally, the accuracy of the control algorithm.

The first behavior investigated was the heat-droop effect of the LEDs, in which the progressive heating of the semiconductor junction reduces the efficiency of electricity-to-light conversion; that is, the light emission gradually decreases until the system reaches thermal equilibrium.

Figure 4.1 shows the graphs analyzing this phenomenon for four distances (4 cm, 7 cm, 11 cm, and 16.5 cm) and six different PWM values (55, 95, 135, 175, 215, 255).

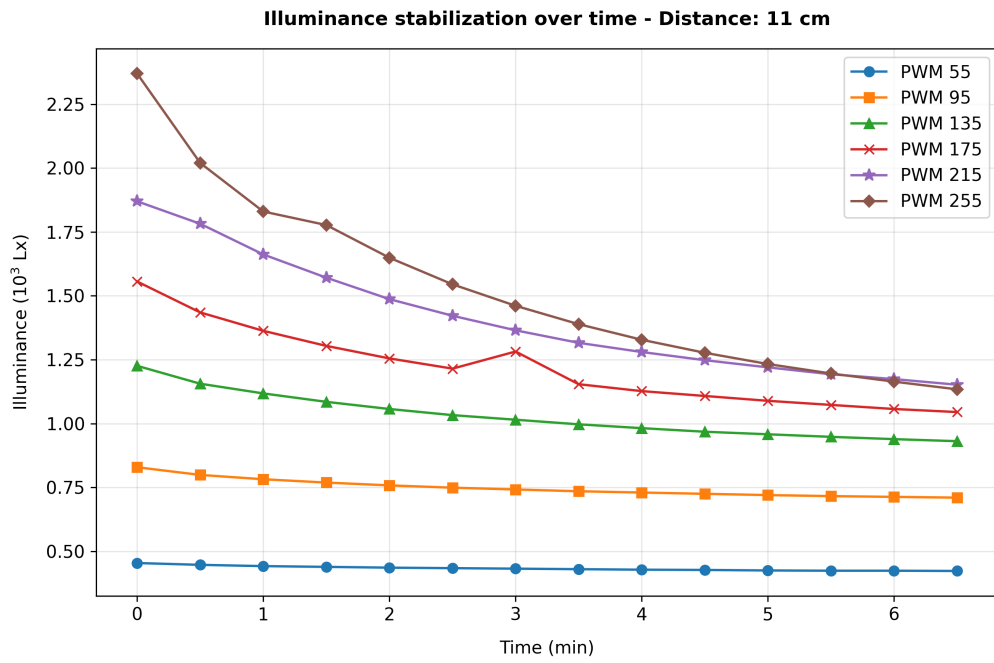


(a)

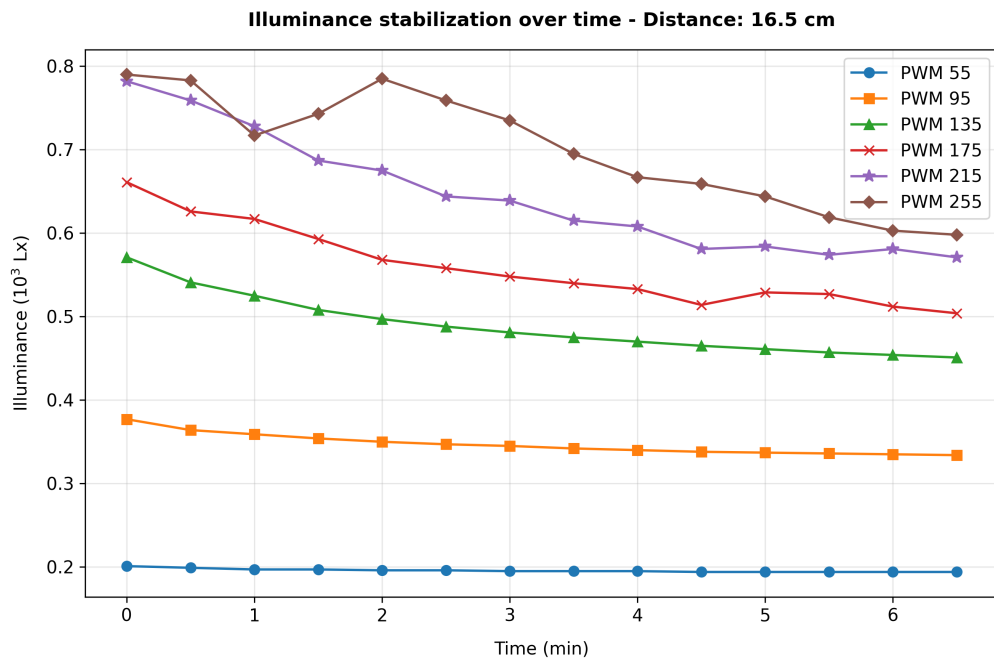


(b)

Figure 4.1: Illuminance stabilization and heat droop effect over time across different PWM duty cycles: (a) 4 cm distance and (b) 7 cm distance (continues on next page).



(c)



(d)

Figure 4.1: Illuminance stabilization and heat droop effect over time across different PWM duty cycles (continued): (c) 11 cm distance and (d) 16.5 cm distance.

To complement this analysis, Figure 4.2 illustrates the percentage variation in illuminance from the activation of the system until stabilization, which occurs around 5 minutes.

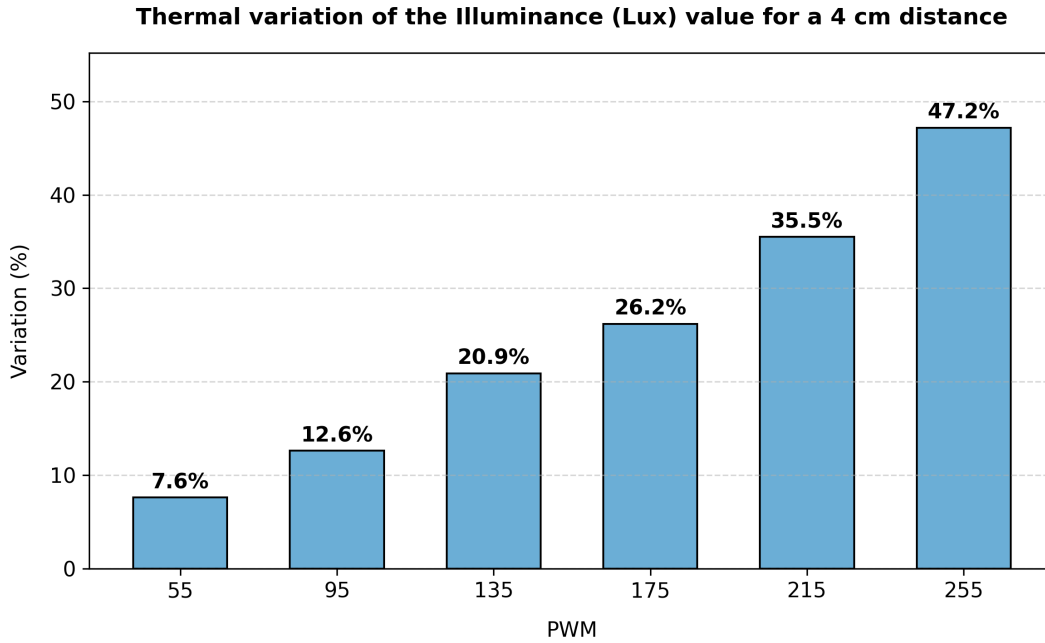


Figure 4.2: Percentage of illuminance attenuation due to thermal variation, from initial activation to steady-state, measured at a 4 cm distance.

It can be observed that illuminance loss increases with the power demanded by the LEDs. Low PWM values, such as 55 and 95, show a slight, controlled degradation, whereas at maximum PWM, losses exceed 40%. Therefore, to ensure safe and controlled system operation, it is important to implement software-based blocking and compensation mechanisms.

The analyses performed based on these results confirm that the system reaches a steady state in approximately 5 minutes. At this point, the dose delivered to the patient becomes constant and expected.

Additionally, the lighting system's transient behavior was verified using linear regression. The results obtained at maximum PWM for the four measured distances were adjusted using the first-order thermodynamic exponential decay equation, as described in

Equation 4.1. Figure 4.3 shows the overlay of the mathematical model onto the collected data.

$$y = ae^{-bx} + c \quad (4.1)$$

The non-linear regression graph for the data collected at a distance of 16.5 cm yielded an R^2 of 0.8767 (Figure 4.3d), indicating a lower correlation between the theoretical model and the experimental data. This is due to the fact that the absolute illuminance measured by the equipment is significantly reduced, and the range between the minimum and maximum values is narrower. Consequently, any minimal noise in the process results in a high relative dispersion. This behavior confirms the low precision and lack of predictability at greater distances, serving as a parameter to establish the maximum operating limits of the system.

