AQUA Manufacturing: Project Management Plan

PhD Research Supervisor: Prof. Lukas du Plessis

Masters Research Supervisor: Mr. Timothy Reddy

Project Timeline: June - December 2025

Executive Overview

This document outlines the strategic project management and development plan for the "Adaptive Quality Upscaling with Advanced Manufacturing" or locally called AQUA Manufacturing, a Masters-level research initiative at the University of Cape Town (UCT).

It details the integration of contributions from undergraduate students undertaking a 6-week engineering vacation work assignment (aligned with EEE3000X/MEC2000X practical training outcomes) and delineates the primary researcher's (Timothy Reddy) roadmap to Masters in Engineering project completion and thesis submission by December 2025.

The plan focuses on achieving core research objectives, developing a functional prototype, and exploring advanced concepts such as high-precision (target: 50-micron) micro-scanning accuracy and preliminary AI integration. The undergraduate projects are designed to provide students with practical engineering experience in system design, firmware configuration, software development, and experimental validation, culminating in formal technical reporting.

Undergraduate Student Vacation Project Summaries

(Duration: 6 Weeks, Full-Time Equivalent)

These projects are designed to meet the practical training requirements for undergraduate engineering students (e.g., EEE3000X, MEC2000X) by providing hands-on experience in a research and development environment. Emphasis is placed on engineering problem-solving, design, implementation, testing, and comprehensive documentation.

Project 1: Research & Development of Advanced Hybrid-Manufacturing Control Systems & In-Process Monitoring.

- **Student Allocation:** 3 Students (Maarij Alam, Saeed Solomon, Josh Smith)

- **ECSA Focus Areas:** Software Engineering, Control Systems, System Integration, Electrical System Design, Circuit Design & Prototyping, Embedded Systems Programming, Sensor/Actuator Interfacing, Machine Vision, Engineering Design, Problem Solving, Technical Documentation.

- **Benefit to AQUA Masters Project:** Delivers a functional core system encompassing tested motion control for all axes, integrated peripherals (including camera systems for live monitoring), a robust electrical architecture, and foundational software for peripheral control, initial slicing capabilities, and basic print error detection. This integrated approach aims to achieve basic printing, scanning, and monitored operation functionalities by the end of the vacation work period.

Project 2: Research & Development of Advanced Laser Triangulation 3D-Scanning Algorithms.

- **Student Allocation:** 1 Student (Azhar Randeree - with potential for FYP continuation)

- **ECSA Focus Areas:** Algorithm Development, Advanced Image Processing, Computational Efficiency, Error Analysis, Research Methodology, Technical Reporting.

- **Benefit to AQUA Masters Project:** Addresses the most computationally intensive and accuracy-critical aspects of the scanning system (Raspberry Pi Camera 3 with line lasers for macro/micro scanning). Provides foundational algorithms and methodologies essential for integration into the real-time feedback loop and the macro-scanning pipeline, directly supporting the project's high-precision goals. Forms a basis for extended research if pursued as a Final Year Project.

Detailed Undergraduate Student Vacation Project Descriptions

Project 1: Research & Development of Advanced Hybrid-Manufacturing Control Systems & In-Process Monitoring.

- **Students:** Maarij Alam (ALMMOH017), Saeed Solomon (SLMMOG032), Josh Smith (SMTJOS022), Mahir Khan (KHNMAH014).

- **Recommended Student Profile:** Mechatronics or Electrical & Computer Engineering (Interests: Firmware, Robotics, Motion Control, Electrical Systems, Software Architecture, UI/UX Design, Embedded Systems, Machine Vision).

Project Synopsis:

This comprehensive project integrates firmware development, electrical system design, peripheral control software, foundational slicer capabilities, and in-process print monitoring to bring the modified Creality Ender 3 V2 (AQUA system) to an initial operational state.

