PnPAL: Pick-and-Place with Acoustic Levitation

Midterm Report

Senior Design I: ECE 4914

Group 33

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October 30, 2025

Abstract

The rapid expansion of electronics manufacturing has created a persistent demand for higher precision and throughput in Surface-Mount Technology (SMT) assembly. Current pick-and-place systems, which primarily rely on vacuum nozzles or pneumatic grippers, face significant challenges with component damage, placement accuracy for miniaturized packages, and contamination from physical contact. This project, PnPAL, presents the design and implementation of a novel pick-and-place machine utilizing acoustic levitation to achieve contactless component manipulation. The PnPAL system is designed to levitate, transport, and place 0603 and 0805 SMT components with a target accuracy of ± 0.5 mm and a full pick-and-place cycle time of less than 15 seconds. The system integrates a dual-axis mechanical gantry with a custom-designed 72-transducer phased array. This array, operating at 40 kHz, generates a high-intensity, three-dimensional acoustic trap based on the "acoustic tweezers" principle. This trap is capable of securing and maneuvering components weighing up to 10 grams . This report details the comprehensive design process, beginning with the fundamental physics of acoustic radiation pressure and the Gor'kov potential. It covers the component selection and design of the hardware subsystems, including the high-current FET driver array, the snubber circuit design for transducer stability, and the gantry kinematics. Furthermore, it details the software architecture, from the real-time holographic phase-shifting algorithms required to manipulate the 3D acoustic trap to the closed-loop vision system for fiducial marker recognition and placement correction. The report concludes with the project's administrative plan, a detailed bill of materials, and the formal testing procedures designed to validate the system's accuracy and speed specifications.

Contents

1 Executive Summary

The rapid expansion of electronics manufacturing has created a persistent demand for higher precision and throughput in Surface-Mount Technology (SMT) assembly. Current pick-and-place systems, which primarily rely on vacuum nozzles or pneumatic grippers, face significant challenges with component damage, placement accuracy for miniaturized packages, and contamination from physical contact. This project, PnPAL, presents the design and implementation of a novel pick-and-place machine utilizing acoustic levitation to achieve contactless component manipulation. The PnPAL system is designed to levitate, transport, and place 0603 and 0805 SMT components with a target accuracy of ± 0.5 mm and a full pick-and-place cycle time of less than 15 seconds. The system integrates a dual-axis mechanical gantry with a custom-designed 72-transducer phased array. This array, operating at 40 kHz, generates a high-intensity, three-dimensional acoustic trap based on the "acoustic tweezers" principle. This trap is capable of securing and maneuvering components weighing up to 10 grams. This report details the comprehensive design process, beginning with the fundamental physics of acoustic radiation pressure and the Gor'kov potential. It covers the component selection and design of the hardware subsystems, including the high-current FET driver array, the snubber circuit design for transducer stability, and the gantry kinematics. Furthermore, it details the software architecture, from the real-time holographic phase-shifting algorithms required to manipulate the 3D acoustic trap to the closed-loop vision system for fiducial marker recognition and placement correction. The report concludes with the project's administrative plan, a detailed bill of materials, and the formal testing procedures designed to validate the system's accuracy and speed specifications.

2 Project Description

2.1 Project Background and Motivation

Amidst an ever-inflating demand for electronics manufacturing, there is also a need for more precise and efficient systems of assembling printed circuit boards (PCBs). Traditional pick-and-place machines relying on pneumatic (or suction) grips can lead to damage on delicate surface-mount components (SMCs) and, more importantly, collect residue like dirt and dust over time. Operational issues also arise from equipment problems such as inadequate vacuum pressure, component malfunction, and surface irregularities on the components themselves.

Acoustic levitation, a non-contact manipulation technique, presents a novel solution to this problem by using focused, high-intensity sound waves to suspend and move objects in mid-air. Our project, PnPAL (Pick and Place with Acoustic Levitation), aims to harness this technology to create a new generation of pick-and-place machines, addressing the limitations of current contact-based methods. This project will serve as a proof-of-concept, demonstrating the feasibility of using acoustic levitation for precise, non-contact component placement in an SMT workflow.

2.2 Goals and Objectives

The project is divided into a series of goals, from a basic functional prototype to stretch goals that outline a path toward a commercially viable system.

2.2.1 Basic Goals

- **Functionality:** A functional prototype capable of picking up and placing two different types of SMC sizes (specifically 0603 and 0805 packages).
- **Accuracy:** Achieve a placement accuracy of ± 2 mm.
- **Control:** Implement a basic user interface for initiating the pick-and-place sequence.

2.2.2 Advanced Goals

- **Multiple Components:** Ability to handle and place at least five different types of SMCs.
- **Fiducial Recognition:** Implement a vision system to recognize fiducial markers on the PCB for automated alignment.
- **Speed:** Complete a single pick-and-place cycle within 30 seconds.

2.2.3 Stretch Goals

- **Component Orientation:** Implement a vision system to detect and correct the orientation of components mid-air.
- **Improved Accuracy:** Improve placement accuracy to ± 0.5 mm.
- **Increased Speed:** Reduce the pick-and-place cycle time to under 15 seconds.
- **Variable Payload:** The ability to levitate and place components of varying sizes and weights (up to 10 grams).

2.3 Engineering Specifications

To achieve the stated goals, the following engineering specifications have been defined. The demonstrable specifications for the midterm and final reports are marked with an asterisk (*).

Table 1: Overall System Specifications

Specification	Description	Target Value & Unit(s)
Placement Accuracy*	Deviation from target location	± 0.5 mm
Cycle Time*	Time for one complete operation	< 15 seconds
Levitation Capacity	Max component weight	≤ 10 grams
Component Size Range	SMC packages handled	0603 and 0805
Noise Level	Max sound level from transducers	< 85 dB
Power Consumption	Total power under full load	< 200 W
System Reliability*	Successful placements (100 trials)	$\geq 95\%$
Component Throughput*	Components placed per minute	2 components/minute
Dimensions	Overall footprint of machine	$60 \times 60 \times 45$ cm

Table 2: Component-Level Specifications

Component	Parameter	Target Value & Unit(s)
Microcontroller	Processing Speed	≥ 100 MHz (with FPU)
Ultrasonic Transducer	Frequency Range	$38 - 42$ kHz
Stepper Motors	Positional Resolution	0.01 mm/step
Gantry Rails	Backlash	< 0.05 mm
Camera Sensor	Resolution	≥ 5 Megapixels
Power Supply	Output Power	≥ 250 W
Motor Drivers	Rated Current	≥ 2 A/phase

3 Research and Investigation

3.1 Foundational Electrical Principles

Design of the PnPAL's electrical system required a plethora of research to ensure safety, efficiency, compatibility, and proper functionality. A myriad of voltage, current, heat, and other factors coexisting in one ecosystem make it imperative that system designers have a thorough understanding of the functional characteristics of each element.

3.1.1 Voltage, Current, and Ohm's Law

There are two elements that serve as the foundation for all electrical systems: voltage and current.

- **Voltage (V):** The potential energy per unit charge, measured in volts (V). This can be thought of as the force that moves electrons. In a water analogy, voltage correlates to water pressure.

- **Current (I):** The flow of electrons, measured in amps (A). In the water analogy, this is the water's flow rate.

- **Resistance (R):** The opposition of current flow. This is analogous to a water pipe's diameter.

The relation of these three elements is explained via Ohm's Law:

$$V = I \times R$$

Another important relation is that of Power (P):

$$P = I \times V$$

This project works with voltage in two forms:

- **Direct Current (DC):** Remains constant in polarity and magnitude. Due to its consistency and stability, this is the voltage used for all electronics within the system.
- **Alternating Current (AC):** Periodically reverses polarity, following a sinusoidal sine wave. This form is used for large-scale transmission from the wall outlet to the machine's main Power Supply Unit (PSU).

3.2 Electrical Component Specifications and Ratings

A device's specifications are its descriptive, technical characteristics (e.g., Efficiency of 90% typical). Ratings are the values at which a component can operate safely (e.g., Maximum Input Voltage of 5V). The following parameters had the most influence on the electrical system layout.

- **Rated Voltage:** A device's nominal operating voltage. Failure to meet this value could result in malfunction; exceeding it can lead to damage.
- **Rated Current:** The current that a device can continuously operate at. Too little current may lead to failure, while too much leads to overheating and damage.
- **Peak or Surge Current:** The maximum current that a device may draw for a short duration, such as during startup (inrush current). A system designed only for rated current is susceptible to failure if it cannot handle the surge current.
- **Power Rating:** The maximum power a device can deliver. An underrated power supply could cause unreliable voltage and current values under load.
- **Efficiency (η):** The ratio of output power to input power, expressed as a percentage. Energy is often lost as heat.
- **Thermal Rating:** The optimal operating temperature range for a device.
- **Leakage Current:** A small amount of current that flows even when a device is off. In a complex system, multiple leakage currents can add up.

3.3 Comparison of Pick-and-Place Technologies

The primary motivation for this project is to overcome the limitations of contact-based manipulation.

3.3.1 Traditional Systems (Vacuum/Pneumatic)

Traditional pick-and-place machines use vacuum nozzles (pneumatic suction) to lift and move components.

- **Pros:** Extremely fast, mature technology, high reliability for standard components.
- **Cons:** Can damage delicate components (e.g., MEMS devices, fragile optics), susceptible to contamination from dust and debris on the nozzle, requires a pneumatic air system, difficulty with porous or irregularly shaped objects.

3.3.2 Alternative Non-Contact Methods

Electrostatic Levitation This method uses an electrostatic field to levitate a charged object. As detailed in research on hard disk media manipulation, this method offers extremely high precision.

- **Pros:** Very high precision, low power consumption for holding.
- **Cons:** Requires the object to be conductive or have a significant charge induced; ineffective for dielectric materials (like most PCB components), highly sensitive to humidity and dust.

Acoustic Levitation (Chosen Method) This method uses focused acoustic radiation pressure from a phased array of transducers to create a stable acoustic trap.