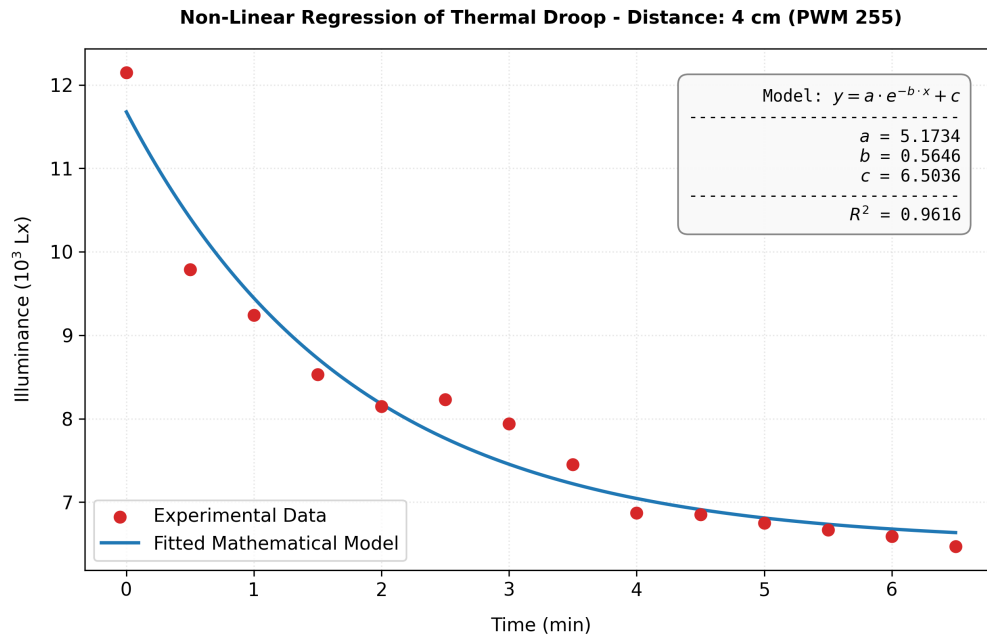
Finally, analyses were performed to verify the system's compliance with the Inverse Square Law, which states that illuminance is inversely proportional to the square of the distance from the emitting source to the target. For this purpose, the illuminance data (after system stabilization) for the different PWM values were correlated to the Equation 4.2. The adjustment curves and the R^2 data are shown in Figure 4.4.

The coefficients of determination (R^2) for the other adjustments indicate a strong correlation between the theoretical model and the system's actual thermal relaxation.

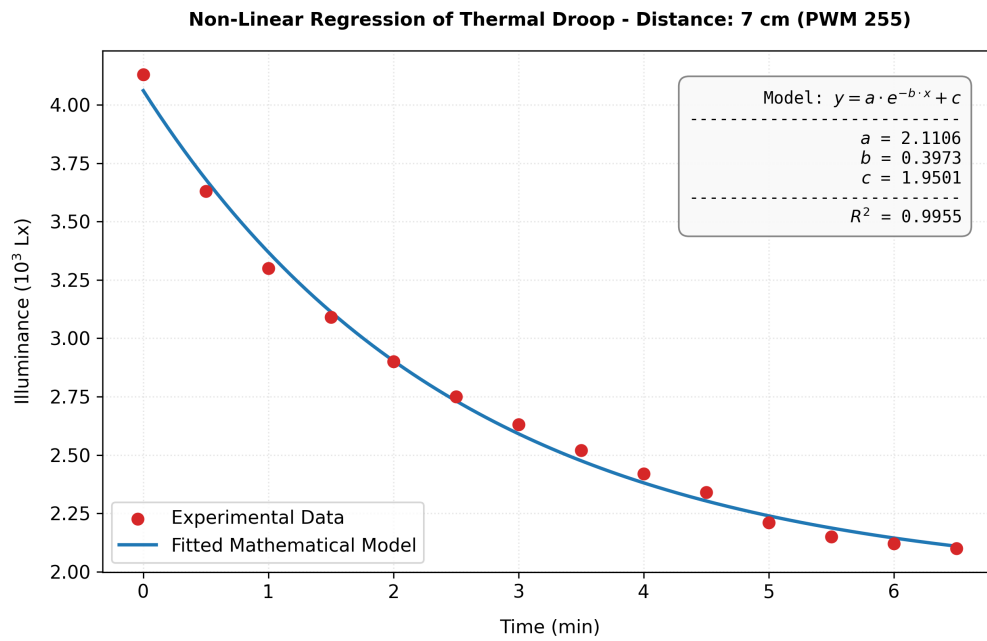
$$y = \frac{a}{x^2} \quad (4.2)$$

The results presented demonstrate that the light beam from the equipment obeys the Inverse Square Law with high accuracy, a relevant characteristic for the equipment, as the system's behavior becomes predictable, enabling calibration and adjustment of control variables to deliver the light dose required by the system operator.

Another noticeable behavior in this analysis was a decrease in illuminance variation as the distance between the LED array and the target increased. This phenomenon can be better observed in Figure 4.5.

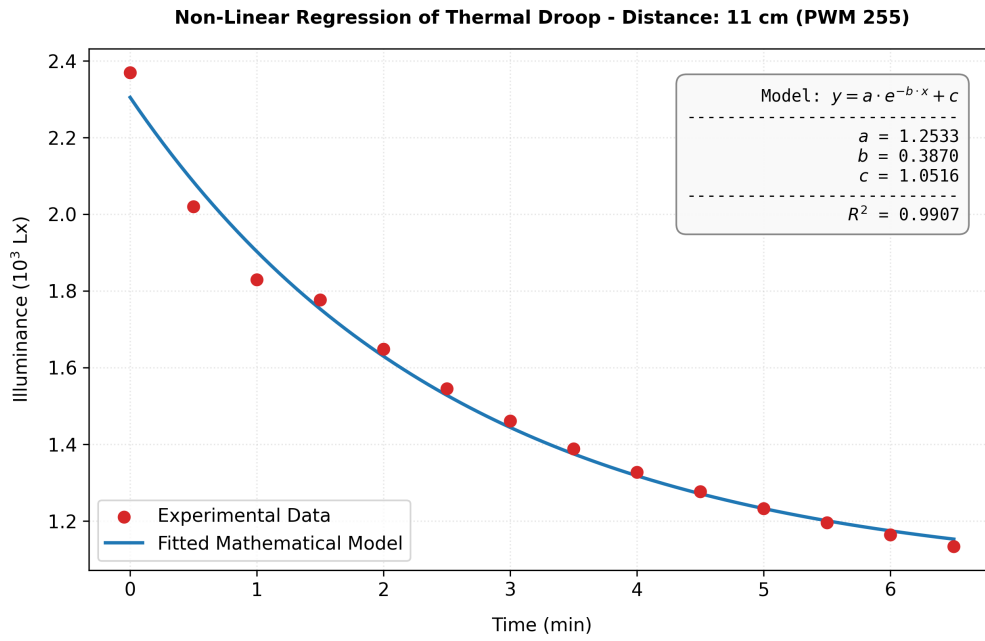


(a)

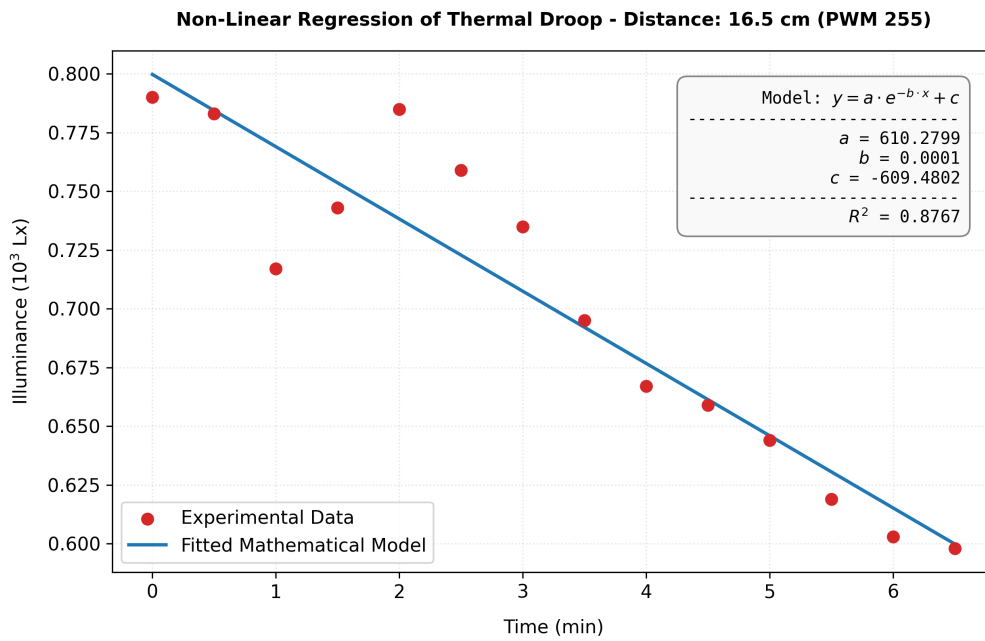


(b)

Figure 4.3: First-order thermodynamic exponential decay model fitted to experimental heat droop data at maximum power (PWM 255): (a) 4 cm distance and (b) 7 cm distance (continues on next page).



