# Protocol: Task 02

## Thermocouple and Thermal Camera Calibration for 3D Printing Thin Wall Analysis

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# 1 Introduction

This protocol describes the systematic calibration of thermal measurement equipment and subsequent data collection for analyzing temperature distribution during PLA (Polylactic Acid) 3D printing processes. The experimental workflow consists of three interconnected phases: thermocouple calibration using a reference incubator, thermal camera (MLX90640) calibration against the calibrated thermocouple, and real-time temperature monitoring during additive manufacturing operations.

# 2 Purpose

The primary objectives of this experimental protocol are:

- Establish accurate temperature measurement standards through systematic thermocouple calibration
- Derive correction equations for MLX90640 thermal camera readings using linear regression analysis
- Implement a robust data acquisition system for continuous thermal monitoring during 3D printing
- Collect comprehensive temperature distribution data across different PLA printing parameters (speed vs. structural quality settings)
- Provide quantitative thermal analysis capabilities for simulation of temperature distribution in wall

# 3 Experimental Protocols

## 3.1 Experiment 1: Thermocouple Calibration

This experiment establishes accurate temperature measurement standards through systematic thermocouple calibration using a reference incubator.

The experimental setup includes a calibrated incubator and reference thermocouple as shown in the following figures:

## 3.2 Experiment 2: Thermal Camera Calibration

This experiment derives correction equations for MLX90640 thermal camera readings using linear regression analysis against the calibrated thermocouple.

Table 1: Thermocouple Calibration Protocol

| Step | Procedure | Remarks |
|---|---|---|
| 1 | Place thermocouple in calibrated incubator | Ensure proper thermal contact |
| 2 | Set incubator to known temperature | Use multiple setpoints (25°C, 48°C, 60°C) |
| 3 | Wait for temperature stabilization | Allow 15-30 min for equilibrium |
| 4 | Record thermocouple reading | Document setpoint vs. actual reading |
| 5 | Accept or adjust thermocouple | Tolerance: ±0.5°C |
| 6 | Repeat for additional setpoints | Minimum 3 points for calibration |

Figure 1: Incubator (left); Thermocouple for MLX90640 Thermal camera calibration

Table 2: Thermal Camera (MLX90640) Calibration Protocol

| Step | Procedure | Remarks |
|---|---|---|
| 1 | Place MLX90640 and calibrated thermocouple on same target | Ensure identical measurement location |
| 2 | Wait for temperature stabilization | Allow thermal equilibrium |
| 3 | Record simultaneous readings from both sensors | Document MLX90640 and thermocouple values |
| 4 | Repeat for multiple temperature points | Collect minimum 3 data pairs |
| 5 | Perform linear regression analysis | Calculate correlation coefficient |
| 6 | Derive calibration equation | $T_{calibrated} = a \cdot T_{camera} + b$ |
| 7 | Apply correction equation to future readings | Use derived coefficients for compensation |

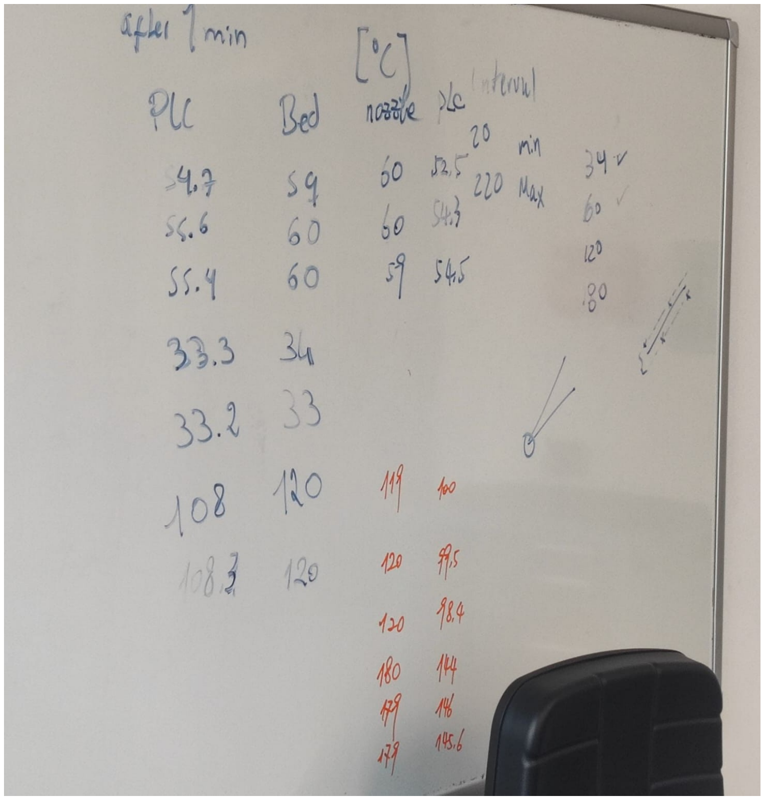


Figure 2: Thermocouple measurement points

### 3.3 Experiment 3: Camera Setup and Data Collection

This experiment implements a robust data acquisition system for continuous thermal monitoring during 3D printing operations.