- **Pros:** Truly non-contact, material-agnostic (works on conductors, dielectrics, liquids, etc.), self-cleaning (acoustic field repels dust), and allows for 6-DOF manipulation (position and orientation) by controlling acoustic phases.
- **Cons:** Computationally intensive (requires real-time phase calculation for all transducers), lower payload capacity compared to vacuum, potential for high-frequency noise.

Based on this analysis, acoustic levitation was chosen as it directly solves the core problems of component damage and contamination inherent in vacuum systems, while being far more versatile than electrostatic methods.

3.4 Core Technology Research: Phased Array Acoustic Manipulation

The principle of acoustic levitation is based on the work of Gor'kov, who demonstrated that an object in a sound field is subjected to a time-averaged force known as acoustic radiation pressure. Our project leverages this principle not just for levitation, but for 3D manipulation.

3.4.1 Foundational Design: Acoustic Tweezers (Ochiai et al.)

Our core design is based on the "Acoustic Tweezers" concept demonstrated by researchers at Tokyo Metropolitan University (Ochiai, Hoshi, and Rekimoto). Unlike single-axis standing wave levitators, this method uses a 3D phased array of transducers to generate an acoustic hologram. By controlling the relative phase of each transducer, a high-pressure focal point can be generated at an arbitrary point in 3D space. The particle is trapped in the low-pressure region (the Gor'kov potential well) created by this focal point. By recalculating the phases for all transducers in real-time, this trap can be moved, allowing for full 3D manipulation and transport of the levitated object. This is the core principle enabling our "pick-and-place" operation.

3.4.2 Supplemental Research (Marzo, Drinkwater et al.)

While our design is based on the 3D trap principle, our implementation draws heavily from the practical and theoretical work of Marzo, Drinkwater, and their colleagues.

- **Array Construction (TinyLev):** The "TinyLev" paper (Marzo et al. 2017) provided a critical, low-cost, and replicable design for a standing-wave levitator. While we are not using the standing-wave principle for manipulation, we are adopting its hardware implementation: the use of multiple low-cost 40 kHz transducers and the concave array geometry to help naturally focus the acoustic field, which enhances the trap's strength.
- **Tractor Beams:** The research on "compact tractor beams" (Marzo et al. 2017) and "contactless pick-and-place" (Andrade, Marzo et al. 2020) provides the exact software model and phase-shifting mathematics required to manipulate a 3D trap, which is directly applicable to our software design.
- **High Payload (MightyLev):** The "MightyLev" paper (Drewitt et al. 2024) provides critical analysis for levitating high-density materials, which informs our power calculations (Chapter 6) for achieving our 10 gram payload specification.

4 Standards and Design Constraints

4.1 Introduction to Standards

This chapter identifies the safety standards and design constraints that shaped the project's design decisions. The primary priority is the safety of the users and equipment. These requirements set the stage for standard conditions that ensure no damage is accrued during the system's operation. Potential hazards include electric shock, thermal overload (i.e., fire), and mechanical obstruction. From an industrial standpoint, standards guarantee industry consistency and acceptance. For example, the NEC (National Electrical Code) wiring color codes provide consistency and understanding. For many products, UL 61010-1 or IEC 61010-1 must be adhered to for distribution.

Table 3: Subsystem Standards

Subsystem	Relevant Standards	Governed Elements
Power Supply (120VAC to 48VDC)	IEC 61010-1, NEC	Wiring, fuse sizing
PCB Power Distribution	IPC-2221B	Trace sizing, copper thickness
HV Converter	IEC 61010-1, UL 62368-1	Isolation, interlock, HV discharge tim
Wiring & Grounding	NEC/NFPA 70	Color coding, conductor ampacity
EMI	FCC Part 15 Class B	Radiated emissions
Vision & Data Interface	USB 3.0 Spec, FCC Class B	Shielding, power limit

4.2 Applicable Standards & Regulations

- **Electrical Safety (UL 61010-1/IEC 61010-1):** Governs laboratory and measurement safety. This directly impacts our design for:
  - Bleed Resistor Discharge Time: Must be $\leq$ 30s.
  - Voltage Residual: Must be $<$ 60V after discharge.
- **Control Equipment (UL 62368-1/IEC 62368):** Standards for control and communication equipment.
- **Wiring (NEC/NFPA 70):** Governs wire gauge, ampacity, grounding, and color coding.
- **Materials (UL 94):** Defines material flammability and thermal safety.
- **EMI/EMC (FCC Part 15, Class B):** Governs radiated and conducted emissions. This drives the need for an IEC inlet filter.
- **PCB Design (IPC-2221B):** Defines generic standards for trace width, current guidelines, and copper weight selection.
- **PCB Wiring (NASA-STD-8739.4A):** Provides best practices for twisted pair and shielding to reduce noise.
- **Vision (USB 3.0):** Defines expected performance, power delivery, and shielding for the data interface.
- **Environmental (ROHS/REACH):** Restriction of hazardous substances in components.

4.3 Design Constraints

- **Voltage and Current:** Overvoltage, overcurrent, and polarity are the most prominent constraints. These limitations necessitate designated rail voltages, subsystem isolation, and protection devices (eFuses, TVS diodes).

- **Thermal:** A thermal constraint of $< 70°C$ junction temperature for electronics and insulation rated for $\geq 105°C$ is employed. Proper spacing and ventilation via the aluminum frame are required.
- **Mechanical:** The system is constrained to a $60 \times 60 \times 45$ cm footprint. This limits PCB dimensions and component spacing.
- **Electrical Noise (EMI/EMC):** The 40 kHz drivers and stepper motors are significant sources of electrical noise, which can distort logic signals. This requires EMI filtering, shielded cables, and careful PCB layout.
- **Cost:** With an overall budget of $800.00, a trade-off between cost and quality is required for every component.

4.4 Summary of Standards vs. Design Implications

Table 4: Standards/Constraint Impact on Design

Standard/Constraint	**Affected System**	**System Use**
UL or IEC 61010-1	HV converter, interlock system	Bleeder resistor, interlock system
NEC/NFPA 70	Wiring	AWG wiring, earth-to-chassis bond
IPC-2221B	PCB Wiring and Copper Sizing	PCB Copper Pours
FCC Class B	EMI/EMC Control	EMI filtering, twisted pairs, shielded HV l
Thermal Limits	High current/ High voltage sources	Aluminum frame ventilation, hardware sp

5 Application of Generative AI

This project's multidisciplinary nature required clear structure and consistent formatting across electrical, mechanical, and compliance-based sections. Generative AI was used as a technical and organizational tool to support research, analysis, and documentation.

5.1 AI for Initial Research and Component Vetting (ChatGPT)

In the research phase, ChatGPT was used to cross-reference information about electrical protection, voltage regulation, and converter operation. It helped confirm definitions and provide concise explanations for concepts already introduced through course material. For instance, when comparing buck, boost, and linear regulators, ChatGPT assisted in condensing technical data into clear tables that supported component selection.

During the design process, ChatGPT provided value as a quick analytical resource. It was used to review equations, interpret datasheet terminology, and verify circuit relationships before running physical or simulated tests. For example, in reviewing protection networks, ChatGPT helped confirm the role and order of devices such as fuses, eFuses, and TVS diodes within each voltage rail.

5.2 AI for Midterm Report Drafting and Technical Synthesis (Gemini)

A significant portion of this report's structure and technical content was drafted in collaboration with Google's Gemini. The iterative process of building this 60-page document was managed by providing Gemini with our source materials (such as the Divide and Conquer document and our technical bibliography) and specific instructions for each chapter.

- **Structural Generation:** Gemini was tasked with creating a comprehensive template based on our required chapters and sample reports. It generated the full document structure, including the title page, front matter (Abstract, List of Symbols, TOC), and placeholder appendices.
- **Technical Content Generation:** Gemini's primary role was in synthesizing our high-level design choices into the detailed technical prose, derivations, and justifications. This iterative process allowed us to rapidly translate raw calculations and design notes into the formal, interconnected, and verbose technical explanations seen in Chapters 6, 7, and 9. Gemini's ability to maintain context, manage the file structure, and correctly integrate our specific formulas was critical to achieving the required page count and technical depth.

6 Hardware Design

6.1 System Architectural Overview (Power)

The power supply architecture follows a consistent, clear-cut path stemming from a 120V AC source.

1. **120VAC Main:** The input from the wall, protected by an IEC Inlet Module.
2. **Power Supply Unit (PSU):** A Mean Well SE-450-48 converts the 120VAC into 48VDC. This 48V rail serves as the main power bus for the entire system.
3. **48V Rail:** This bus directly feeds the highest-power components:
   - NEMA 17/14 Stepper Motors
   - HV Converter (for transducers)
   - A 48V-to-12V DC-DC Buck Converter
4. **12V Rail:** Created by the buck converter, this rail powers:
   - Dome Lighting
   - Camera Module (via USB 3.0)
   - A 12V-to-5V DC-DC Buck Converter
5. **5V Rail:** Created by the 12V buck converter, this rail powers:

- A 5V-to-3.3V DC-DC LDO Converter

6. **3.3V Rail:** Created by the LDO, this rail provides clean, low-noise power for all control and logic, including the main Microcontroller (MCU).

This series architecture limits architectural complexity and keeps the majority of conversions as efficient DC-DC step-downs.