(c)



(d)

Figure 4.3: First-order thermodynamic exponential decay model fitted to experimental heat droop data at maximum power (PWM 255) (continued): (c) 11 cm distance and (d) 16.5 cm distance.

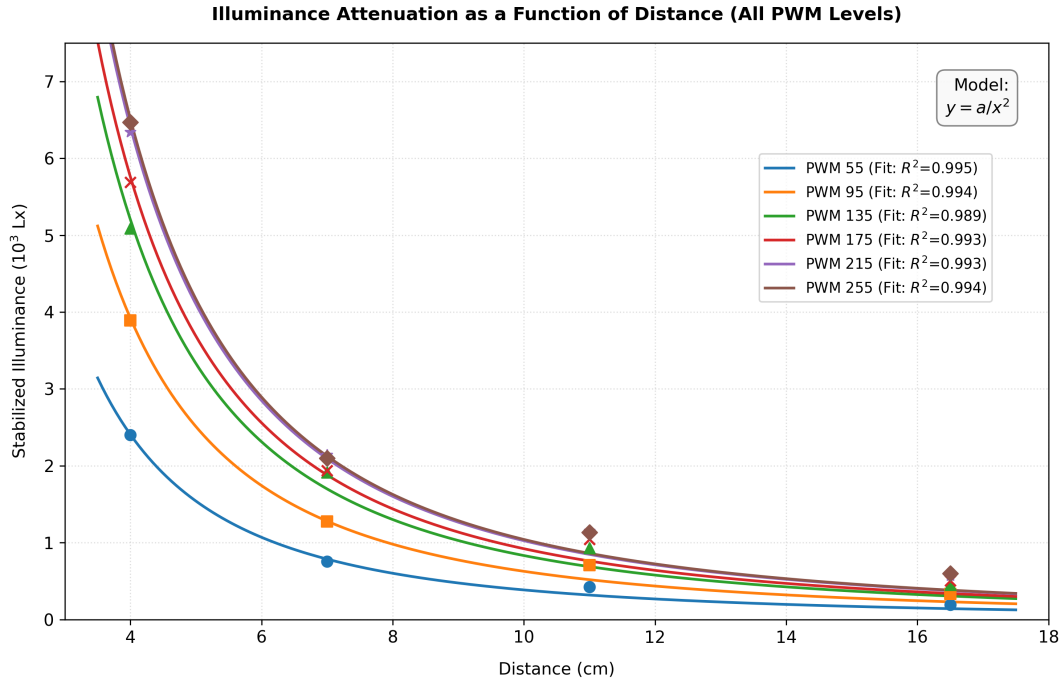


Figure 4.4: Inverse-square law mathematical fit demonstrating stabilized illuminance attenuation as a function of distance across all tested PWM levels.

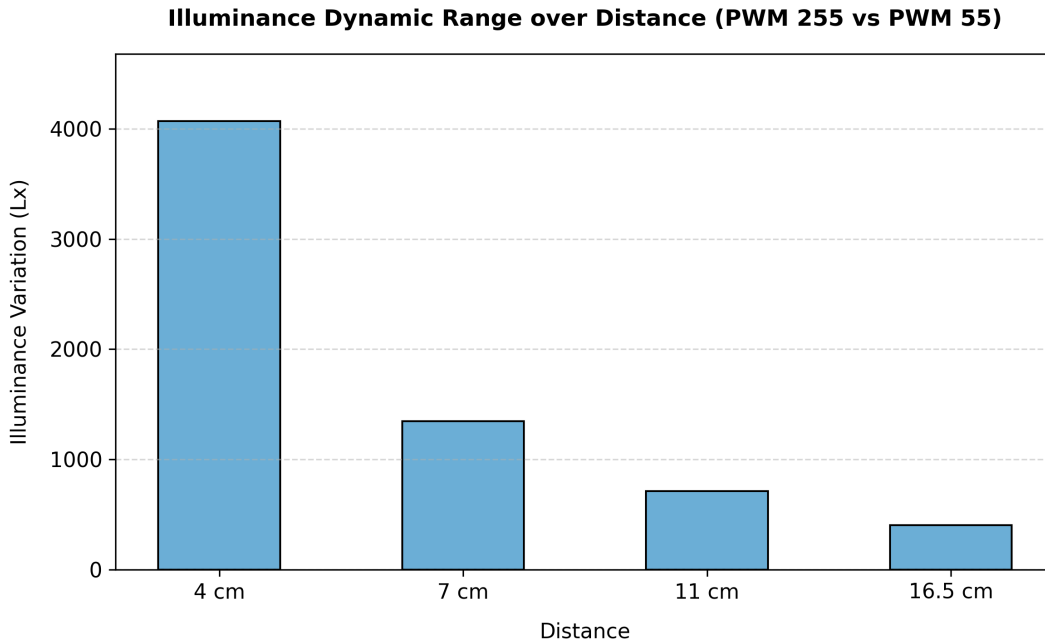


Figure 4.5: Illuminance dynamic range comparing maximum (PWM 255) and minimum (PWM 55) power outputs across the evaluated distances.

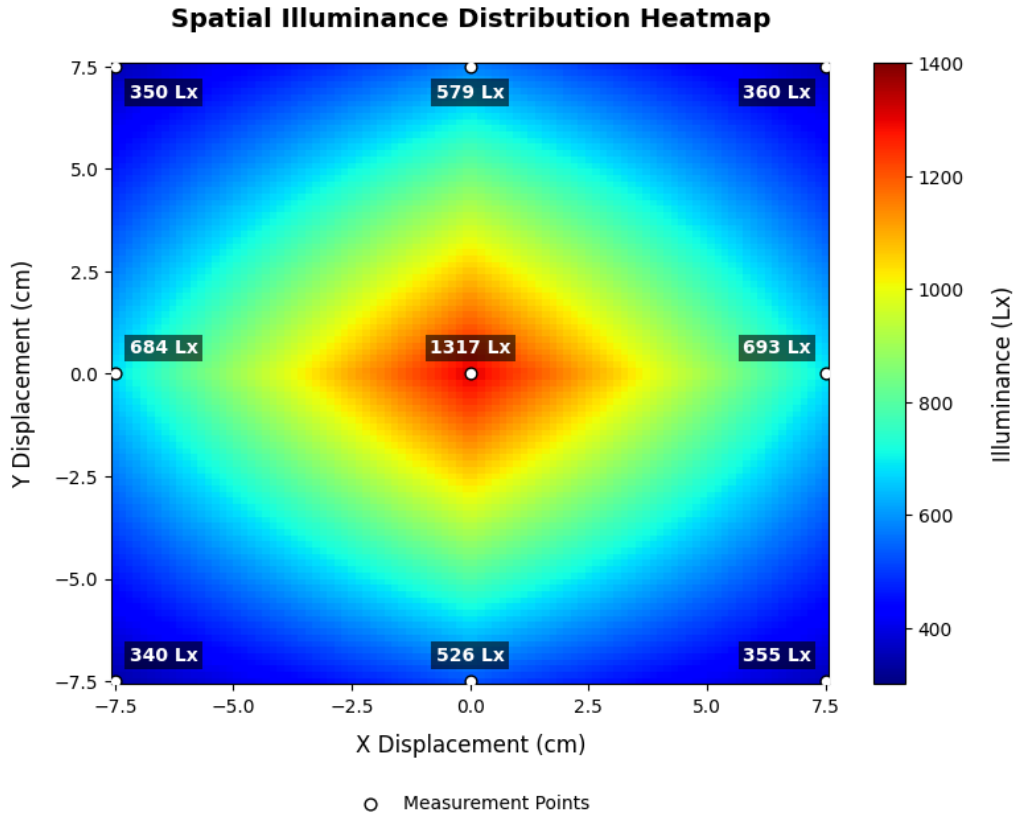


Figure 4.6: Spatial illuminance distribution and beam uniformity heatmap, mapped over a 15 cm x 15 cm target area at a fixed distance of 10 cm.