The team will:

1. Develop and document the complete Klipper firmware for all original and new axes (Bed Rotation 'Theta', Camera Z-axis 'Z_cam'), including robust homing and peripheral integration (sensors, lasers, lighting, camera triggers).
2. Finalize and implement the electrical architecture, including power distribution, sensor/actuator interfacing (including USB endoscope cameras and Raspberry Pi Camera 3), and necessary control circuitry.
3. Develop a Python module for low-level peripheral control and synchronized actions.
4. Investigate and implement initial slicer functionalities, enabling STL import and G-code generation for the AQUA system's Cartesian capabilities, and lay the groundwork for polar coordinate G-code generation.
5. Integrate USB endoscope cameras for live print monitoring and develop a proof-of-concept for basic, real-time print error detection using OpenCV.

Core Objectives:

- To implement and validate a stable, multi-MCU Klipper firmware configuration controlling all 6 axes (X, Y, Z_print, E, Theta, Z_cam) and associated homing sensors, with integrated control for essential peripherals.
- To finalize, implement, and verify the complete electrical system design, including all wiring, power distribution, and actuator control circuits for all sensors, actuators, and camera systems.
- To develop a robust, well-documented Python module (aqua_io.py) for low-level control of all non-motor peripherals and synchronized hardware triggering.
- To enable an existing open-source slicer (or a custom tool leveraging its components) to import STL files and generate functional Cartesian G-code for the modified printer.
- To research methods for polar G-code generation and implement a foundational capability to produce polar G-code for basic test geometries, compatible with Klipper's polar kinematics.
- To implement a system for live video feed acquisition from USB endoscope cameras and develop a proof-of-concept for basic, real-time print error detection using OpenCV.
- To achieve basic, integrated printing (with live monitoring) and scanning operations on the AQUA system.

Key Tasks & Methodologies:

1. **Multi-MCU Klipper Firmware Configuration & Peripheral Integration (Firmware/Motion - A):**
    - Establish and document printer.cfg for dual MCU operation (Ender 3 mainboard; RPi5+HAT).
    - Define and parameterize all axes (rotation_distance, kinematics, motor settings).
    - Implement and test sensor-based homing for all axes.
    - Develop Klipper macros for calibration, fundamental scanning/printing movements, and synchronized GPIO triggers for Pi Camera 3, lasers, and lighting.
    - Investigate and document Klipper's polar kinematics configuration for printing/scanning.

2. **Electrical System Design & Implementation (Electrical/Hardware - B):**
    - Finalize and verify comprehensive wiring diagrams for the entire system (power, motors, sensors, Raspberry Pi Camera 3, USB endoscope cameras, lasers, lighting).
    - Implement correct common grounding and ensure signal integrity.
    - Design, specify, prototype (if needed), and implement MOSFET-based driver circuits for lasers and LED lighting.
    - Oversee and verify all physical electrical connections, including USB camera connections to the Raspberry Pi 5, and manage power-up sequences.

3. **Python Peripheral Control Module & Synchronization (Software/Control - B):**
    - Develop the aqua_io.py Python module with a clean API for:
        - Reading limit switches and Hall effect sensors (with debouncing).
        - Controlling lasers and LED lighting (ON/OFF, PWM intensity) via MOSFET circuits.
        - Error handling and status feedback.
    - Research and implement methods for tightly synchronized hardware triggering (lasers, Pi Camera 3) with Klipper motion, coordinating with Klipper macros.

4. **Slicer Development & Integration (Slicer/Software - C):**
    - **Cartesian Slicing:**
        - Select a suitable open-source slicer (e.g., Cura, PrusaSlicer, OrcaSlicer).
        - Configure it to generate G-code compatible with the AQUA system's Cartesian axes (X, Y, Z_print, E) and new bed dimensions/setup.
        - Test STL import and G-code generation for standard 3D printing on the modified machine.
    - **Polar Slicing (Foundational):**
        - Research existing open-source Python tools or algorithms for converting Cartesian G-code to polar G-code, or for direct polar path generation from simple geometries.
        - Implement or adapt a tool/script to generate polar G-code (for Theta and a linear extrusion axis, or Theta and Z_cam for scanning paths) for basic test shapes (e.g., cylinders, discs).
        - Ensure the generated polar G-code is compatible with Klipper's configured polar kinematics.
    - **Slicer Extensibility Research (Conceptual):**
        - Briefly document findings on the chosen slicer's architecture regarding future modularity for multi-process manufacturing (3D Scanning, CNC, etc.), as a hand-off for future work.

