

Automatic Solder Fume Extractor Positioning System

Project Proposal

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1 Introduction

1.1 Problem

Hand soldering releases flux fumes that move with the iron as the operator works across a board. Rosin flux fume is a respiratory sensitizer and irritant, and campus guidance calls for ventilation such as a benchtop fume extractor whenever soldering [1]. An extractor only works close to the source: OSHA guidance keeps the source within about 1.5 duct diameters of a simple hood, and capture velocity falls roughly tenfold between one and two diameters [2]. A fixed or hand-positioned hood is therefore in the wrong place for most of a large board, and operators rarely stop soldering to move it.

1.2 Solution

We propose a motorized arm that keeps the hood of an existing benchtop extractor above the active solder joint (Figure 1). Two stepper-driven joints rotate parallel to the table, so two 400 mm links sweep the hood over the board while bearings, not motors, carry the arm's weight. A thermal array on the hood finds the hot iron, and an STM32 microcontroller on our PCB steers the motors to follow it. A third stepper raises or lowers the arm on a lead screw, and a range sensor holds the hood clearance. A hardware emergency stop cuts motor power independently of software.

1.3 Visual aid

Figure 1 shows the system in use: the operator solders normally while the hood follows the iron, and the extractor, control PCB, and emergency stop stay in place.

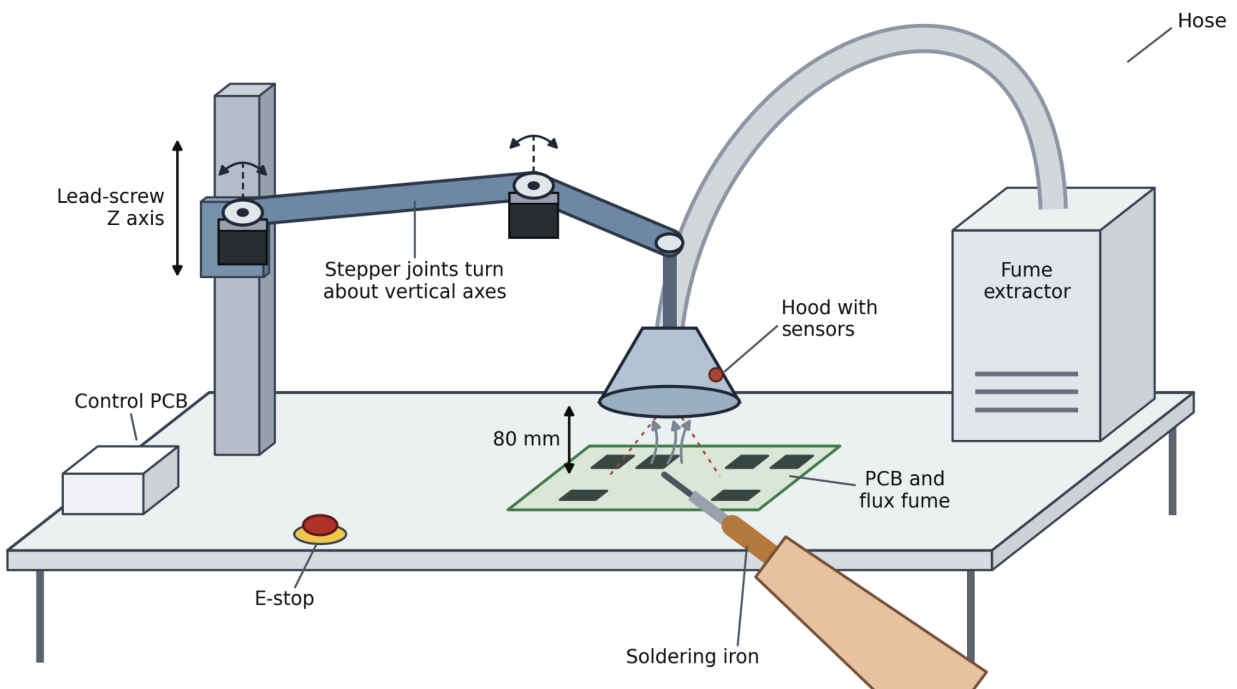


Figure 1. Proposed use at a soldering bench. The hood follows the iron while the extractor remains stationary. Not to scale.

1.4 High-level requirements

- **HLR1:** The system shall locate the heated iron within 1s of it entering the thermal field of view and then keep the hood axis within 30 mm horizontally of the solder joint while the iron moves at up to 30 mm/s.
- **HLR2:** The arm shall reach every point of a 400 x 300 mm workspace, up to 696 mm from the shoulder, while the vertical axis holds hood clearance at 80 ± 10 mm above work surfaces 0 to 50 mm tall.
- **HLR3:** With tracking active, the particle concentration at a fixed operator-side sampling point, integrated over 60s, shall be at least 50% lower than with the same hood parked 200 mm from the joint.