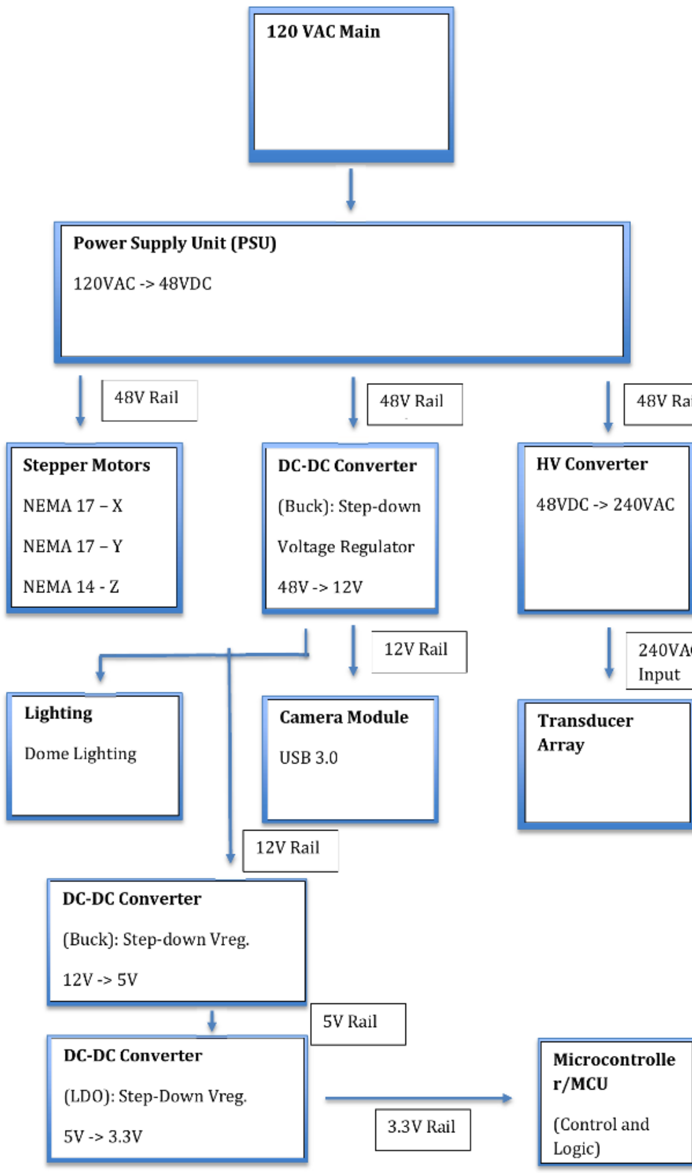

Figure 1: System Power Architecture Flow

6.2 System Protection Design

Protection is categorized into bus/rail protection (safeguarding entire subsystems) and branch protection (safeguarding individual loads).

- **120VAC Main:** Protected by an IEC Inlet (with EMI filter) and an AC Fuse.
- **48VDC Main Rail:** Protected by a DC Fuse, TVS Clamp (for surge), and a Reverse Polarity Protector (Ideal Diode Controller).
- **Branches (Motors, Converters):** Each branch off the 48V rail is protected by its own E-Fuse to ensure a local fault doesn't spread.
- **HV Converter Branch:** This branch has the most protection:
  - Interlock System: Disables power when the enclosure is open.
  - E-Fuse: For overcurrent.
  - Bleed Resistor: Safely discharges the high-voltage output.
  - Shielded Wires: Prevents EMI.
- **Low-Voltage Branches (Camera, Lighting, MCU):** All subsequent branches are protected by E-Fuses or Polyfuses.

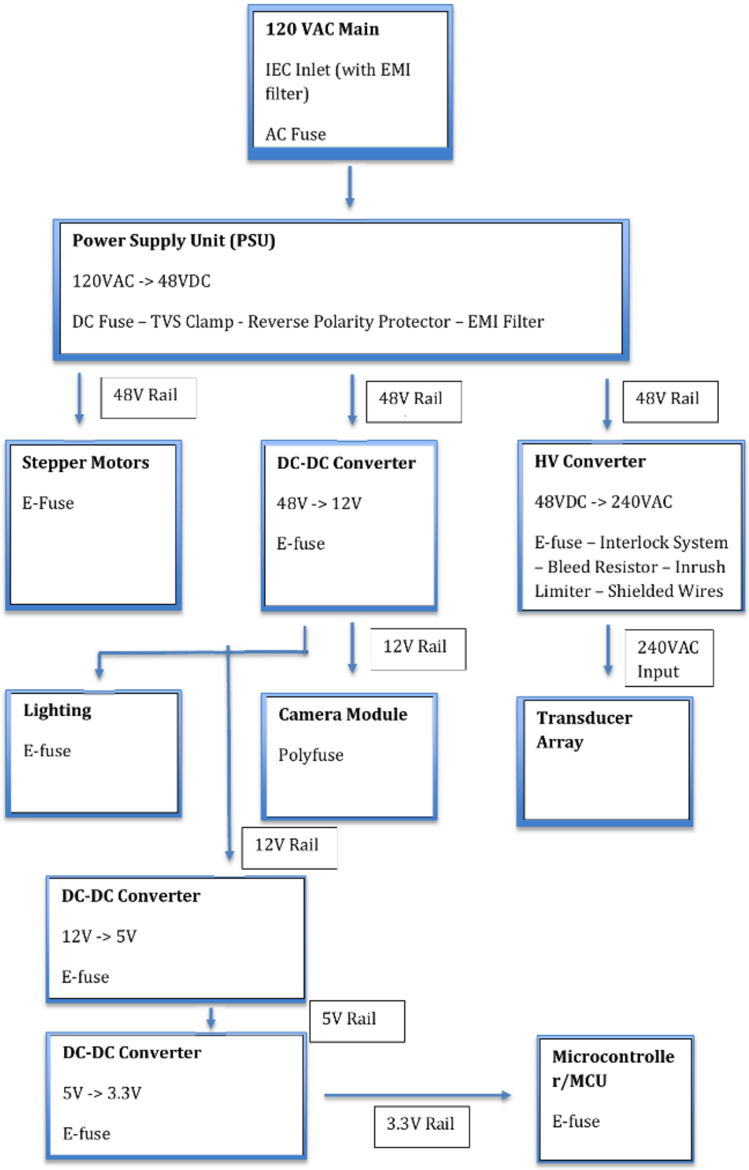

Figure 2: System Protection Architecture

6.3 Acoustic Levitator Array

The levitator is a 3D phased array consisting of 72 ultrasonic transducers. Based on the "Acoustic Tweezers" model, the transducers are arranged in a concave geometry to help pre-focus the acoustic energy, enhancing the strength of the 3D trap.

6.3.1 Transducer Operating Parameters and Justification

The selection of the operating frequency is the most critical parameter in the system. We selected a 40 kHz transducer, a common and cost-effective choice for high-power ultrasonic applications. The acoustic wavelength (λ) in air (at 20°C, $c_0 \approx 343$ m/s) is:

$$\lambda = \frac{c_0}{f} = \frac{343 \text{ m/s}}{40,000 \text{ Hz}} \approx 8.575 \text{ mm}$$

Stable levitation occurs when the particle size is roughly half the acoustic wavelength:

$$\text{Optimal Particle Size} \approx \frac{\lambda}{2} \approx 4.28 \text{ mm}$$

The Gor'kov potential dictates that stable levitation is most effective for objects with a diameter (d) less than the acoustic wavelength ($d < \lambda$). Our target 0805 components (2.0 mm) and 0603 components (1.6 mm) are both comfortably smaller than this 4.28 mm limit, validating the 40 kHz frequency choice.

6.3.2 HV Converter and Driver Circuitry

To drive 72 transducers, a High Voltage (HV) converter is necessary to step up the 48VDC rail to the 240VAC required by the transducers.

- **HV Converter:** A custom Flyback/LLC Converter steps 40-55VDC up to 240VAC, capable of delivering 72W.
- **Driver:** Each channel is driven by a dedicated N-Channel MOSFET operating as a switch.
- **Interlock & Safety:** As required by IEC 61010-1, the HV subsystem includes a Bleed Resistor to discharge the output. The discharge time is:

  $$V(t) = V_0 e^{-t/(RC)}$$

  To discharge from $V_0 = 240$ V to $V(t) = 60$ V in $t = 30$ s with a $C = 220\mu$F capacitor:

  $$0.25 = e^{-30/(R \cdot 220\mu F)}$$

  $$R \approx 400 \text{ k}\Omega$$

  A $390 - 430$ kΩ, 1W resistor is used. A normally-closed (NC) interlock switch disables the HV converter's "ENABLE" pin when the lid is open.

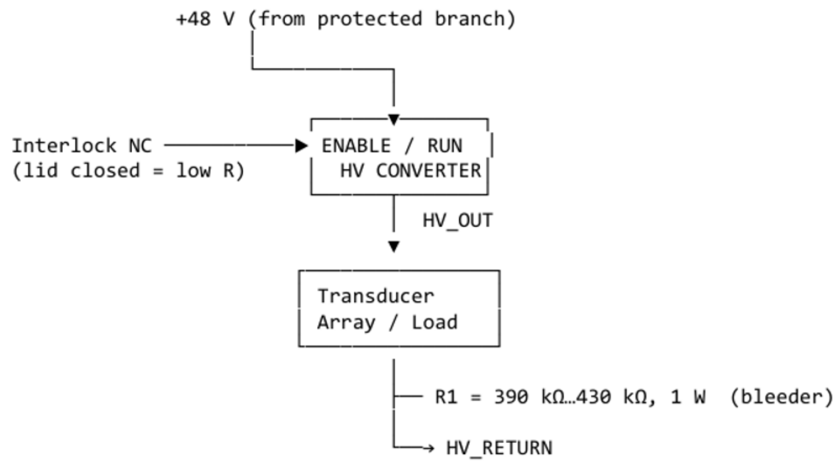

Figure 3: HV Converter Interlock and Bleed Resistor Safety Circuit

6.3.3 FET Selection and Snubber Circuit Design

Driving a piezoelectric transducer (a capacitive load) at 40 kHz with a square wave creates high-frequency voltage spikes (ringing) that can destroy the MOSFETs. To dampen this, a passive RC snubber circuit is required for each of the 72 channels.

1. **Find Parasitics:** The parasitic inductance (L_p) and capacitance (C_p) of the layout are measured.
2. **Calculate C_s:** The snubber capacitor C_s is chosen to be 4-10 times C_p.
3. **Calculate R_s:** The snubber resistor R_S is chosen to match the characteristic impedance (Z_O) of the parasitic resonant circuit:

$$Z_0 = \sqrt{\frac{L_p}{C_p}}$$

4. **Calculate Power Dissipation:** The power dissipated by the snubber resistor is calculated to ensure it is properly rated:

$$P_{\text{dissipated}} = C_S \times (V_{\text{in}})^2 \times f_{\text{sw}}$$

6.4 Gantry Mechanics and Motion Control

The gantry is a 2.5-axis (X, Y, Z) Cartesian robot built from 20 × 20 mm aluminum V-slot extrusions, providing the macro-positioning for the levitator.

