

Automatic Solder Fume Extractor Positioning System

Design Document

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1 Introduction

1.1 Problem and solution

Hand soldering produces flux fumes as the iron moves between joints. Illinois soldering guidance calls for appropriate ventilation and safe handling of soldering materials [1]. A stationary extraction inlet must be repositioned as work moves around a board. When the inlet is too far from the joint, local fume capture can be poor even while the extractor is running.

The system moves an extraction inlet horizontally to follow the soldering iron while maintaining a manually set height. A thermal array near the inlet detects the iron, and a microcontroller estimates the tip position and commands a lightweight two-link arm. Tracking pauses when the sensor cannot reliably identify the target. Verification measures positioning accuracy with the printed inlet and flexible hose installed.

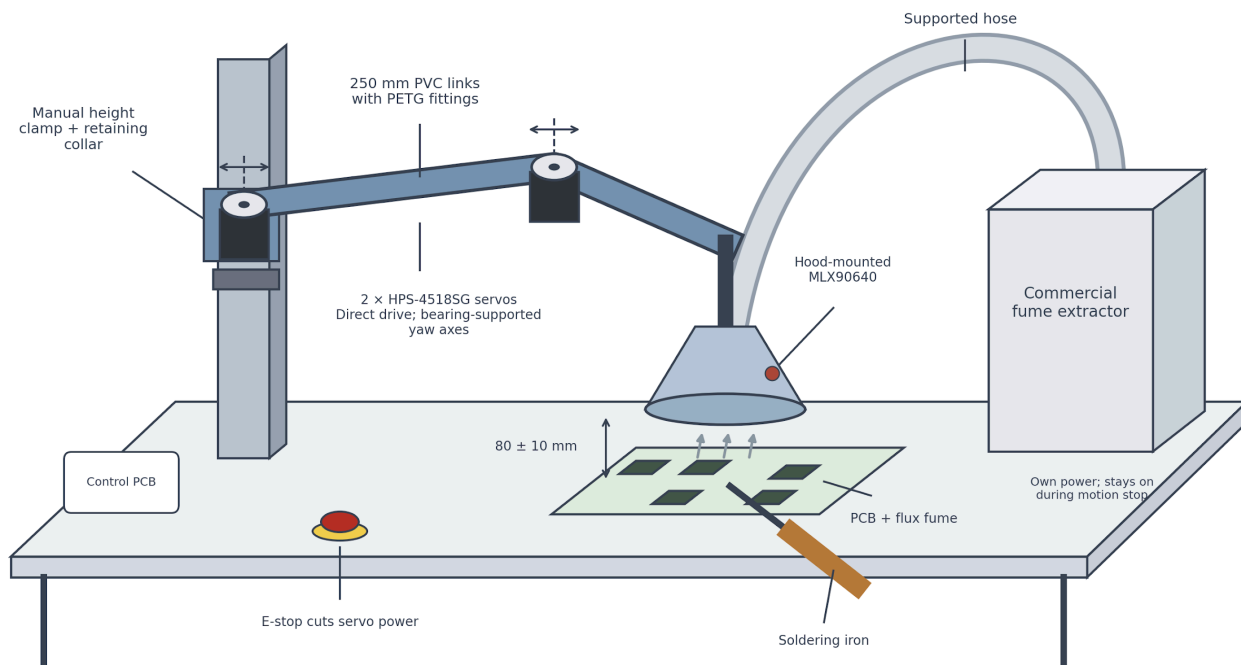


Figure 1. Intended bench use with an external extractor. The positioning demonstration uses the printed inlet and hose.

1.2 High-level requirements

- **HLR1.** Within 1 second of a heated iron entering the central 40 x 40 mm thermal test field, the system shall acquire its working tip. The horizontal error (misalignment of hood center to heated tip point) shall remain at most 30 mm after the startup procedure (further specified in requirement C1) at tip speeds up to 30 mm/s.
- **HLR2.** The inlet shall reach a 250 x 250 mm planar workspace ($x = 150$ to 400 mm and $y = -125$ to $+125$ mm relative to the shoulder) while maintaining 80 ± 10 mm clearance above a fixed work surface after manual height adjustment.
- **HLR3.** Pressing the hardware emergency stop shall interrupt motor supply independently of firmware within 100 ms. Normal operation shall require release of the stop and a fresh START command before tracking resumes.