2 Design

2.1 Block diagram

Figure 2 shows the four subsystems and their connections; all custom electronics share one PCB. Figure 3 gives the mechanical layout.

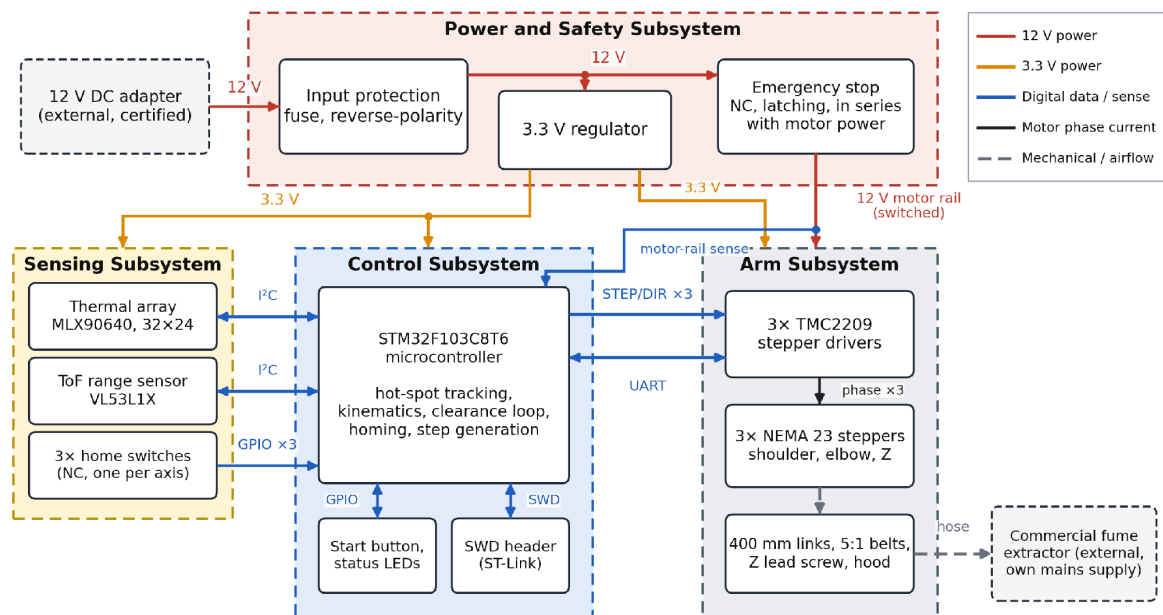


Figure 2. Block diagram. Dashed regions are subsystems; line colors identify supply voltages and data connections.

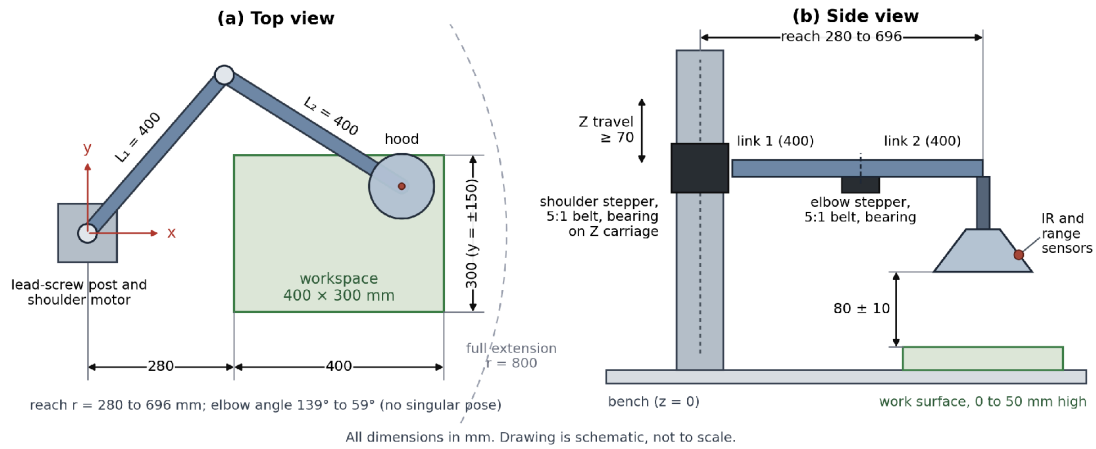


Figure 3. Mechanical layout: (a) top view of the two-link arm and workspace; (b) side view. Dimensions in mm.