### 3.4 Data Collection Summary

The following table summarizes the comprehensive temperature distribution data collected across different PLA printing parameters:

## 4 Data Preprocessing and Analysis

### 4.1 Thermal Data Preprocessing Pipeline

The collected thermal data undergoes systematic preprocessing to ensure data quality and reliability. The pipeline includes file validation, thermal image loading, data shape handling (2D/3D/4D to 3D conversion), and optional Y-axis flipping for proper orientation. Temperature filtering is applied (25-230°C range) to remove unrealistic values and sensor noise.

### 4.2 Critical Implementation Considerations

#### 4.2.1 Camera-to-Wall Distance Optimization

Optimal positioning of the MLX90640 camera relative to the printing wall is crucial for accurate thermal measurements. The distance must balance field-of-view coverage with spatial resolution while avoiding

Table 3: Camera Setup and PLA Temperature Distribution Data Collection

| Step | Procedure | Remarks |
|---|---|---|
| 1 | Connect MLX90640 to ESP32 via I2C | 24×32 thermal sensor array |
| 2 | Program ESP32 to read sensor data | Reads 768 temperature values (32-bit floats) |
| 3 | Connect ESP32 to Windows laptop via USB | Serial communication at 921600 baud |
| 4 | Run Python mlxdatalogger.py visualization script | Detects COM port automatically |
| 5 | Position camera to monitor PLA printing wall | Ensure clear view of build area |
| 6 | Start data collection during 3D printing | Record thermal distribution continuously |
| 7 | Monitor active printing session | Use recommended crop ranges for analysis |
| 8 | Process collected thermal frames | Apply inferno colormap for visualization |

Table 4: PLA Printing Temperature Distribution - Data Collection Summary

| File | Print Settings | Total Frames | Start Frame | End Frame | Crop Range |
|---|---|---|---|---|---|
| 30×1×50_Speed | High Speed | 10,224 | ∼800 | ∼8,500 | 800-8500 |
| 30×1×50_Structural | Structural (normal) | 7,617 | ∼400 | ∼7,200 | 400-7200 |
| 70×1×50_Speed | High Speed | 16,711 | ∼1,000 | ∼14,500 | 1000-14500 |
| 70×1×50_Structural | Structural (normal) | 15,402 | ∼1,200 | ∼13,000 | 1200-13000 |