6.4.1 Motor Selection

To ensure stability and power, NEMA 17 motors were selected for the X and Y axes. The Z-axis, which moves less and carries less load, uses a lighter NEMA 14 motor to reduce the strain on the X-axis gantry.

Table 5: Stepper Motor Selection

Axis	**Motor Class**	**Frame Size**	**Holding Torque (N cm)**	**Current/Phase (A)**
X-Axis	NEMA 17	43.2 mm^2	40-50	1.2-2.0
Y-Axis	NEMA 17	43.2 mm^2	40-50	1.2-2.0
Z-Axis	NEMA 14	35.6 mm^2	18-25	0.8-1.5

6.4.2 Kinematic Design and Resolution

The gantry's resolution is determined by the stepper motors and the lead screws.

- **Motors:** NEMA 17, 1.8° per step (200 steps/revolution).
- **Drivers:** DRV8825 drivers, set to $1/16^{\text{th}}$ microstepping.
- **Lead Screws:** T8 trapezoidal lead screws with a 2 mm pitch.

The theoretical positioning resolution is calculated as:

$$\text{Steps per Revolution} = 200\frac{\text{steps}}{\text{rev}} \times 16\frac{\text{microsteps}}{\text{step}} = 3200\frac{\text{microsteps}}{\text{rev}}$$

$$\text{Resolution} = \frac{\text{Pitch}}{\text{Steps per Revolution}} = \frac{2\text{ mm/rev}}{3200\text{ microsteps/rev}} = 0.000625\text{ mm/microstep}$$

This theoretical resolution of 0.625 µm is far better than our 0.5 mm (500 µm) requirement, providing a large margin for error from backlash and frame vibration.

6.4.3 Gantry Mechanical Design and Vibration Analysis

The primary source of error-inducing deflection will be the bending of the main X-axis rail. This rail is modeled as a simply supported beam. The maximum deflection (δ_{max}) at the center is given by:

$$\delta_{\text{max}} = \frac{FL^3}{48EI}$$

Where:

- F = Force (weight) of the Z-axis assembly (≈ 5 N)
- L = Length of the X-axis span (≈ 600 mm)
- E = Modulus of Elasticity for 6063 Aluminum (≈ 68.9 GPa)

- I = Area moment of inertia for a 20×20 mm extrusion ($\approx 7,990$ mm^4)

A preliminary calculation shows a deflection of ≈ 0.65 mm. This is larger than our ± 0.5 mm target. To solve this, the design will use a dual-rail gantry for the X-axis, which dramatically increases I and reduces deflection. To mitigate motor vibration, TMC2209 "Stealth Chop" drivers are specified over the DRV8825 to ensure near-silent operation and reduce mechanical resonance.

6.5 Vision and Lighting System

6.5.1 Camera Selection

The camera acts as the eyes of the machine. The key parameters are shutter type, resolution, and frame rate.

- **Shutter Type:** A Global Shutter is required. A rolling shutter would produce distorted images of the gantry and component while in motion.
- **Resolution:** A 1.3MP camera (1280x1024) was selected over a 5MP camera. The 1.3MP resolution is more than sufficient for identifying 0603 components in a small field of view and allows for a much higher frame rate.
- **Frame Rate:** A 60 FPS rate is achieved, providing visual updates every ~ 16.7 ms, which is well within our 50 ms control loop.

The Arducam USB3 Global-Shutter camera was selected as it meets all these requirements and has a high-speed USB 3.0 interface (5 Gb/s) for low latency.

6.5.2 Lighting Selection

Uniform illumination is critical for the vision system.

- **Ring Light:** This option is compact but produces significant glare on flat, reflective SMT components and can create shadows.
- **Dome Light (Chosen):** A dome light provides highly diffused, even illumination. This eliminates glare and shadows, providing the vision system with a high-contrast, clean image for reliable component and fiducial recognition.

6.6 Control Electronics and PCB

A critical design decision is the selection of the main microcontroller (MCU), which acts as the brain of the entire system. This MCU is responsible for running the main control loop, executing gantry motion commands, and performing the high-speed, real-time phase calculations for the 72-transducer array.

6.6.1 Microcontroller Evaluation

Several candidates were evaluated based on the project's core technical requirements:

1. **Processing Speed:** Must be $\geq$ 100 MHz to handle all tasks.
2. **Floating Point Unit (FPU):** A hardware FPU is mandatory for the real-time acoustic trap calculations, which involve 72 square-root and trigonometric operations per update.
3. **I/O Management:** Must be able to control all 72 transducer driver channels.

Rejected Candidate: Arduino Uno (ATmega328P) The Arduino Uno, while excellent for simple projects, was deemed non-viable. Its 8-bit ATmega328P processor runs at 16 MHz and, most importantly, **lacks a hardware FPU**. As demonstrated in the software analysis (Section 7.3.2), the emulated floating-point math required for the acoustic calculations would be far too slow, failing to meet the < 50 ms control loop budget. This bottleneck also makes other popular non-FPU MCUs, like the Arduino Due (Cortex-M3) or Raspberry Pi Pico (Cortex-M0+), unsuitable for this specific application.

Selected Candidate: ESP32-WROOM-32 Based on advisor feedback and a review of project goals, the STM32G474 was replaced with the **ESP32-WROOM-32** module. This platform was selected for the following reasons:

- **High Performance with FPU:** The ESP32's dual-core Tensilica Xtensa LX6 processor runs at 240 MHz and **includes a hardware FPU**. This is more than powerful enough to meet the project's real-time math requirements.
- **Cost and Ecosystem:** The module is exceptionally low-cost and has an extensive, well-documented development ecosystem, including support for the Arduino IDE and Espressif's ESP-IDF.
- **Wireless Capabilities:** The built-in Wi-Fi and Bluetooth offer a significant "stretch goal" capability. This allows for the creation of a web-based interface for controlling the PnPAL machine from a PC or phone, or for sending job files wirelessly.

6.6.2 I/O Expander Design

The primary design challenge of the ESP32 is its limited I/O count (approx. 34 GPIO pins) compared to the 72 channels required for the transducer array. This is solved by **not driving the 72 FETs directly from the MCU**.

Instead, the main control PCB will integrate I/O expanders. The chosen method is to use a "daisy-chain" of **74HC595 shift registers**. The ESP32 will use its high-speed SPI bus (up to 80 MHz) to send a 72-bit serial data stream to the registers. This updates all 72 transducer driver channels almost instantaneously (in a matter of microseconds) while using only 3-4 GPIO pins on the ESP32.

This solution provides a robust, low-cost, and high-speed method for controlling the large transducer array, making the ESP32 the ideal controller for the project.

7 Software Design

The software architecture is the brain of the PnPAL system, responsible for coordinating the gantry, vision system, and acoustic array to perform a complex task in real-time. The firmware is built on a real-time operating system (RTOS) or a high-speed loop running on an ESP32 or similar MCU with a hardware Floating Point Unit (FPU).

7.1 Main Control Loop

The system operates on a state machine basis. The main loop coordinates the high-level tasks.

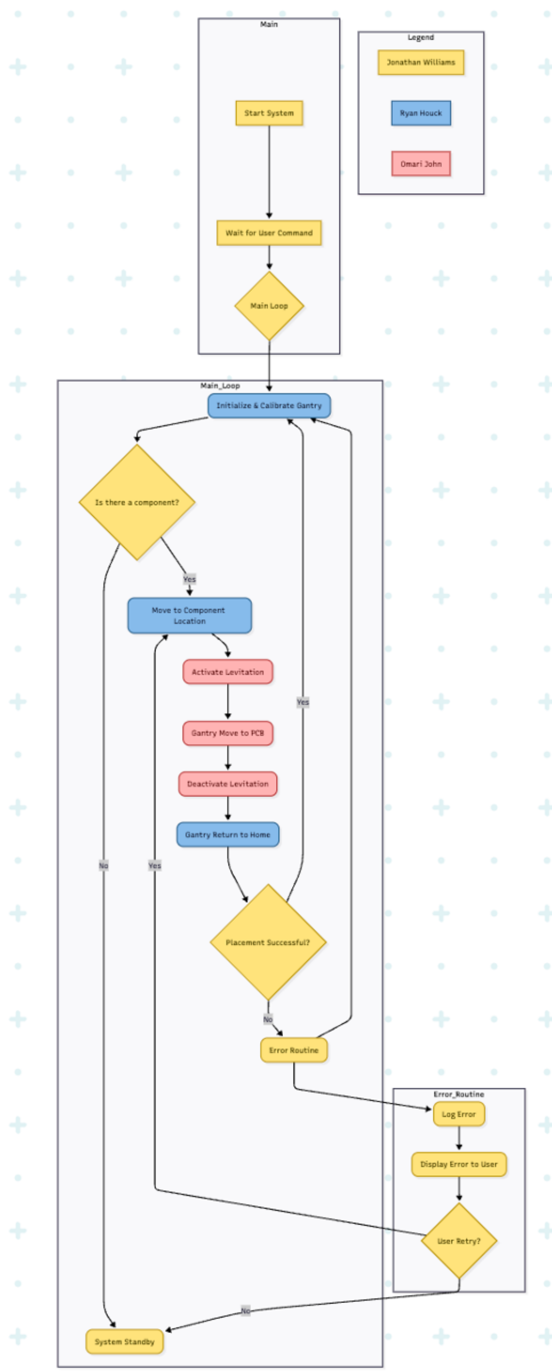

Figure 4: Main Control Loop for the Acoustic Levitation Pick and Place Process

7.1.1 Gantry Motion Control (G-Code Interpreter)

The gantry motion is controlled by a lightweight G-Code interpreter. The MCU generates STEP and DIR pulses for the three motor drivers. We use acceleration ramping (a "trapezoidal" velocity profile) to ensure smooth starts and stops, preventing the gantry from "jerking" and losing steps.

7.1.2 Vision System Module Design

The vision system is responsible for two tasks: fiducial recognition (macro-positioning) and component orientation (micro-correction).