2 Design

2.1 Block diagram

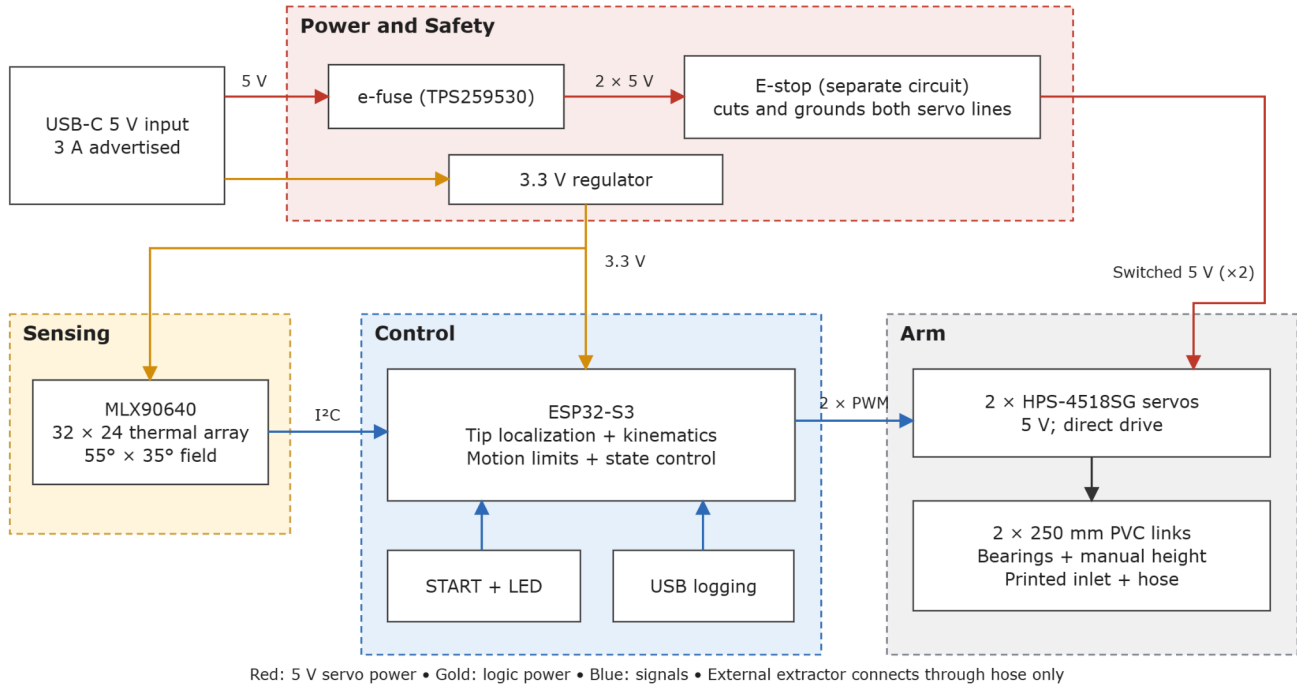


Figure 2. Block diagram. Dashed regions are subsystems; line colors identify supply voltages, data connections and mechanical links.

The Power and Safety subsystem takes 5 V from a single USB-C input and supplies switched 5 V servo power and regulated 3.3 V logic power, with a hardware E-stop. Sensing locates the iron using a 32 x 24 thermal array. The ESP32-S3 Control subsystem converts position error into servo commands and manages operating states. The Arm subsystem moves the inlet and hose across the 250 x 250 mm workspace. An external extractor, when used, has its own power supply and connects through the hose.

2.2 Physical design

The arm uses two nominal 1-inch Schedule 40 PVC links with 250 mm joint-center spacing and vertical joint axes. PETG clamps, brackets and bearing housings join the links; the hood and structural base fittings are also PETG. PLA is limited to fit prototypes, the enclosure and nonstructural covers. Each joint has an 8 mm shaft, two radial bearings spaced 40 mm apart, thrust support and a direct-drive servo horn. A bench-clamped mast sets inlet height using a sliding collar and backup collar. The thermal sensor mounts inside the open hood, 20 mm above the inlet plane, with a clear downward view. A park cradle fixes the startup pose, a metal lip and standoff prevents iron contact with plastic, and overhead hose support limits drag.