2.2 Subsystem overview

Power and safety. A certified 12 V DC adapter powers the board, so no mains wiring enters the project. After a fuse and reverse-polarity protection, the 12 V rail reaches the stepper drivers through a latching, normally closed emergency-stop button wired in series, so pressing it removes motor power with no firmware involved. A regulator ahead of the stop supplies 3.3 V to the microcontroller, sensors, and driver logic, and the microcontroller senses the motor rail so it knows when a stop has occurred.

Sensing. An MLx90640 thermal array (32 x 24 pixels, $55^\circ \times 35^\circ$ field of view, objects to 300 °C [3]) rides on the hood, looks down at the board, and sends frames to the microcontroller over 400 kHz I²C. The iron is far hotter than anything else in view, so locating it needs only a threshold and a centroid. A VL53L1x time-of-flight range sensor [4] beside it measures hood clearance for the vertical axis, and three normally closed home switches, one per axis, give the steppers their position reference.

Control. The controller is the STM32F103C8T6 (72 MHz Cortex-M3, 64 KB flash, 20 KB SRAM [5]) on our custom PCB, programmed over SWD. Firmware finds the hot region, converts the hood-frame error into shoulder and elbow angles through the arm kinematics, and generates step and direction signals for three stepper drivers from hardware timers while limiting speed, acceleration, and workspace. It also runs the clearance loop and homing. A start button and status LEDs form the user interface.

Arm. Three NEMA 23 stepper motors (1.16 N·m holding torque, 1.5 A per phase [6]) are driven from the 12 V rail by TMC2209 drivers on the PCB [7]. Two turn the shoulder and elbow of a two-link arm with 400 mm aluminum-extrusion links through 5:1 belt reductions (Figure 3), and the third turns a self-locking lead screw that raises or lowers the whole arm. Both joint axes are vertical, so the links swing parallel to the table and joint bearings, not motor torque, carry the arm's weight. The arm holds the hood, the sensors, and the supported end of the hose.

2.3 Subsystem requirements

2.3.1 Power and safety

Both HLR1 and HLR2 need a motor rail that does not sag under load, and the stop bounds what the arm can do to a person.

- The 12 V motor rail shall supply at least 5 A continuously at $12\text{ V} \pm 5\%$ with all three motors energized.
- The 3.3 V rail shall stay within $3.3\text{ V} \pm 0.1\text{ V}$ at loads up to 0.3 A while all three motors run.
- Pressing the emergency stop shall remove motor power within 100 ms regardless of firmware state, and the hood shall travel no more than 10 mm afterward.
- Restoring motor power shall not resume tracking; the controller shall re-home the arm and wait until start is pressed.

2.3.2 Sensing

Sensing sets the localization term of the HLR1 error budget and supplies the height feedback for HLR2.

- The sensor shall deliver at least 8 complete 32 x 24 frames per second to the controller.
- The estimated iron position shall be within 6 mm of a marked solder location for iron setpoints of 250 to 350 °C at 70 to 90 mm clearance.
- The range sensor shall report hood-to-surface distance at 20 Hz or faster with error no greater than $\pm 5\text{ mm}$ from 60 to 120 mm.
- Each home switch shall set its axis reference so the hood returns to the same point within 3 mm after homing.

2.3.3 Control

Control owns the latency term of the HLR1 error budget.

- Latency from the start of a thermal frame's acquisition to the first resulting step pulse shall not exceed 250 ms.
- Step commands shall limit hood motion to 60 mm/s and 200 mm/s² inside the workspace, and the clearance loop shall update at least 20 times per second.
- If no valid target is seen for 250 ms, the controller shall hold the arm still until a target returns.

2.3.4 Arm

The arm must cover the workspace of HLR2 and carry the hood at the speeds assumed for HLR1.

- The hood shall reach every point of the 40 x 30 cm workspace without a singular pose or hose kink while carrying at least 0.5 kg.
- Each joint shall deliver at least 4.5 N·m, twice the calculated load, without losing steps while moving the loaded hood at the speed limits.

- The vertical stage shall provide at least 70 mm of travel at 15 mm/s or faster and shall drop no more than 2 mm when motor power is removed.
- Hood position shall repeat within 10 mm for a repeated motor command (ie. the hood position shouldn't be too sensitive if movements are within a cm, or variable length depending on physical testing).

2.4 Tolerance analysis

Two questions decide feasibility: whether the stepper motors can move an arm with 80 cm of reach, and whether a 32 x 24 image and the arm's positioning resolution can hold the 30 mm limit of HLR1.