To assess the spatial distribution of illuminance, a uniformity mapping was performed at a fixed distance of 10 cm. A target area of 15 cm x 15 cm was defined, and measurements were collected at 9 points along a grid pattern. The measured values are shown in the heatmap in Figure 4.6.

As observed by the spatial distribution, the system exhibits a peak intensity (1317 lux) at the optical center, with a steep decline towards the edges, where values reach approximately 350 lux. This gradient confirms the overlapping radiation of the LED array, a typical behavior in non-collimated light sources.

This behavior is detailed in Figure 4.7, which shows the cross-sectional light emission profiles of the LED module. Both the vertical and horizontal curves demonstrate a Gaussian-like distribution, confirming the concentration of energy at the central point. This characterization is important for determining the effective area of the irradiation

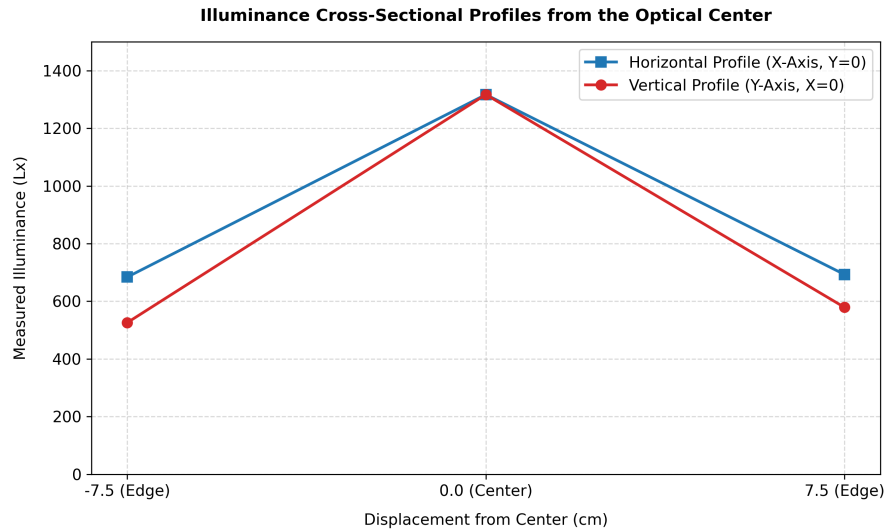


Figure 4.7: Horizontal and vertical cross-sectional illuminance profiles measured from the optical center, illustrating a Gaussian-like energy concentration.

device.

4.2 Electric circuit and PCB validation

The physical implementation of the electronic circuits was carried out by fabricating PCBs and soldering the components selected and dimensioned for the project. The system underwent several tests to verify the integrity of components, traces, and solder joints, as well as to evaluate equipment behavior under load and the agreement between the theoretical model and the physical prototype.

4.2.1 Printed Circuit Boards

The PCBs used in the equipment assembly were manufactured by Computer Numeric Control (CNC) milling at the IPB facilities. A visual inspection followed this to identify possible manufacturing defects. After this verification step, the components were also soldered at IPB. The quality of the solder joints was assessed using a multimeter in continuity mode, which confirmed the absence of short circuits. Cold solder joints were

evaluated and repaired during practical testing. Figure 4.8 presents the two PCB models produced for this project, both already soldered and verified.

The implementation of GND and Voltage at the Common Collector (VCC) planes on the PCBs provided isolation between the logic and power circuits and ensured effective thermal dissipation. Prolonged temperature variation tests with the LED modules decoupled from the central system and connected directly to the power supply, operating under maximum circuit load conditions with the current reaching 2.1 A after 5 minutes of operation, revealed that the board's GND plane reached 71.2 °C, while the copper surrounding the sensor registered only 33.4 °C.

Under normal operating conditions, with the LED modules coupled to the prototype and controlled by the driver, new thermal stress tests were performed. After 6.5 minutes of operation with the PWM set to its maximum, the temperature on the copper surface was 49.2 °C, well below the previously recorded value. The temperature difference between the two tests is justified because the first test was performed to determine the absolute physical limit of the plates. In contrast, the second test evaluated the system under real operating conditions.

Although the temperature data from the second scenario is much lower, they still require attention regarding the safety of the PDT application. Therefore, treatment application is blocked if the distance measured by the sensors is less than 40 mm, which is the minimum operating limit defined in the software.

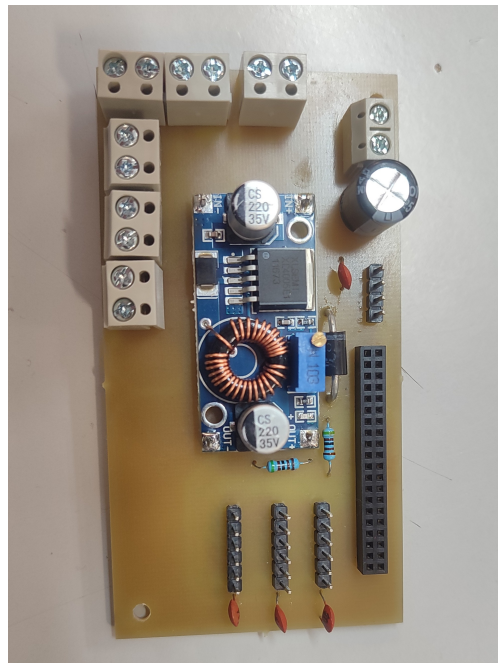
4.2.2 Electric circuit and components

The electrical circuit was evaluated through a detailed analysis of its main blocks: the power supply and voltage regulation stage, the sensors, the driver, the logic signals, and the LED arrays. Finally, the behavior of the complete circuit under load was evaluated.

For the tests, the system was powered using a Keithley 2231A-30-3 [79] bench power supply and a Digital Oscilloscope TBS 1052B-EDU [80], both manufactured by Tektronix and available in the IPB laboratories for student use.



(b)



(d)

Figure 4.8: Fully assembled and verified PCBs: (a) and (b) Front and rear views of the LED array and sensor module; (c) and (d) Front and rear views of the main control and power supply board.

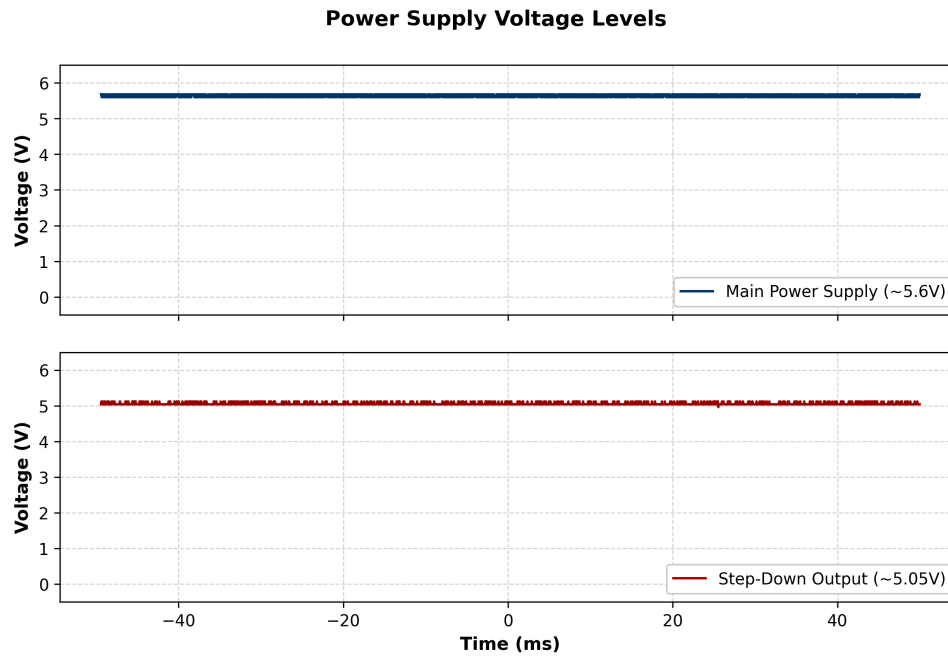


Figure 4.9: Power supply voltage levels: main line (top) and step-down converter output (bottom).

Initially, the tests were carried out using a 5.5 V input voltage, which was delivered to the driver and switched by the MOSFETs to power the LEDs. This voltage was also stepped down to 5 V by the LM2596 step-down module in order to supply the microcontroller.

Some tests were performed using an oscilloscope to verify the stability of the power supply rails, since both the microcontroller and the LED driver IC require a stable 5 V supply. The results of these tests are shown in Figure 4.9. These tests demonstrate the importance of the decoupling capacitors placed near the power supply points, which ensured voltage stability.