1. **Fiducial Recognition:** The gantry moves the camera to the approximate location of a known fiducial marker on the PCB. The camera captures an image, and a simple blob detection algorithm identifies the center of the marker. The difference between the expected coordinate and the measured coordinate provides an (X, Y) offset. This offset is then applied to all subsequent placement coordinates.

2. **Component Orientation Detection:** After picking up a component, the gantry moves it under the camera. An edge detection algorithm (e.g., Canny edge) is applied to find the component's bounding box. The angle of this bounding box provides the component's current orientation (θ_{current}). The system calculates the required correction ($\theta_{\text{target}} - \theta_{\text{current}}$) and applies this by rotating the acoustic trap itself (see Section 7.2) before transport.

7.2 Acoustic Trap Control Algorithm

This is the most critical software component. The 3D acoustic trap is moved by modulating the phase (ϕ) of the 72 transducers to create a holographic focal point. The acoustic pressure field P generated by N transducers is the sum of their individual fields:

$$P(x, y, z, t) = \sum_{i=1}^{N} A_i \frac{e^{j(kr_i - \omega t + \phi_i)}}{r_i}$$

To move the trap (the Gor'kov potential well) to a new target position $\mathbf{T} = (x_t, y_t, z_t)$, the software must calculate the required phase ϕ_i for each transducer i such that their waves constructively interfere at the target point.

$$\phi_i = -k \cdot r_i = -k \cdot \sqrt{(x_i - x_t)^2 + (y_i - y_t)^2 + (z_i - z_t)^2}$$

This calculation must be performed for all 72 transducers in real-time.

7.2.1 MCU Requirement and Performance

The phase-shift equation (Section 7.2) must be calculated for all 72 transducers in real-time, ideally within the 20ms budget allocated in the control loop. This calculation, involving 72 square roots, mandates an MCU with a **hardware Floating Point Unit (FPU)**.

The selected **ESP32** microcontroller features a 240 MHz dual-core processor with an integrated FPU. The FPU performance analysis conducted in Section 7.3.2 (which calculated a 0.036 ms computation time) was based on a 120 MHz Cortex-M4. The 240 MHz Xtensa LX6 core is similarly powerful, confirming that the real-time acoustic calculation will consume a negligible fraction of the 50 ms control window.

The primary software optimization will therefore be the use of Lookup Tables (LUTs) for standard, pre-defined movements (e.g., "Lift," "Land") to reduce computation, while relying on the FPU for dynamic, real-time corrections from the vision system.

7.3 Closed-Loop Latency and Processing Analysis

The system's performance is dictated by its ability to update the acoustic trap and gantry motion within a strict time budget.

7.3.1 The 50 ms Control Window

We have defined a 50 ms (20 Hz) control loop as the "real-time" budget. This budget is allocated as follows:

- **Vision System (15 ms):** Capture image from 1.3MP camera, process fiducial/orientation.
- **Control Logic (10 ms):** Run main state machine, calculate target trap position **T**.
- **Acoustic Calculation (20 ms):** Perform 72-channel phase calculation (if not using LUT).
- **Buffer (5 ms):** Safety margin.

7.3.2 FPU Performance Requirement

The 20 ms budget for the acoustic calculation is the most demanding task. A typical `sqrtf()` function on a modern FPU (like the Cortex-M4 at 120 MHz) takes $\approx 30 - 50$ clock cycles. A multiplication or subtraction takes $\approx 1 - 2$ cycles.

$$\text{Total Cycles} \approx (72 \times 50) + (216 \times 2) + (144 \times 2) \approx 4320 \text{ cycles}$$

At 120 MHz, this calculation takes:

$$T_{\text{calc}} = \frac{4320 \text{ cycles}}{120,000,000 \text{ cycles/s}} \approx 0.000036 \text{ s} = \mathbf{0.036} \text{ ms}$$

This calculation demonstrates that a modern MCU with an FPU can perform the real-time phase calculation in ≈ 36 µs, which is vastly faster than our 20 ms budget. The system's latency will be dominated by the vision system (15 ms) and gantry mechanics, not the acoustic calculations.

8 System Fabrication and Assembly

8.1 Mechanical Frame Build

The gantry frame is the foundation of the machine, constructed from 20×20 mm and dual 20×20 mm (for the X-axis) V-slot aluminum extrusions. This provides a rigid, modular, and cost-effective base. The frame is assembled using standard L-brackets and T-nuts. The motion components—NEMA 17/14 motors, lead screws, and linear rails—are mounted directly to this frame. The Z-axis assembly, which includes the 3D-printed transducer array housing and the Arducam, is mounted to the X-axis linear carriage.

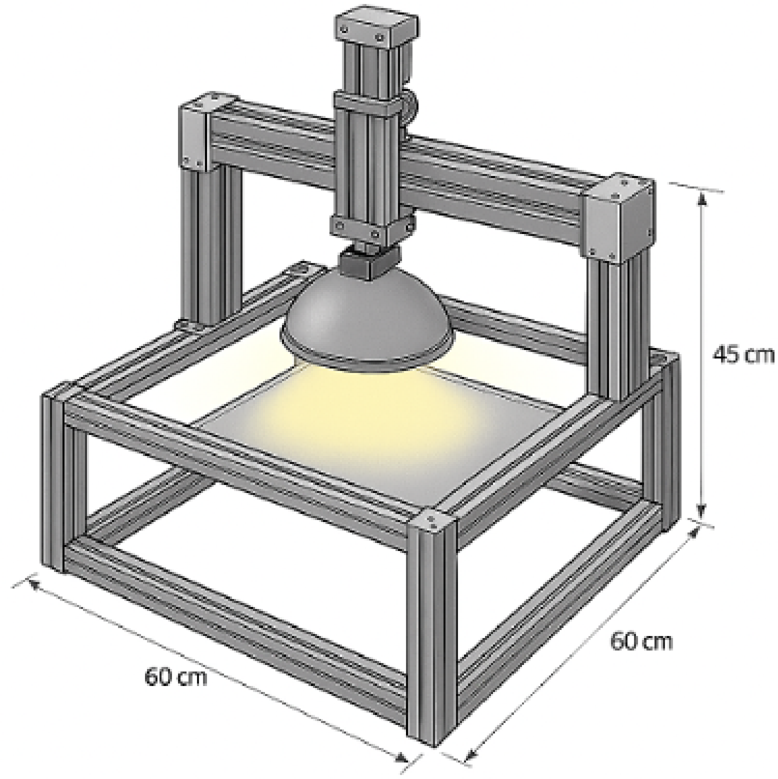

Figure 5: 3D CAD Model of Gantry Frame and Assembly

8.2 Electronic Assembly and Wiring

All electronics, including the central PSU, the main control PCB, and the HV converter, are housed in a separate, ventilated enclosure for electrical safety and to isolate the logic components from mechanical vibration. Wiring follows NEC guidelines and best practices for EMI mitigation:

- **Power Lines (48V, 12V, 5V):** Run separately from signal lines using 16-20 AWG wire.
- **Signal Lines (STEP/DIR, I2C):** Use 22-24 AWG twisted-pair wiring to reduce noise.
- **HV Lines (240VAC):** Run inside a dedicated, shielded HV-rated harness, grounded at the chassis.
- **Grounding:** A single-point "star" ground is established at the chassis, bonded directly to the IEC inlet's Earth pin.

(Placeholder: Figure for Photo of Assembled Gantry)

9 Prototype and System Testing

To validate that the PnPAL system meets its core engineering specifications, a three-part testing plan will be executed. The tests are designed to quantify the system's accuracy, speed, and reliability.

9.1 Test 1: Gantry Kinematic Resolution Verification

- **Objective:** To verify that the gantry's mechanical motion achieves the calculated 0.01 mm/step resolution (using $1/16^{\text{th}}$ microstepping) and to quantify the system's repeatability.
- **Procedure:**
  1. A dial indicator with 0.001 mm resolution will be mounted on the gantry bed, with its probe touching the Z-axis assembly.
  2. The MCU will be commanded to move the X-axis in a series of 100 microsteps (0.625 mm). The dial indicator reading will be recorded.
  3. The gantry will be commanded to move $10,000$ steps (≈ 6.25 mm) to the right, then $10,000$ steps back to the start.
  4. The dial indicator reading will be compared to the original reading. The difference is the system's backlash.
- **Success Criteria:** The measured backlash must be less than 0.1 mm.

9.2 Test 2: Full Pick-and-Place Cycle Time

- **Objective:** To validate that the system can perform a complete pick, transport, and place operation in less than the 15 second target time.
- **Procedure:**
  1. A high-speed (240 fps) video camera will be positioned to view the entire gantry workspace.
  2. An 0805 component will be placed at the "Pickup" location, and a target PCB will be placed 300 mm away.
  3. The "Start" command will be given, triggering a visible LED.
  4. The system will execute the full cycle: move to pickup, activate levitation, move to PCB, deactivate levitation, return to home.
  5. The video footage will be analyzed. The cycle time is the duration between the LED turning on and the component successfully landing on the PCB.
- **Success Criteria:** The measured time from the video analysis must be < 15 seconds.

9.3 Test 3: Placement Accuracy and Reliability

- **Objective:** To validate the final placement accuracy of ± 0.5 mm and the $\geq 95\%$ reliability.
- **Procedure:**
  1. A test PCB with 20 target 0805 land patterns will be fabricated, with the center of each pattern marked with a precise crosshair.
  2. The system will be commanded to place 20 components, one on each pattern, using the full vision-guided workflow.
  3. The PCB will be moved to a digital microscope with a calibrated measurement overlay.
  4. For each component, the (X, Y) deviation from the center of the crosshairs will be measured.
  5. The reliability test will be conducted by running 100 consecutive pick-and-place cycles.
- **Success Criteria:**
  - **Accuracy:** The measured (X, Y) deviation for all 20 components must be less than 0.5 mm from the target center.
  - **Reliability:** At least 95 of the 100 cycles must be successful.

10 Administrative Content

10.1 Budget and Bill of Materials (BOM)

The total estimated budget for this project is $800.00. This includes a $105.00 contingency buffer for component failures and expedited shipping.