5. **Live Print Monitoring & Basic Error Detection (Software/Vision - D):**
    - Integrate video stream acquisition from the two USB endoscope cameras on the Raspberry Pi 5.
    - Develop a basic Python application using OpenCV to display and manage these live feeds.
    - Research and implement proof-of-concept OpenCV algorithms for rudimentary real-time 3D printing error detection (e.g., detection of excessive "spaghetti," large-scale print detachment, or nozzle dragging).
    - Investigate methods for alerting the user or signaling Klipper/the main control application upon detection of a critical, predefined error type (e.g., logging, triggering a pause via Klipper's API).

6. **System Integration, Testing & Documentation (A AND B AND C AND D):**
    - Collaboratively integrate firmware, electrical systems, and all software modules (peripheral control, slicer outputs, monitoring).
    - Conduct iterative testing to achieve basic printing (Cartesian, initial polar tests) with live monitoring, and fundamental scanning operations.
    - Maintain detailed logs, version control (e.g., Git), and prepare a comprehensive consolidated technical report and presentation covering all aspects of the project.

Principal Deliverables (6 Weeks):

- A functional AQUA system capable of basic Cartesian printing with live monitoring, initial polar printing/motion tests, and fundamental scanning movements.
- A fully documented and validated Klipper printer.cfg for multi-MCU control and integrated peripherals.
- A comprehensive suite of tested Klipper G-code macros for system operations.
- Complete, verified, and professionally drawn electrical schematics and implemented wiring, including all power, camera, laser and lighting systems.
- Design documentation and (if prototyped) test results for actuator control circuitry.
- A robust, well-documented Python Peripheral Control module (aqua_io.py) with example usage.
- A configured open-source slicer capable of importing STLs and generating Cartesian G-code for the AQUA printer.
- A documented tool/script and demonstration of generating polar G-code for basic test geometries, compatible with Klipper.
- A proof-of-concept application for live print monitoring via endoscope cameras, with basic OpenCV-based error detection capabilities.
- A brief report on the selected slicer's potential for future multi-process modularity.
- A final consolidated technical report and presentation detailing the design, implementation, challenges, and results.

Project 2: Research & Development of Advanced Laser Triangulation 3D-Scanning Algorithms

- **Student:** Azhar Randeree (RNDAZH001)
- **Recommended Student Profile:** Final Year Mechatronics or Computer Engineering (Strong skills: Python/C++ for optimization, Advanced Image Processing, Algorithm Development, Applied Mathematics, interest in research).

Project Synopsis:

This project forms the foundational stage of a more extensive research endeavor into high-accuracy, in-situ 3D metrology for additive manufacturing. During the 6-week vacation period, the student will focus on developing, implementing, and benchmarking computationally efficient algorithms for processing laser scan data specifically from the Raspberry Pi Camera Module 3, targeting the 50-micron resolution goal.

Core Objectives:

- To implement, compare, and optimize various algorithms for high-precision (sub-pixel) laser line extraction from 2D images captured by the Raspberry Pi Camera Module 3.
- To develop and implement robust triangulation mathematics for converting 2D laser line image coordinates into 3D spatial points relative to the camera's reference frame.
- To conduct an initial performance analysis and optimization of the developed algorithms for efficient execution on the Raspberry Pi 5 platform.
- To research and define a preliminary high-precision calibration methodology for the micro-scanner configuration (Pi Camera 3 + potential microscopic lens + line laser).
- To identify and document primary sources of error impacting scanning accuracy and propose initial mitigation strategies.