The system data lines were validated following the same methodology, but with analyses focused on the signal lines. It was verified that the 3.3 V and 5 V outputs of the microcontroller, together with the decoupling capacitors, provide a sufficiently stable voltage and the required logic levels for the proper operation of the sensors and integrated circuits. Figure 4.10 presents the clock and data waveforms of the SPI communication

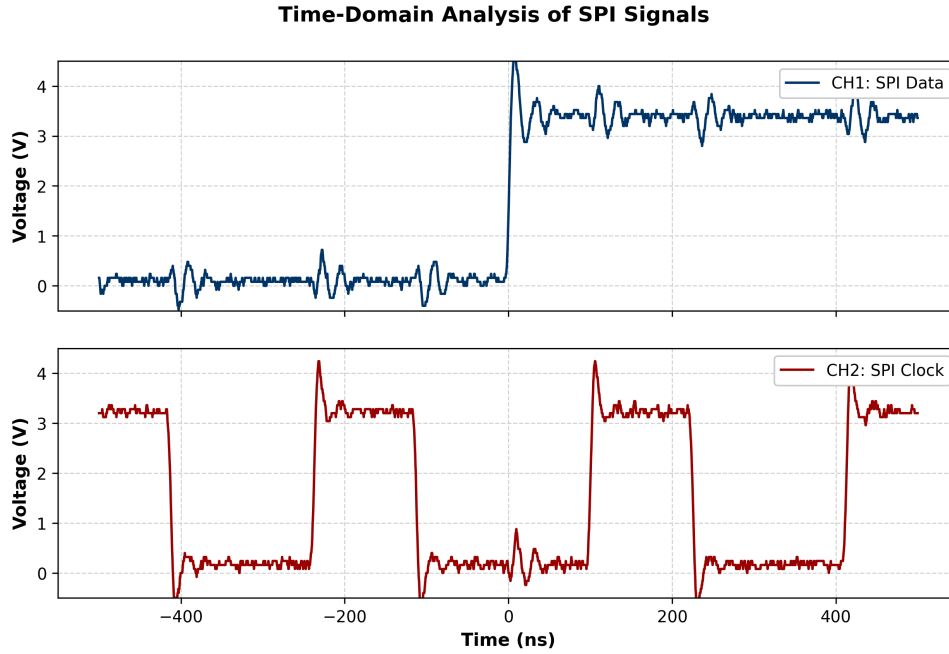


Figure 4.10: : Time-domain analysis of the driver communication signals, detailing the data (CH1) and clock (CH2) lines.

interface used by the LED control driver.

Within the scope of the system communication analysis, Figure 4.11 presents the waveforms of the Serial Data (SDA) and Serial Clock (SCL) pins for the I2C protocol used by the sensors. In this figure, the operation of the pull-up resistors can be observed, which rapidly drives the voltage to 3.3 V during data transmission.

Finally, some tests were performed to quantify the system's operating current. Initially, one of the lighting modules was decoupled from the prototype and powered directly by the source. This test validated the theoretical calculations developed in Chapter 3, as for an input voltage of 5.54 V, the instrument-measured current delivered to the circuit was 2.1 A.

Subsequently, the system was evaluated under maximum load to characterize the circuit's electrical behavior. The prototype was powered at 5.5 V, and the microcontroller was programmed to continuously send the maximum PWM value to all power driver channels for 6 minutes. After the thermal stabilization period, the total current measured by

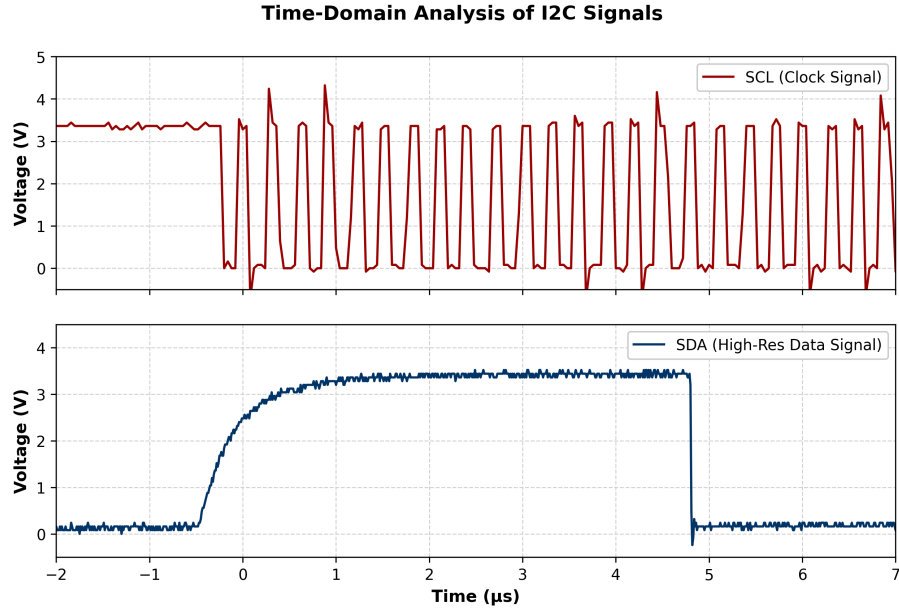


Figure 4.11: Time-domain analysis of the I2C communication signals, illustrating the behavior of the clock (SCL) and data (SDA) lines.

the power supply was 2.48 A.

The discrepancy between the theoretical nominal values and the practical consumption in integrated operation is due to non-ideal electrical losses in the system. Cables, connectors, and copper traces on the PCBs introduce parasitic impedances, in addition to voltage drops caused by the conduction resistances of the driver MOSFETs. Since the resistors on the LED boards operate with a very small potential difference (approximately 0.7 V), even a slight variation in the voltage delivered to the operating modules results in a significant drop in current.

The system's sizing, conceived to operate in worst-case scenarios under full load and ideal conditions, proved necessary for the equipment's operational safety. The continuous operation below 50% of maximum capacity drastically reduces thermal stress on the LEDs, protects other components, and ensures safety in the application of Photodynamic Therapy, whose effectiveness depends directly on the light source's thermal and luminous stability.

4.3 Firmware and HMI

The results of implementing the source code for state machine control and peripheral devices were analyzed. The firmware and HMI tests demonstrated smooth, stable performance and reliable, efficient communication.

4.3.1 Firmware

During the firmware tests, several important aspects of the equipment's operation were identified, particularly regarding the sensors and the control of the LED power driver.

One of the main results of this stage concerns the initialization of the I2C bus used by the sensors. In the first firmware execution routine, distinct addresses are assigned to each sensor via the XSHUT pin, which is connected to the microcontroller General Purpose Input/Output (GPIO) ports. Implementing this logic enables simultaneous sensor reading and communication on the I2C bus without address collisions.

Figure 4.12 presents the source code debug output during execution, including the assigned addresses, the sensor readings, and the corresponding PWM values sent to the driver.

In data processing, reading validation is performed by discarding measurements outside the range of 40 mm to 130 mm, points where the treatment loses security due to the heat emitted by the LEDs, or becomes ineffective due to the high distance. In these cases, it is possible to confirm that the firmware correctly processes the information and resets the PWM, turning off the LEDs.

Regarding the LED control logic, software testing confirmed the system's correct operation. Communication between the microcontroller and the driver was successful, and the control system operated stably, correctly mapping the user-selected illuminance level to the driver's corresponding PWM value.

Figure 4.13 shows the HMI screen during treatment under both proper operating conditions and measurement conditions outside the specified range.

To evaluate the control algorithm's reliability, another positioning test was performed.


```

rst:0x1 (POWERON_RESET),boot:0x17 (SPI_FAST_FLASH_BOOT)
configsip: 0, SPIWP:0xee
clk_drv:0x00,q_drv:0x00,d_drv:0x00,cs0_drv:0x00,hd_drv:0x00,wp_drv:0x00
mode:DIO, clock div:2
load:0x3fff0030,len:1184
load:0x40078000,len:13232
load:0x40080400,len:3028
entry 0x400805e4
Driver ok!
Sensor 1 OK. Endereco: 0x30
Sensor 2 OK. Endereco: 0x31
Sensor 3 OK. Endereco: 0x32
Os 3 sensores estao enderecados!
Sensores inicializados!
Leitura do sensor 1: 113 mm
Leitura do sensor 2: 220 mm
Leitura do sensor 3: 293 mm
PWM Enviado:
Braco 1 (R): 231
Braco 2 (G): 0
Braco 3 (B): 0

```

Figure 4.12: Microcontroller debug output captured via serial monitor, displaying system initialization and dynamic I2C sensor address assignment.