2.4.1 Motor torque

Assume a 0.25 kg first link, the 0.7 kg elbow motor [6] at 0.4 m, a 0.20 kg second link, and a 0.5 kg hood, sensor, and hose end at 0.8 m. Because both joint axes are vertical, gravity produces no torque about them on a level base. It produces only a bending moment at the shoulder:

$$M_g = g \sum m_i r_i = 9.81(0.05 + 0.28 + 0.12 + 0.40) = 8.34 \text{ N}\cdot\text{m}$$

which the shoulder bearing and Z carriage carry. Had the joints lifted this load directly, it would exceed even the geared motor's 5.8 N·m holding torque. The motor instead supplies only what it takes to accelerate the arm, drag the hose, and overcome a base that is slightly out of level. With the arm fully extended, its inertia about the shoulder is:

$$\begin{aligned} J &= \frac{1}{3}m_1 L_1^2 + m_s L_1^2 + m_2(r_c^2 + \frac{L_2^2}{12}) + m_h R^2 \\ &= 0.013 + 0.112 + 0.075 + 0.320 = 0.520 \text{ kg}\cdot\text{m}^2 \end{aligned}$$

The largest angular acceleration is $\alpha = a/r_{\min} = 0.2/0.28 = 0.71 \text{ rad/s}^2$. With a 2 N hose drag at $R = 0.8 \text{ m}$ and the base 2° out of level, the required shoulder torque is:

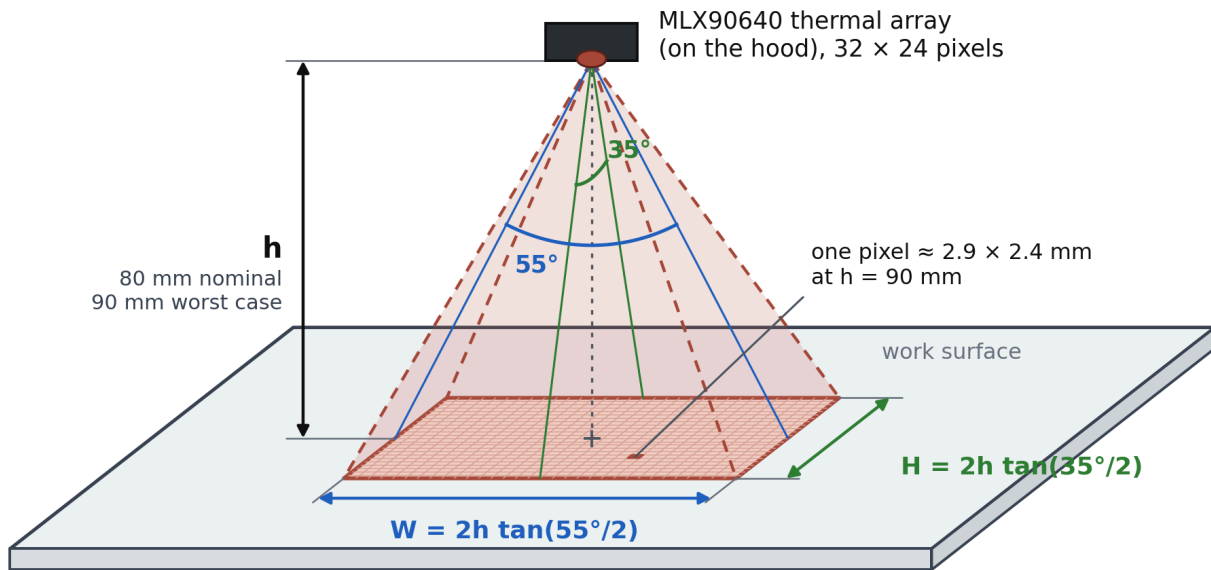
$$\tau = J\alpha + F_{\text{hose}} R + M_g \sin 2^\circ = 0.37 + 1.60 + 0.29 = 2.26 \text{ N}\cdot\text{m}$$

A 5:1 belt reduction turns the motor's 1.16 N·m holding torque [6] into 5.8 N·m at the joint, 2.6 times this load; the arm requirement asks for twice the load, 4.5 N·m. The elbow carries less than half as much. Speed is not limiting: the hood needs at most $60/280 = 0.21 \text{ rad/s}$ at the joint, about 10 rpm at the motor. The vertical axis lifts about 3 kg; on a 2 mm-lead screw at 30% efficiency that takes $T = Fl/2\pi\eta = 29 \times 0.002/(2\pi \times 0.3) = 0.03 \text{ N}\cdot\text{m}$, under 3% of holding torque, and the screw holds the arm with power off.