Key Tasks & Methodologies:

1. **Literature Review & Algorithm Selection:**
   - Conduct a literature review on techniques for sub-pixel laser line detection, 3D laser triangulation, and point cloud processing for machine vision and metrology.
   - Select a set of promising algorithms for implementation and comparison.

2. **High-Precision Laser Line Extraction Algorithms:**
   - Implement selected algorithms in Python using OpenCV. Examples include Gaussian fitting, center of mass/intensity, Steger's method, or other relevant techniques.
   - Develop test metrics to evaluate accuracy, noise, and computational speed.

3. **3D Point Calculation & Initial Point Cloud Processing:**
   - Implement the mathematical framework for 3D triangulation based on known camera intrinsic parameters and calibrated laser plane geometry (initial calibration parameters may be assumed or roughly estimated for this phase, with full calibration being a later step).
   - Develop basic routines for generating a point cloud from the extracted 3D points and initial filtering techniques (e.g., statistical outlier removal).

4. **Computational Efficiency Analysis for Raspberry Pi 5:**
   - Profile the implemented algorithms to identify computational bottlenecks when running on the Raspberry Pi 5.
   - Investigate initial optimization strategies (e.g., algorithmic improvements, efficient OpenCV usage, potential for NEON SIMD if transitioning to C++).

5. **Micro-Scanner Calibration & Error Analysis Strategy (Preliminary for Pi Camera 3 setup):**
   - Research established and advanced calibration procedures for camera-laser scanning systems, including those involving microscopic lenses (if applicable to the Pi Camera 3 configuration).
   - Define a detailed, step-by-step preliminary calibration protocol suitable for achieving high accuracy with the Pi Camera 3 setup.
   - Conduct a theoretical analysis and literature review to identify and categorize potential sources of error (mechanical, optical, algorithmic, environmental) in this specific scanning setup. Propose initial thoughts on mitigation.

6. **Documentation and Reporting:** Maintain a detailed research log, version-controlled code, and prepare a formal technical report summarizing findings, methodologies, and results. This report will serve as a key input for any subsequent FYP proposal.

Principal Deliverables (6 Weeks):

- A library of implemented and benchmarked Python/OpenCV modules for high-precision laser line extraction and 3D point calculation, tailored for the Pi Camera 3 input.
- A technical report section detailing the implemented algorithms, their performance comparison, and computational efficiency analysis on the Raspberry Pi 5.
- A research document outlining a proposed high-precision calibration methodology for the Pi Camera 3 based micro-scanner.
- A preliminary error budget analysis identifying key error sources and potential mitigation strategies for the Pi Camera 3 scanning system.
- A final consolidated technical report and presentation suitable for ECSA training validation and as a foundation for a Final Year Project proposal.

Potential Final Year Project (FYP) Extension (Beyond 6 Weeks - for Azhar):

Should this project be continued as an FYP, the scope would expand to include:

- Advanced Algorithm Development: Exploration and implementation of more sophisticated image processing, machine learning (e.g., for noise reduction or feature enhancement), or adaptive algorithms.
- Full System Calibration: Meticulous implementation and validation of the high-precision calibration protocol for the entire micro-scanning system (Pi Camera 3), including characterization of lens distortions with microscopic optics if used.
- Rigorous Experimental Validation: Extensive testing with precision artifacts to quantify the achievable scanning accuracy and repeatability, aiming for the 50-micron target.
- Integration with Feedback Loop: Interfacing the validated scanning algorithms with the AQUA system's control software to provide data for potential closed-loop print parameter adjustments.
- Comprehensive Error Propagation Analysis: In-depth mathematical and experimental analysis of how various error sources contribute to the final measurement uncertainty.
- Thesis/Dissertation: A substantial research dissertation detailing the methodology, results, analysis, and contributions to the field.