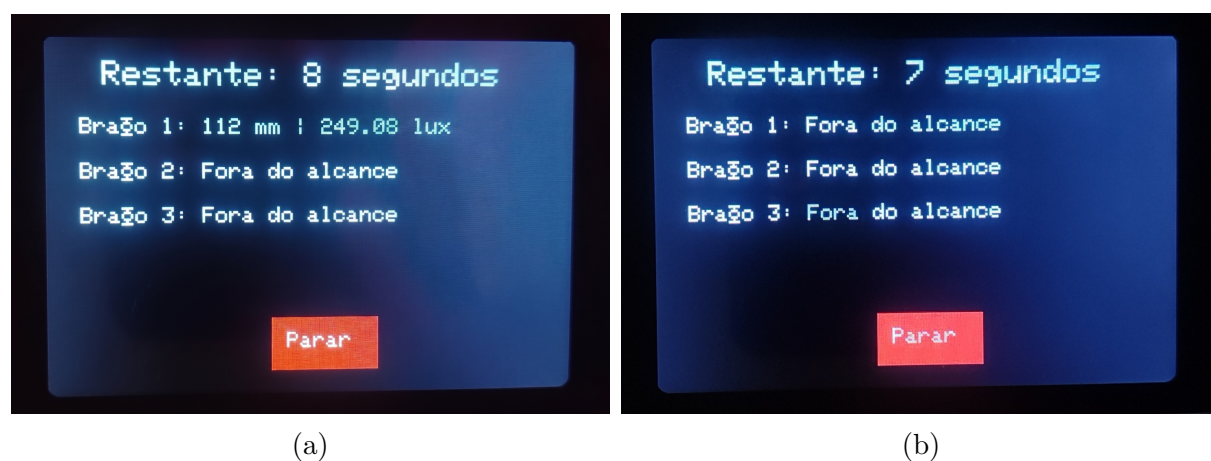


Figure 4.13: HMI display during an active treatment session illustrating: (a) normal operation with real-time dosimetry variables, and (b) safety intervention when the target distance exceeds the operational range.

This time, the system was configured with a setpoint of 300 lux, while the distance between the LED module and the optical sensor was varied in five different values. Illuminance measurements were taken after the system's thermal stabilization, with values recorded every 30 seconds for 2 minutes. The objective of this test was to verify the software's ability to compensate for illuminance by automatically adjusting PWM.

Figure 4.14 shows the behavior of the illuminance measured at each of the distances in relation to the established setpoint.

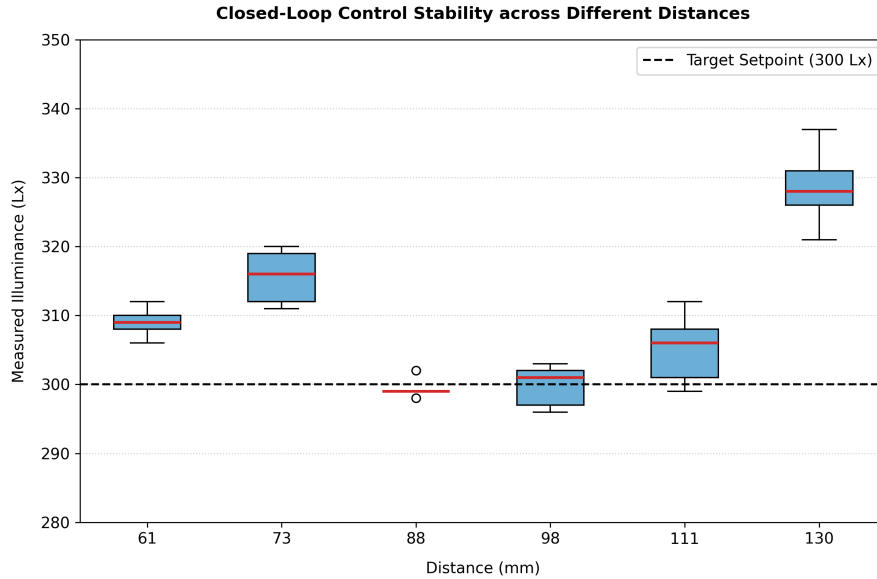


Figure 4.14: Dynamic stability analysis of the closed-loop control system under a target setpoint of 300 Lx.

Analysis of the boxplot reveals that the system exhibits good stability and the ability to adapt illuminance across most of the measured range. At intermediate distances, the control presents high precision, as proved by the median of the data being almost superimposed on the reference line. Furthermore, the graph shows low vertical dispersion among the data, confirming the lack of oscillations in the system output and its stability.

To verify the overall accuracy of the prototype, deviations were mapped using the calculation of the Mean Absolute Percent Error (MAPE), as illustrated in Figure 4.15.

The overall average system error was 3.29%, demonstrating the prototype's viability and accuracy, as dosimetric fluctuations of up to 10% are tolerated and considered safe in

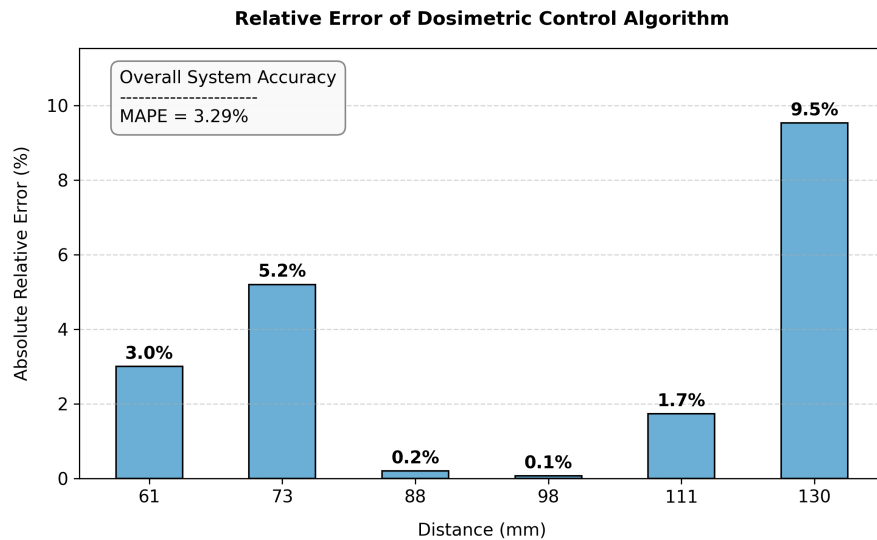


Figure 4.15: Absolute relative error of the dosimetric control algorithm as a function of irradiation distance.

the literature on biomedical systems for PDT [84]. However, the relative error tended to increase at the test's maximum. At this distance, the recorded error was 9.5%, leading to optical overdosing. This behavior occurs because of the equipment's physical limitations and component constraints: as the distance increases, the PWM duty cycle increases, and the driver and LEDs begin to operate in non-linear regions near saturation.

Given the limitations encountered in this test and the thermal constraints mentioned earlier in the text, the prototype was configured to operate within a 40-130 mm distance range, an interval within which the treatment can be applied without temperature concerns, and the light dose values can be adjusted more precisely.

4.3.2 HMI - Human-Machine Interface

The HMI tests demonstrated that the graphical rendering was performed without failures and confirmed the correct operation of the state machine developed for the device. Navigation between screens occurs without perceptible delays and follows the sequence established for all treatment stages.

During the touchscreen interaction tests, it was confirmed that the debounce algorithm correctly operates, scanning the touchscreen and eliminating duplicate touches by ignoring interactions within 250 ms of the previous one. In addition, the device exhibited a stable refresh rate, without flickering and with instantaneous response, mainly due to the LovyanGFX library, which provides highly optimized low-level hardware control and efficient CPU cycle management, ensuring much faster data transmission to the display compared to standard libraries.

Touch inputs were processed by mapping the sensor's raw coordinates (0–720) to the physical screen resolution (0–480). This process guaranteed that the buttons and the virtual keyboard operated without failures or touch-detection errors. Other HMI operational tests verified the input boundary controls. The system limits power levels and treatment time to a safe operating range. Whenever a value is entered outside this safe interval, the system automatically constrains it to the nearest acceptable boundary.

Finally, the state machine guarantees several protection barriers: the treatment only starts after State 3, which corresponds to the validation and confirmation of the inserted data, allowing the user to cancel the operation and re-enter the information if necessary. In addition, the Stop button on the active treatment screen (State 4) immediately interrupts equipment operation, resets all variables, and returns the system to State 0 (initial screen).

Figure 4.16 presents the HMI screens operating during all stages of treatment configuration and application.

4.4 Mechanical integration and thermal stability

The equipment structure was manufactured at the IPB FABLAB (Fabrication Laboratory) using a CNC laser cutting machine, based on 2D models developed in the open-source software Inkscape. The main function of the structure is to accommodate electronic components and circuits while ensuring safe handling.