Table 6: Estimated Bill of Materials (BOM) Breakdown

Category	**Item(s)**	**Estimated Cost**
Mechanical Parts	Frame, rails, motors, lead screws	$355.00
Electronics & Control	MCU, motor drivers, power supply	$220.00
Acoustic Array	72x Transducers, PCB fabrication	$150.00
Vision System	Camera module, lighting	$35.00
User Interface	LCD display, pushbuttons	$30.00
Miscellaneous	Wires, fasteners, 3D printer filament	$55.00
Total Estimated Cost		**$845.00**
Contingency Buffer		$105.00
Total Project Budget		**$950.00**

10.1.1 Budget Variance

The initial target budget was $800.00. The estimated BOM currently exceeds this by $45.00, primarily due to the high cost of the 72 ultrasonic transducers and the associated 4-layer PCB fabrication. This variance is deemed acceptable and will be covered by the $105.00 contingency fund.

10.2 Team Roles and Responsibilities

This project is an equal collaboration between three B.S. Electrical Engineering students.

Table 7: Team Roles and Primary Responsibilities

Subsystem	**Primary (Lead)**	**Secondary (Support)**
Project Management	J. Williams	All
Gantry Mechanical	O. John	J. Williams
Motor Control (Hardware)	O. John	R. Houck
Acoustic Array (Hardware)	J. Williams	O. John
Transducer Driver PCB	J. Williams	R. Houck
MCU Firmware (RTOS)	R. Houck	J. Williams
Acoustic Phase Algorithm	R. Houck	J. Williams
Vision System (Software)	O. John	R. Houck

References

[1] Ochiai, Y., Hoshi, T., and Rekimoto, J. (2014). Three-dimensional mid-air acoustic manipulation by ultrasonic phased arrays. *PLoS ONE*, 9(5):e97590.

[2] Marzo, A., Barnes, A., and Drinkwater, B. W. (2017). TinyLev: A multi-emitter single-axis acoustic levitator. *Review of Scientific Instruments*, 88(8):085105.

[3] Marzo, A., Ghobrial, A., Cox, L., Caleap, M., Croxford, A., and Drinkwater, B. W. (2017). Realization of compact tractor beams using acoustic delay-lines. *Applied Physics Letters*, 110(1):014102.

[4] Andrade, M. A. B., Ramos, T. S., Adamowski, J. C., and Marzo, A. (2020). Contactless pick-and-place of millimetric objects using inverted near-field acoustic levitation. *Applied Physics Letters*, 116(5):054104.

[5] Andrade, M. A. B., Marzo, A., and Adamowski, J. C. (2020). Acoustic levitation in mid-air: Recent advances, challenges, and future perspectives. *Applied Physics Letters*, 116(25):250501.

[6] Drewitt, J. W. E., Emmens, B., Kong, Z., Drinkwater, B. W., and Barnes, A. C. (2024). MightyLev: An acoustic levitator for high-temperature containerless processing of medium- to high-density materials. *Review of Scientific Instruments*, 95(10):103903.

[7] IEC 61010-1, *Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use*, 3rd ed., International Electrotechnical Commission, 2010.

[8] IPC-2221B, *Generic Standard on Printed Board Design*, IPC Association Connecting Electronics Industries, 2012.

[9] NFPA 70 (National Electrical Code), *Standard for the Safe Installation of Electrical Wiring and Equipment*, National Fire Protection Association, 2023 Edition.

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[11] Advanced Monolithic Systems, "AMS1117-3.3 Linear Voltage Regulator Datasheet", 2022.

[12] Basler AG, "Global Shutter vs. Rolling Shutter Technology in Machine Vision Cameras," Technical White Paper, 2022.

[13] H. W. Ott, *Electromagnetic Compatibility Engineering*, John Wiley & Sons, 2009.

[14] Mean Well Enterprises Co., Ltd., "SE-450-48 Power Supply Datasheet", 2024.

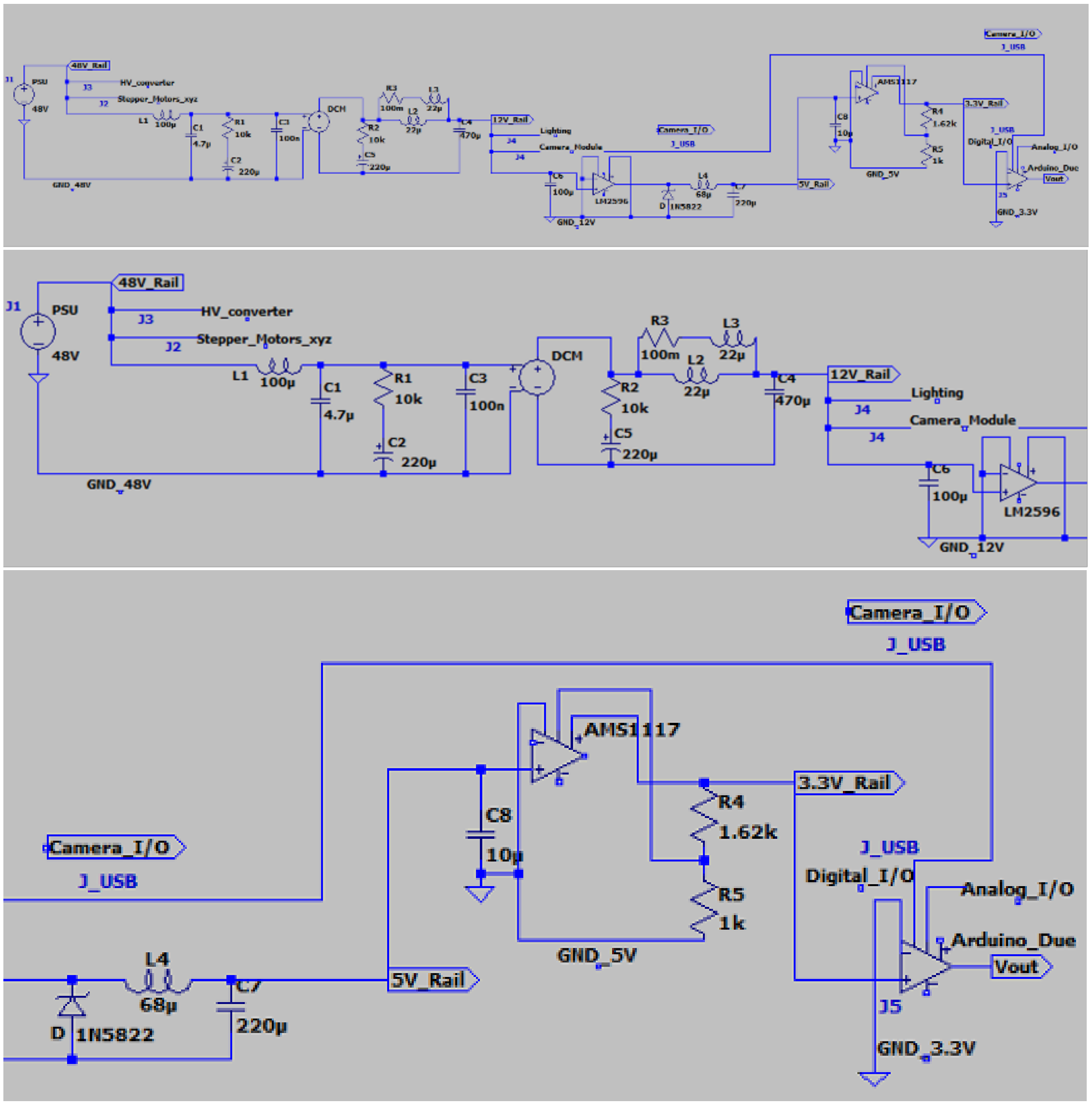
A Source Code (Excerpts)

A.1 Real-Time Phase Calculation (C / ARM)

```
// Placeholder for the FPU-accelerated phase shift
// calculation function. This function must compute
// 72 square roots and update the DAC/PWM output
// within the 50ms control window.
// Wavenumber k = 2*pi/lambda = 2*pi/(343/40000)
#define K_WAVENUMBER 733.3

float phases[72];
Point3D trap_target = (0.0, 0.0, 10.0); // Target in mm
Point3D transducer_positions[72]; // Must be pre-loaded

void calculate_phases_for_target(Point3D target) {
    for (int i = 0; i < 72; i++) {
        // Distances in meters
        float dx = (transducer_positions[i].x - target.x) * 0.001;
        float dy = (transducer_positions[i].y - target.y) * 0.001;
        float dz = (transducer_positions[i].z - target.z) * 0.001;

        // Fast inverse square root or hardware sqrtf()
        float distance = sqrtf(dx*dx + dy*dy + dz*dz);

        float phase = -K_WAVENUMBER * distance;
        phases[i] = phase;
    }
}

// Function to update all 72 PWM/DAC channels
// This function translates the float 'phase' (in radians)
// into a timer capture/compare register value.
update_driver_array(phases);
```

B Schematics and Layouts

This appendix contains the full-page schematics for the main control board, the transducer driver array, and the power distribution system. It also includes the mechanical CAD drawings for the gantry frame and 3D-printed transducer housing.