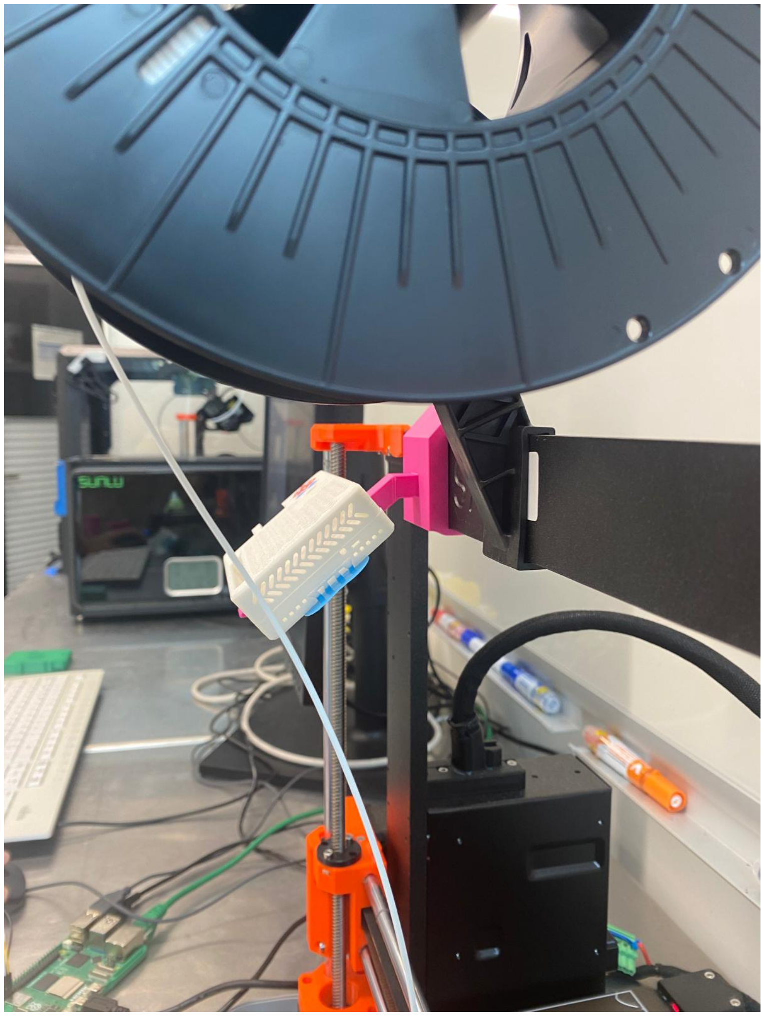

Figure 3: Incubator (left); Thermocouple for MLX90640 Thermal camera calibration

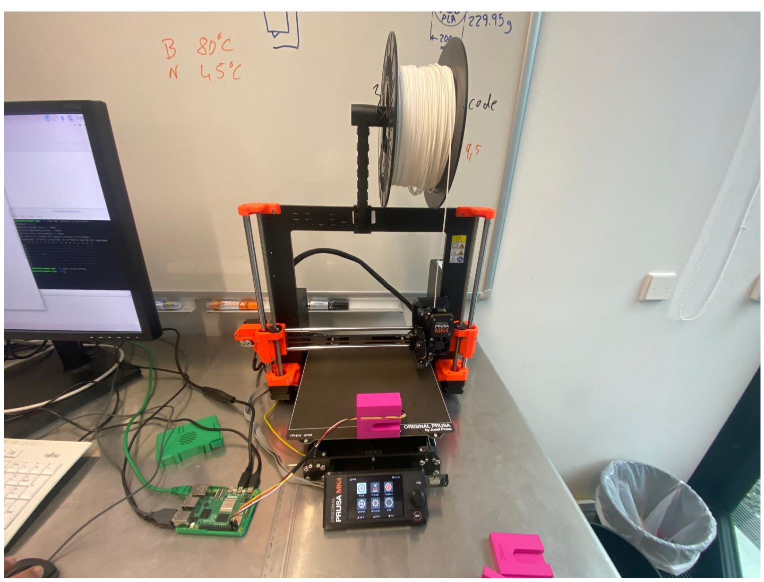


Figure 4: Incubator (left); Thermocouple for MLX90640 Thermal camera calibration

interference with the 3D printer's movement. A fixed mounting position approximately 6-7 cm from the build plate provides adequate thermal resolution for wall temperature analysis.

#### 4.2.2 MLX90640 Warm-up Period

The MLX90640 sensor requires approximately 180 seconds of warm-up time before producing stable thermal readings. During this initial period, the sensor exhibits thermal drift and may report erroneous temperature values. Data collection should only commence after this stabilization period to ensure measurement accuracy.

#### 4.2.3 Broken Pixel Compensation

Manufacturing defects in thermal sensor arrays can result in broken or dead pixels that consistently report incorrect temperature values. The preprocessing pipeline identifies and replaces temperatures above 180°C with NaN (Not a Number) values, effectively filtering out these faulty readings. This threshold-based approach prevents corrupted pixels from affecting the overall thermal analysis.

#### 4.2.4 Real-time Data Collection Challenges

Several practical difficulties arise during live data collection:

- **Frame rate consistency:** Maintaining stable data acquisition rates during extended printing sessions
- **Thermal interference:** Minimizing heat reflection from the camera housing and surrounding equipment
- **Print bed adhesion artifacts:** Distinguishing between actual wall temperatures and thermal signatures from the heated bed
- **Ambient temperature variations:** Accounting for laboratory temperature fluctuations that affect baseline measurements

### 4.3 Data Quality Assurance

The preprocessing pipeline incorporates frame limitation (maximum 1500 frames) to manage computational load while maintaining temporal resolution. Progress monitoring and statistical analysis provide real-time feedback on data quality. The final output includes thermal distribution plots, frame statistics, and animated GIF visualizations for comprehensive analysis of temperature evolution during the printing process.

### 4.4 File Processing Workflow

Each HDF5 file is processed through the following steps:

- File validation and structural integrity checks
- Data loading and dimensional standardization
- Temperature filtering (25-230°C range) with outlier removal
- Optional Y-axis orientation correction
- Generation of thermal distribution plots and statistical summaries
- Creation of animated visualizations for temporal analysis

## 5 Conclusion

This protocol provides a comprehensive framework for thermal analysis of 3D printed PLA walls through systematic calibration procedures and data collection methods. The integration of thermocouple calibration, thermal camera validation, and real-time monitoring enables accurate temperature distribution analysis during the additive manufacturing process.

# 6 Appendix

*See attached flowchart: Thermal Data Preprocessing Pipeline showing the complete data processing workflow from HDF5 file loading through final analysis and visualization.*