The structure was entirely machined from 3 mm-thick transparent cast acrylic sheets,

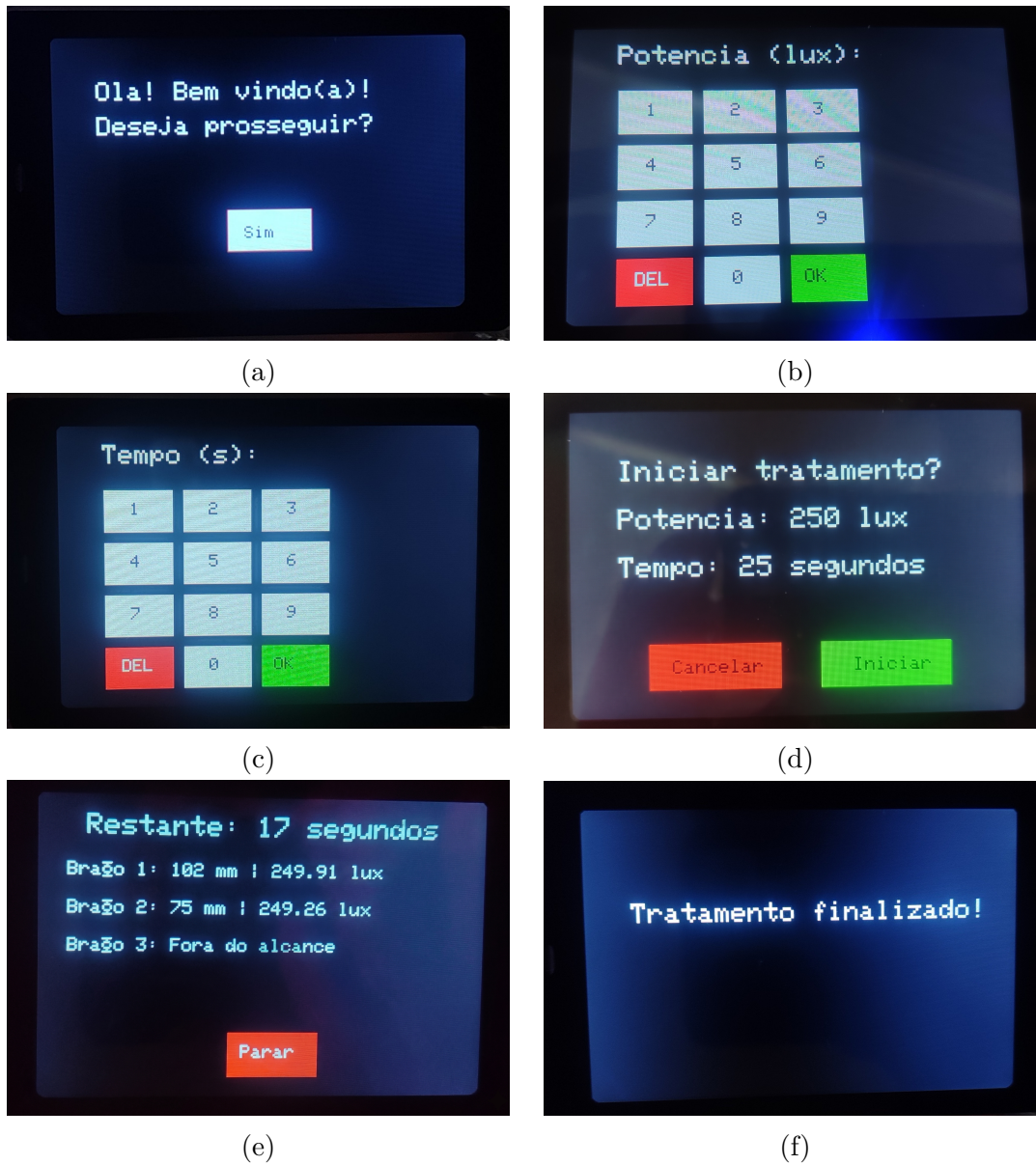


Figure 4.16: HMI operational workflow: (a) welcome screen, (b) power configuration, (c) duration setup, (d) parameter confirmation, (e) active treatment monitoring, and (f) completion notification.

which proved highly suitable for this application due to their electrical insulation properties, low weight, and ease of cleaning.

The manufacturing process using the CNC laser cutting machine achieved high cutting precision, resulting in a perfect fit between the structural parts and in the fixation of the PCBs and other components.

The use of finger-joint fittings was important for the alignment of the enclosures, eliminating the excessive need for screws. The handling of the structure was performed without issues of looseness or vibration.

Figure 4.17 presents the fully assembled LED enclosures, with the components installed and operating properly, demonstrating the successful prototyping of the structure. The slots on the upper part of the enclosure assisted in thermal dissipation of the LEDs, protecting the system and preventing acrylic deformation caused by residual heat from the circuit.

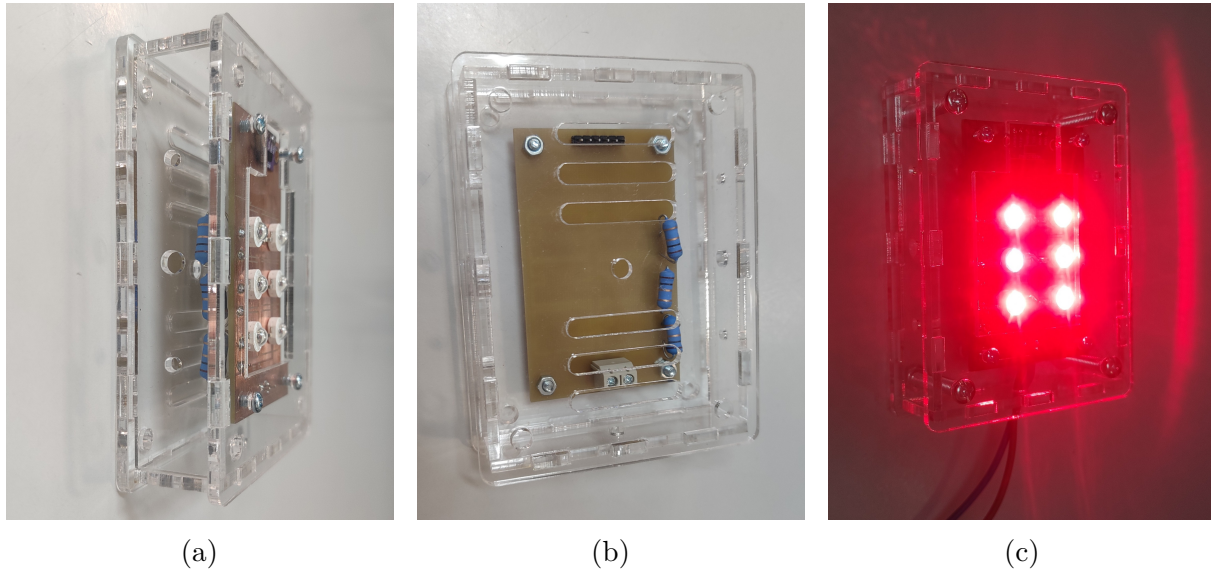


Figure 4.17: Final assembled prototype of the illumination module: (a) side profile highlighting the modular acrylic enclosure, (b) rear view of the integrated PCB, and (c) front view of the active LED array.

The central enclosure, which houses the entire circuit logic, also exhibited precise component fit, particularly the display module, which was mounted to the structure using screws and nuts that keep the board aligned with the upper part of the enclosure, thereby

protecting the screen edges from mechanical impacts. These details are shown in Figure 4.18.

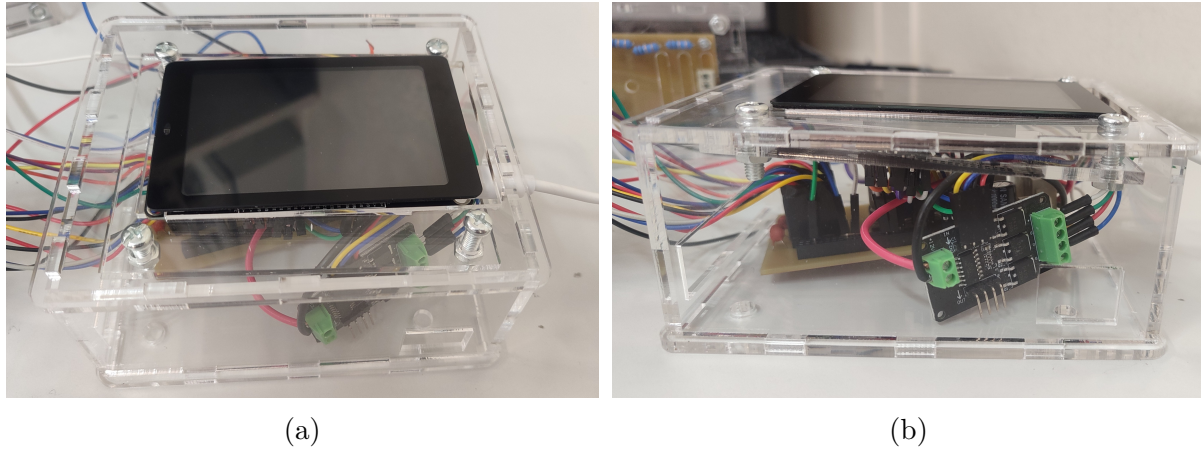


Figure 4.18: Central control unit prototype in acrylic enclosure: (a) front view highlighting the touch-based HMI; (b) side view detailing the internal arrangement of the printed circuit boards.