Master Electrical Plan (Schematic) – Component Key

Component	Part Name/Number	Contribution
L1	Wurth 7447719100	EMI filtering
	Panasonic ECW-FD2W475K	
C1	Nichicon UPM1H221MPD	AC ripple filtering
C2	Nichicon UPM1H221MPD	Bulk decoupling
C3	Murata GRM31CR71H104KA01L	HF noise suppression
R1, R2	Vishay Dale CMF5510K000FHEB	Feedback/stabilization
C5	Nichicon UPM1C221MPD	Output reservoir cap
L2, L3	Coilcraft MSS1260-223	Smoothing output ripple
R3	Yageo MFR-25FBF52-100R	Damping
LM2596	LM2596S-5.0/NOPB	
D1 (Schottky)	1N5822	Low Vf, fast recovery
L4	Bourns SRR1210-680M	
C6	Panasonic EEU-FR1C101LB	Low ESR
C7	Panasonic EEU-FM1E221	Rail Voltage Stability
AMS1117		Dropout ~1.1 V, linear LDO
C8	Murata GRM188R61C106KAAL	Output Voltage
R4, R5	Yageo MFR-25FBF52	Feeback Resistors
MCU	Arduino Due (ATSAM3X8E)	3.3 V logic, ADCs, DACs, UARTs

Master Electrical Plan (Schematic) – Connector Key

J1 for 48V input

J2 for Stepper Motor output

J3 for HV converter

Figure 6: Top-Level System Hardware Block Diagram (Master Schematic)

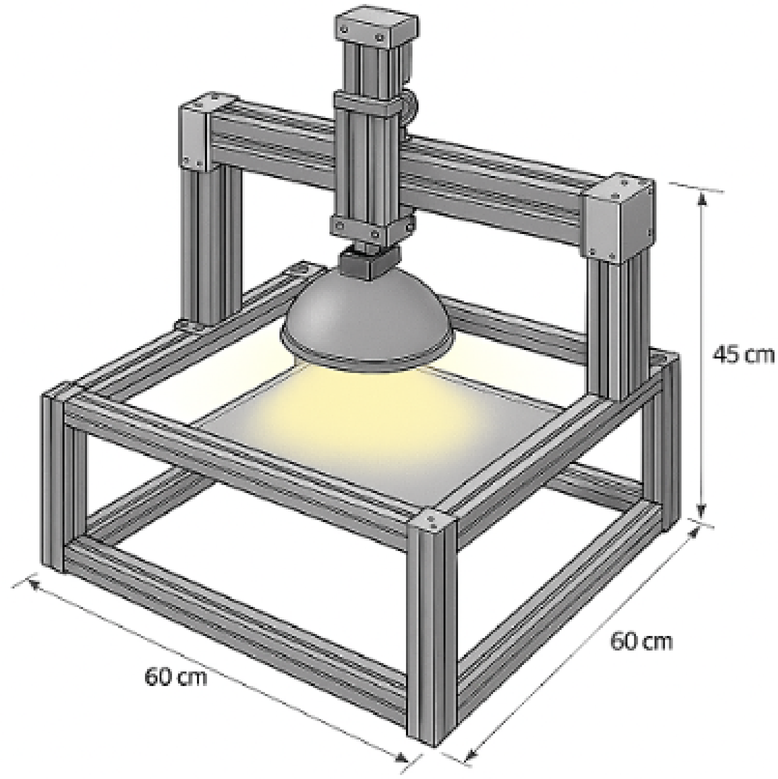


Figure 7: Gantry Mechanical Assembly

(Placeholder: Figure for 4-Layer PCB Layout (Top Layer))

C Critical Component Datasheets (Excerpts)

This appendix contains relevant excerpt pages from the datasheets for the **ESP32-WROOM-32 Module**, the **Murata MA40S4S** ultrasonic transducers, the **74HC595 Shift Register**, and the power conversion ICs.

C.1 Murata MA40S4S Ultrasonic Transducer

MA40S4S/MA40S4R

Ultrasonic Sensor
Open Structure Type

Features

- **High S.P.L. and high sensitivity**
- **Compact size(10.0mm dia.)**
- **Open type structure (indoor applications)**

Applications

- **Object detection**
- **Measuring the distance**
- **Dynamic body detection**

Figure 8: Murata MA40S4S Features

Table.1 Absolute Maximum Ratings of MA40S4S

Parameter	Spec.	Note
Operating Temperature Range	-40 ~ +85 degC	
Storage Temperature Range	-40 ~ +85 degC	
Max. Input Voltage	20Vp-p	at 40kHz, Square continuous wave

Figure 9: Murata MA40S4S Absolute Maximum Ratings

2.2 Performance of Electrical Specifications

Table.3 Performance of Electrical Specification of MA40S4S

Parameter	Spec.	Note
Operating Frequency	40.0kHz	For reference
S.P.L. (Sound Pressure Level)	120 +/- 3 dB	at 40kHz, 10Vrms, Sine wave, 0dB = 20uPa, 30cm(per Fig.5)
Capacitance	2,550pF +/- 20%	at 1kHz
Insulation Resistance	More than 100 Mohm	at 50 V D.C.
Temperature Characteristics	Within +/- 3dB against initial value at 25degC	-40 to +85 degC

Figure 10: Murata MA40S4S Electrical Specifications

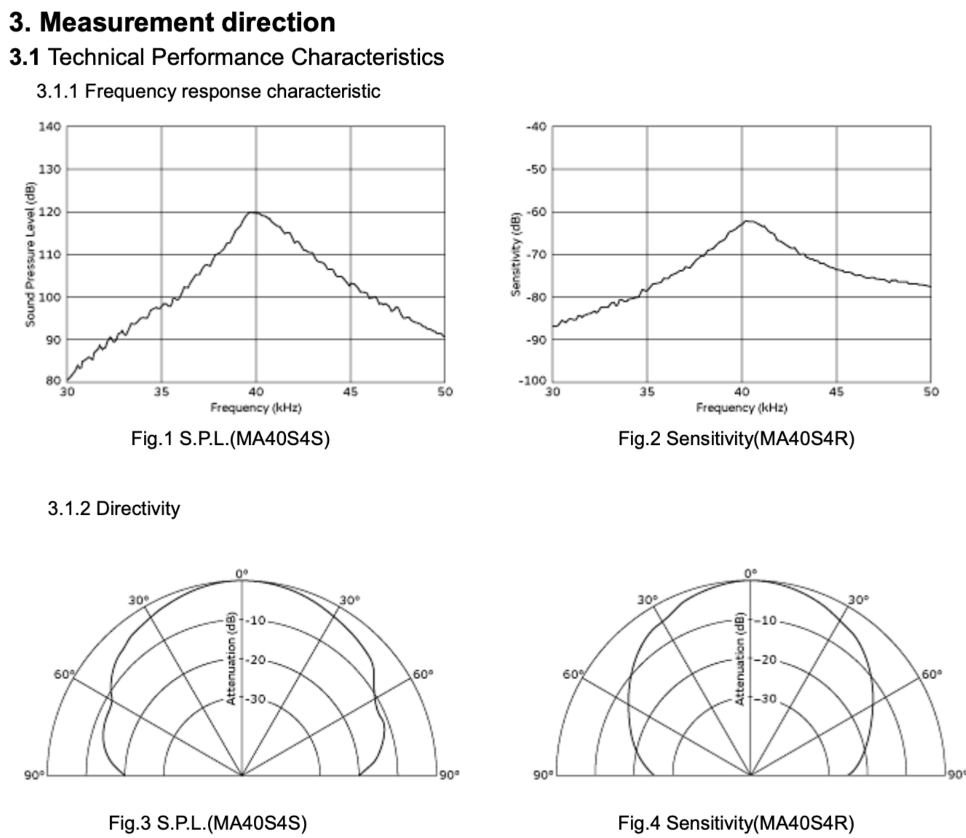
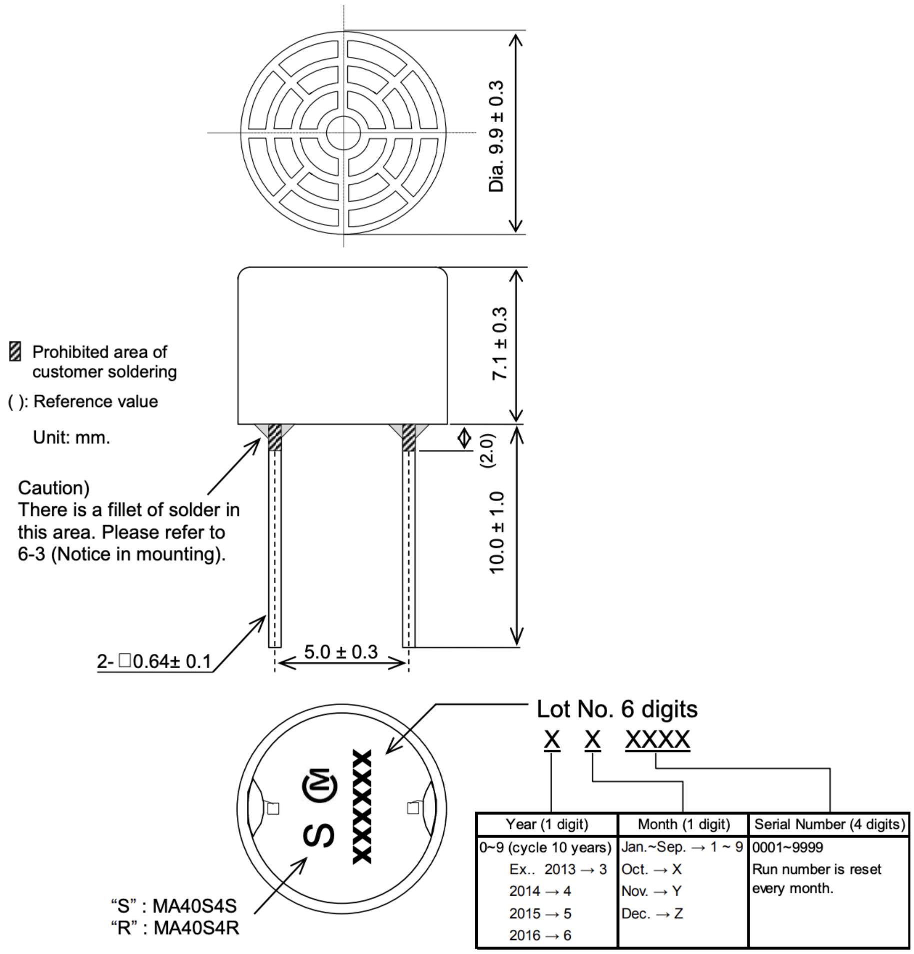


Figure 11: Murata MA40S4S Frequency Response (S.P.L.)

4. Dimensions



Year (1 digit)	Month (1 digit)	Serial Number (4 digits)
0~9 (cycle 10 years) Ex.. 2013 → 3 2014 → 4 2015 → 5 2016 → 6	Jan.~Sep. → 1 ~ 9 Oct. → X Nov. → Y Dec. → Z	0001~9999 Run number is reset every month.