For HLR2, a 20 x 20 mm aluminum-extrusion ($EI \approx 480 \text{ N}\cdot\text{m}^2$) deflects $\delta = PL^3/3EI = 4.9 \times 0.8^3/(3 \times 480) = 1.7 \text{ mm}$ under the 0.5 kg tip load. Allowing 0.2° of bearing play at each joint adds about 4 mm, for roughly 6 mm of sag, which the vertical axis removes because the range sensor measures clearance at the hood.

2.4.2 Tracking error

At sensor height h , the thermal array covers:



Viewed area: 83.3 × 50.4 mm at $h = 80$ mm; 93.7 × 56.8 mm at $h = 90$ mm. Drawn for $h = 90$ mm.

FOV	X direction	Y direction	Central pointing from normal (X & Y direction)
	Typ	Typ	Max
MLX90640-ESF-BAA	110°	75°	5°
MLX90640-ESF-BAB	55°	35°	3°

Table 15 Available FOV options

Figure 4. MLX90640 IR tracker layout: side view of the sensor's viewing range over the workspace available FOVs from MLX90640 datasheet [3]

$$W = 2h \tan (55^\circ/2), \quad H = 2h \tan (35^\circ/2)$$

At the worst-case $h = 90$ mm this is 93.7 × 56.8 mm, or 2.93 × 2.37 mm per pixel. A one-pixel error on each axis is 3.8 mm; adding 2 mm for calibration and the offset between the iron's hot barrel and the joint gives the 6 mm localization limit.

With 16x microstepping and the 5:1 reduction, one microstep is 0.0225°, or 0.39 mrad: 0.27 mm at the hood from the shoulder plus 0.16 mm from the elbow. Allowing 0.1° of belt backlash at each joint adds 1.2 mm and 0.7 mm, about 2.4 mm in total, well inside the 10 mm we budget for the arm.

Eight frames per second requires the sensor's 16 Hz subpage setting, so the oldest data in a frame is 125 ms old. Reading the last 1,664-byte subpage at 400 kHz takes 37 ms; we budget 60 ms for processing on

the FPU-less microcontroller and 10 ms for step generation, for 232 ms against the 250 ms limit. For an iron moving at $v = 30$ mm/s with $\tau = 0.25$ s and $a = 200$ mm/s²:

$$e_{total} = e_{loc} + e_{arm} + v\tau + \frac{v^2}{2a} = 6 + 10 + 7.5 + 2.25 = 25.75 \text{ mm} < 30 \text{ mm}$$

HLR1 is therefore feasible with about 4 mm of margin, using a pessimistic linear sum. The looser 30 mm limit costs little capture: at 90 mm clearance it moves the source only 5 mm farther from the inlet (94.9 mm versus 90 mm) [2].

Two risks remain. The shiny tip emits weakly, so the sensor sees the hot barrel; firmware will extrapolate along the hot region's long axis to the tip. The STM32F103 has 20 KB of SRAM, and the sensor's calibration data plus one frame need about 8 KB, so processing will use integer math on offset-corrected raw data. If either fails in early tests, the fallbacks are a high-emissivity marker on the barrel and a larger STM32 in the same family.

3 Ethics, safety, and societal impact

Ethics. Following the IEEE Code of Ethics [8], we hold user safety paramount and will be honest about what the device does. Better hood placement improves capture, but it does not make air safe to breathe, and our single-point particle measurement is not an exposure assessment. The documentation will say so, and we will report failed trials along with passing ones. We will credit the open-source designs and libraries we adopt.

Safety. The arm is the main hazard: each geared joint can exert about 6 N·m, enough to pinch a finger near a joint. Firmware caps hood speed at 60 mm/s, the joints and lead screw are guarded, hard stops bound the sweep, the self-locking screw keeps the arm from dropping, and the emergency stop cuts motor power in hardware. Tests run on a cold fixture before a hot iron is used. Nothing on the PCB exceeds 12 V DC, mains stays inside the certified adapter and the extractor, and there is no battery, so the course's battery and high-voltage training requirements do not apply.

Standards. The emergency stop follows the principles of ISO 13850 (a latching actuator, a stop that overrides all other functions, and a deliberate restart), and joint guarding follows the intent of OSHA 29 CFR 1910.212. We do not claim certification. We will follow campus soldering safety guidance and ECE 445 laboratory rules.

Societal impact. If it works, the device makes ventilation the default for students and repair technicians while reusing an extractor they already own. It adds little cost, power, or material, and spent filters and solder waste still need proper disposal.

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