As with the rest of the structure, the side openings for the routing of communication and power cables successfully fulfilled their function of providing cable protection and fixation, while also contributing to the organization and overall design of the final prototype.

Figure 4.19 shows the fully assembled final prototype. The connection of all lighting modules to the central unit demonstrates the system in its final operating configuration.

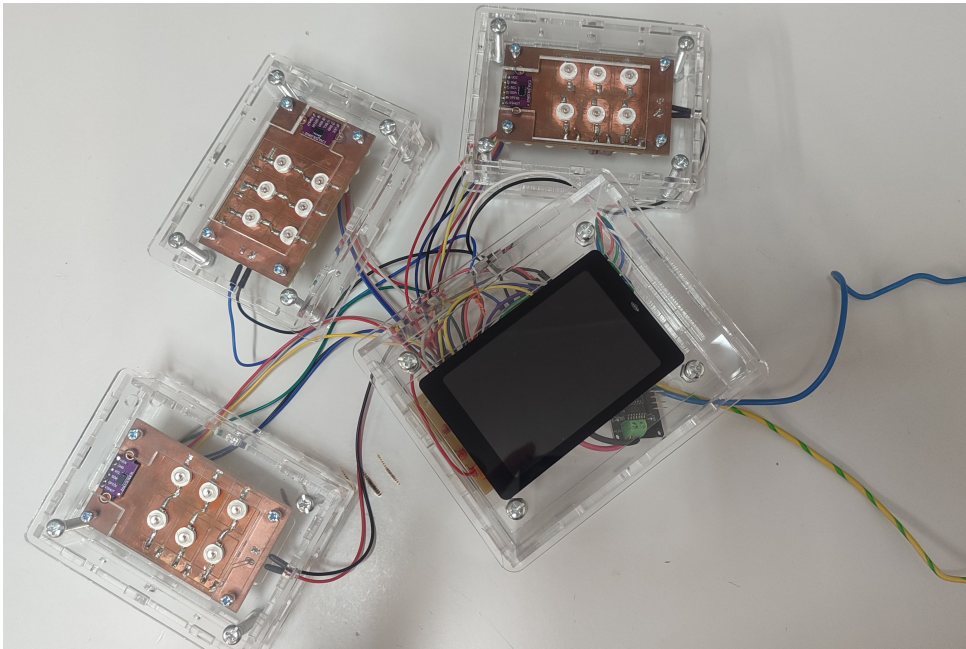


Figure 4.19: Fully assembled controlled irradiation device, showing the integration between the central control unit and the LED illumination modules.

Chapter 5

Conclusion

The main objective of this work was to develop a functional prototype for controlled light irradiation, with a focus on applications in Photodynamic Therapy. The project consisted of optimizing light dosimetry by controlling illuminance based on the distance between the light source and the target.

The final prototype demonstrated the ability to control light dosimetry based on the distance between the equipment and the target, as evidenced by a Mean Absolute Percent Error (MAPE) of 3.29% during equipment validation tests. Furthermore, the system's behavior was consistent with theoretical models, as adjustments of the test data to the theoretical equations yielded $R^2 > 0.98$ in virtually all scenarios.

The hardware architecture was designed with safety and operational stability as top priorities. This was achieved through the separation of power and data lines on the printed circuit boards, the use of isolated ground planes, and the oversizing of the circuit, taking into account the operation of all components at their nominal capacities. Theoretical calculations indicated a current of 6.3 A, while the prototype's operation at maximum load required only 2.48 A, ensuring a large safety margin and allowing the LEDs and PCBs to operate at lower temperatures suitable for Photodynamic Therapy applications, reaching less than 50 °C at maximum load and achieving thermal stability in approximately 5 minutes.

In the electronics and component selection, the implemented Time-of-Flight sensors

proved to be accurate. The LED driver based on the P9813 integrated circuit demonstrated robust control of the LEDs, easily managing current and power throughout the circuit, and fast response times that smoothly adjusted illuminance according to the calculated PWM.

The system integrated a fluid HMI with safety steps throughout the treatment, including data confirmation before starting the treatment and the ability to interrupt the application at any time, as well as power value locks that ensured the equipment did not operate outside the stipulated distance limit of 40 mm to 130 mm.

Regarding thermal management, heat dissipation can be improved by using heat sinks or micro-fans coupled to the mechanical structure. This measure would decrease the operating temperature of the LEDs and, consequently, the system's stabilization time. Furthermore, integrating temperature sensors on the PCBs to monitor data in real time and implementing software-based safety locks in case of overheating are suggested.

About software matters, polynomial correction codes can be implemented in the control algorithm to mitigate the non-linear behavior observed at the points of highest power demand in the system, such as the 9.5% error presented in the PWM adjustment at a distance of 130 mm and the uncharacteristic behavior of the calibration curve obtained at a distance of 165 mm.

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Appendix A

Optical Dosimetry and Thermal Calibration Tables

This appendix presents the raw experimental data obtained during the calibration process of the irradiation system. The tables record the measured illuminance values (in lux) over time for different Pulse Width Modulation (PWM) duty cycles and distances.

Table A.1: Measured illuminance (lux) over time for a distance of 4 cm.

Time (s)	PWM (0-255)					
	55	95	135	175	215	255
0	2620	4530	6440	8200	10010	12150
30	2560	4370	6050	7560	9090	9790
60	2540	4290	5880	7210	8570	9240
90	2520	4220	5710	6920	8160	8530
120	2500	4160	5570	6730	7790	8150
150	2480	4110	5470	6530	7510	8230
180	2470	4070	5380	6380	7200	7940
210	2450	4030	5290	6160	6960	7450
240	2430	3990	5190	6110	6760	6870
270	2420	3960	5130	6010	6500	6850
300	2420	3940	5070	5890	6370	6750
330	2410	3920	5130	5790	6370	6670
360	2410	3910	5120	5750	6350	6590
390	2400	3890	5090	5690	6340	6470

Table A.2: Measured illuminance (lux) over time for a distance of 7 cm.

Time (s)	PWM (0-255)					
	55	95	135	175	215	255
0	831	1470	2160	2650	3450	4130
30	746	1410	2030	2500	3150	3630
60	735	1382	2020	2390	2960	3300
90	724	1315	1990	2310	2810	3090
120	748	1309	1960	2250	2690	2900
150	744	1314	1940	2190	2580	2750
180	761	1313	1910	2140	2490	2630
210	758	1311	1890	2100	2420	2520
240	759	1295	1983	2060	2360	2420
270	757	1282	1968	2030	2300	2340
300	756	1276	1955	2000	2260	2210
330	753	1295	1944	1980	2220	2150
360	754	1266	1925	1960	2170	2120
390	753	1274	1916	1940	2140	2100

Table A.3: Measured illuminance (lux) over time for a distance of 11 cm.

Time (s)	PWM (0-255)					
	55	95	135	175	215	255
0	454	829	1226	1556	1870	2370
30	447	799	1156	1435	1782	2020
60	442	782	1118	1363	1662	1830
90	439	769	1085	1304	1571	1777
120	436	758	1057	1255	1487	1649
150	434	749	1033	1215	1422	1545
180	432	742	1015	1282	1365	1461
210	430	735	997	1154	1316	1389
240	428	730	982	1127	1280	1328
270	427	725	968	1108	1248	1277
300	425	720	958	1089	1220	1233
330	424	716	948	1073	1193	1196
360	424	713	939	1057	1174	1164
390	423	710	931	1045	1152	1134

Table A.4: Measured illuminance (lux) over time for a distance of 16.5 cm.

Time (s)	PWM (0-255)					
	55	95	135	175	215	255
0	201	377	571	661	782	790
30	199	364	541	626	759	783
60	197	359	525	617	728	717
90	197	354	508	593	687	743
120	196	350	497	568	675	785
150	196	347	488	558	644	759
180	195	345	481	548	639	735
210	195	342	475	540	615	695
240	195	340	470	533	608	667
270	194	338	465	514	581	659
300	194	337	461	529	584	644
330	194	336	457	527	574	619
360	194	335	454	512	581	603
390	194	334	451	504	571	598