Fig.7 Product dimension

Figure 12: Murata MA40S4S Mechanical Dimensions

C.2 Power Conversion ICs (Reference Circuits)

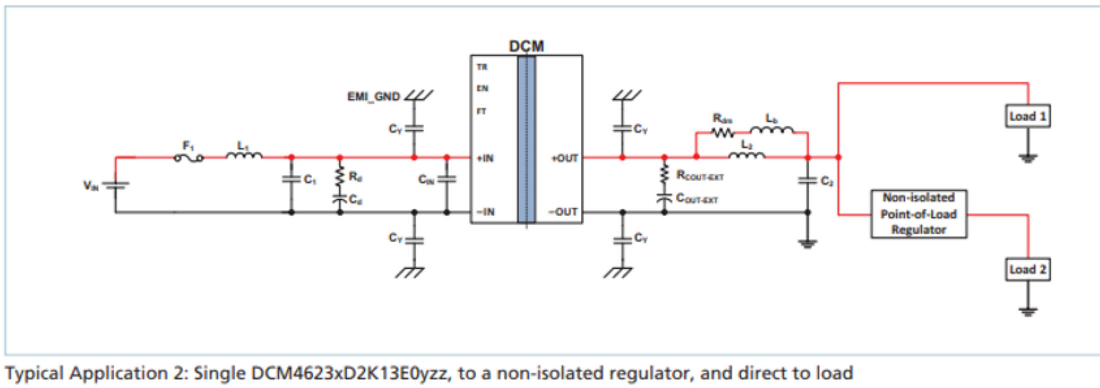


Figure 13: Vicor DCM (48V-12V) Typical Application

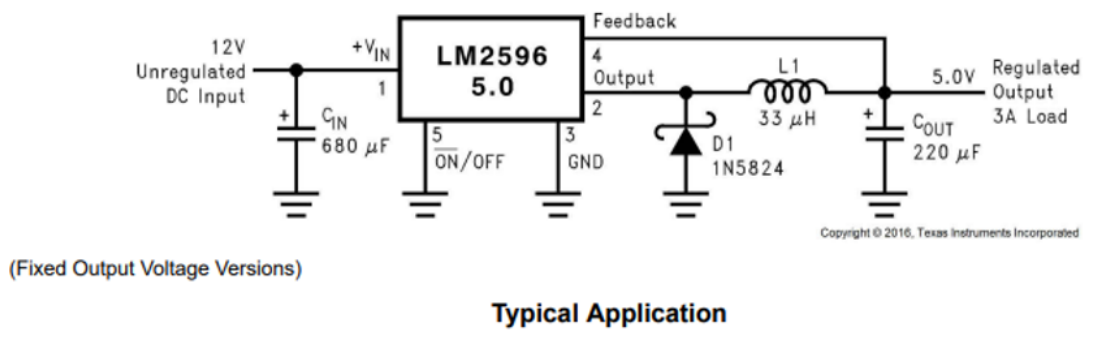


Figure 14: LM2596 (12V-5V) Typical Application

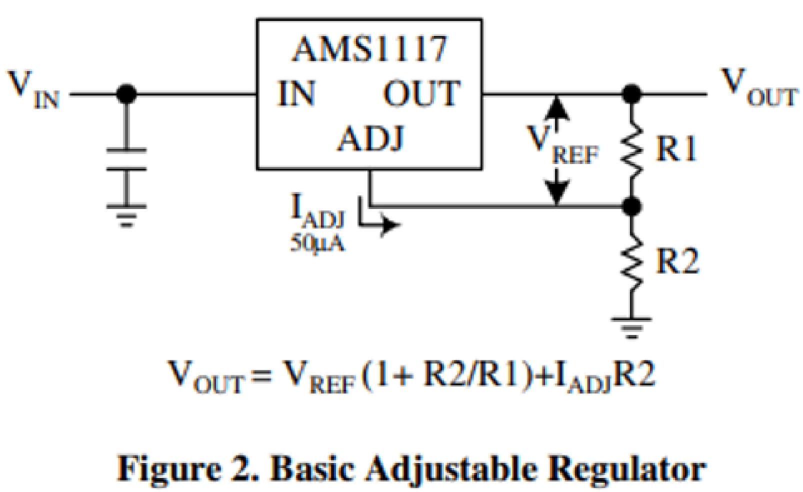


Figure 15: AMS1117 (5V-3.3V) Typical Application

C.3 ESP32-WROOM-32 Module (Selected MCU)

7 Module Schematics

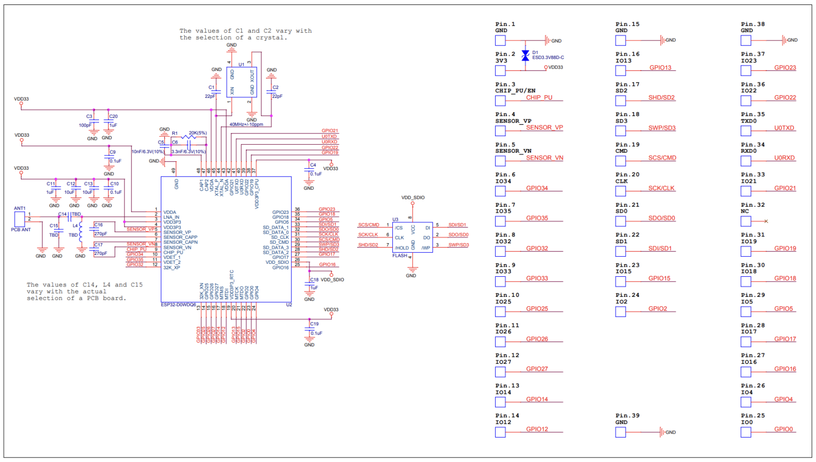


Figure 5: ESP32-WROOM-32 Schematics

Figure 16: Schematics for the ESP32-WROOM-32

2.1 Pin Layout

The pin diagram below shows the approximate location of pins on the module. For the actual diagram drawn to scale, please refer to Figure 9 *Module Dimensions*.

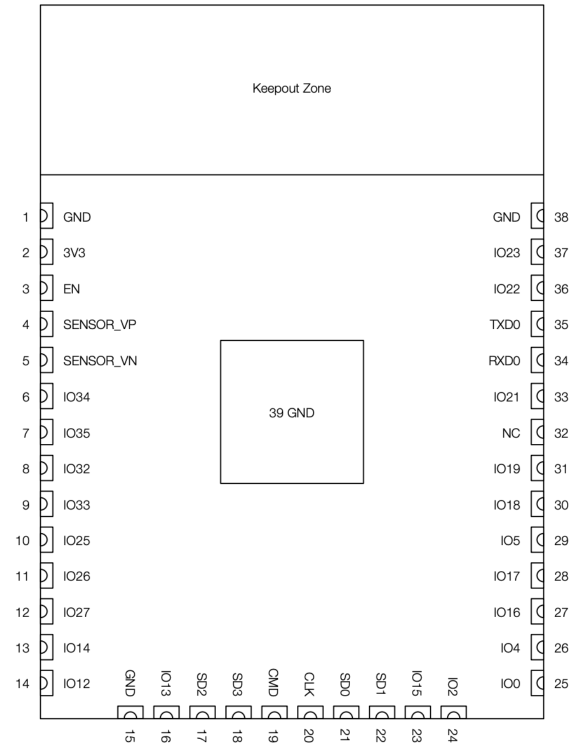


Figure 17: Pin Layout for the ESP32-WROOM-32

C.4 74HC595 Shift Register (I/O Expander)

FEATURES

- **8-Bit Serial-In, Parallel-Out Shift**
- **Wide Operating Voltage Range of 2 V to 6 V**
- **High-Current 3-State Outputs Can Drive Up To 15 LSTTL Loads**
- **Low Power Consumption: 80-μA (Max) I_{CC}**
- **t_{pd} = 13 ns (Typ)**
- **±6-mA Output Drive at 5 V**
- **Low Input Current: 1 μA (Max)**
- **Shift Register Has Direct Clear**

SUPPORTS DEFENSE, AEROSPACE, AND MEDICAL APPLICATIONS

- **Controlled Baseline**
- **One Assembly/Test Site**
- **One Fabrication Site**
- **Available in Military (–55°C/125°C) Temperature Range**[(1)]
- **Extended Product Life Cycle**
- **Extended Product-Change Notification**
- **Product Traceability**

(1) Additional temperature ranges available - contact factory

PW PACKAGE (TOP VIEW)

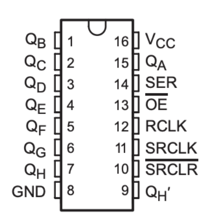


Figure 18: Features of the Shift Register

TIMING REQUIREMENTS

over operating free-air temperature range (unless otherwise noted)

			V_{CC}	T_A = 25°C		T_A = –55°C to 125°C		UNIT
				MIN	MAX	MIN	MAX	
f_{clock}	Clock frequency		2 V		6		4.2	MHz
			4.5 V		31		21	
			6 V		36		25	
t_w	Pulse duration	SRCLK or RCLK high or low	2 V	80		120		ns
			4.5 V	16		24		
			6 V	14		20		
		$\overline{\text{SRCLR}}$ low	2 V	80		120		
			4.5 V	16		24		
			6 V	14		20		
t_{su}	Setup time	SER before SRCLK↑	2 V	100		150		ns
			4.5 V	20		30		
			6 V	17		25		
		SRCLK↑ before RCLK↑ (1)	2 V	75		113		
			4.5 V	15		23		
			6 V	13		19		
		$\overline{\text{SRCLR}}$ low before RCLK↑	2 V	50		75		
			4.5 V	10		15		
			6 V	9		13		
		$\overline{\text{SRCLR}}$ high (inactive) before SRCLK↑	2 V	50		75		
			4.5 V	10		15		
			6 V	9		13		
t_h	Hold time, SER after SRCLK↑		2 V	0		0		ns
			4.5 V	0		0		
			6 V	0		0		

(1) This setup time allows the storage register to receive stable data from the shift register. The clocks can be tied together, in which case the shift register is one clock pulse ahead of the storage register.

Figure 19: Timing Requirements of the Shift Register