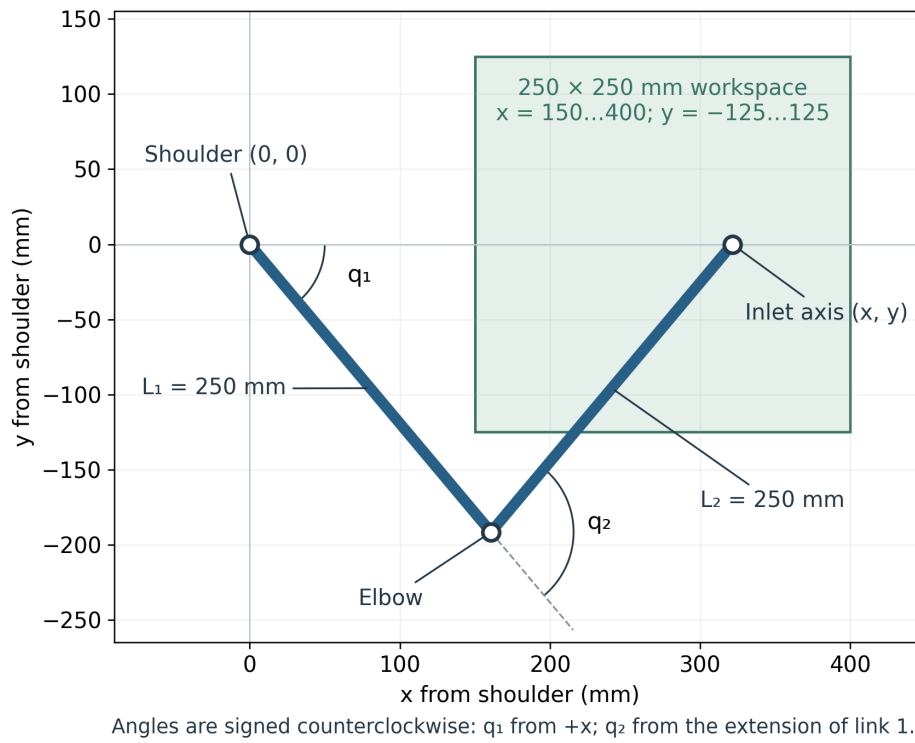


Figure 3. Arm geometry and workspace drawn to scale. Link lengths are measured between joint centers; positive angles are counterclockwise. Assembly CAD will define fitting and guard clearances.

2.3 Power and safety subsystem

All power enters through one USB-C connector; the source must advertise 3 A at 5 V, which the TUSB320 detects. The TPS259530 e-fuse limits input current, and the AP7361C regulates USB 5 V to 3.3 V for the ESP32-S3 and thermal sensor. Two PCB ports carry 5 V to the shoulder and elbow servos. The E-stop is a separate circuit between those ports and the servos: when pressed, its two latching changeover contacts open both 5 V lines from the PCB and tie the servo side of each line to ground. The controller and sensor stay powered during a stop. This subsystem implements HLR3.

Breaking the servo lines directly at the E-stop stops the arm without relying on firmware, a relay or the PCB, which keeps the stop path short and easy to test. Tying the servo side to ground discharges the servo supply so the motors stop driving immediately, and break-before-make contacts keep the PCB 5 V from being shorted. A single USB-C input removes the need for a separate bench supply. Its 3 A budget is below the servos' combined stall current [2], so the e-fuse current limit protects the source during a stall.

The input is USB-C 5 V at up to 3 A. The two servo lines must stay within 4.75–5.25 V at the servo connectors during motion, and the 3.3 V logic rail must stay within 3.20–3.40 V at the PCB and at or above 3.10 V at the sensor. The E-stop connects by cable between the PCB servo ports and the servo power leads, and servo grounds return directly to PCB ground. The E-stop has no signal connection to the microcontroller.

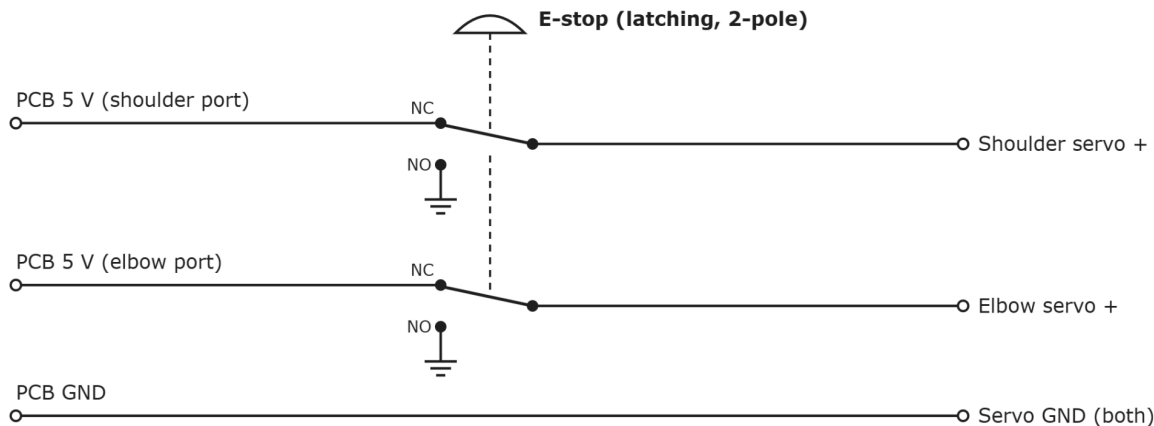


Figure 4. E-stop wiring. Released, each PCB 5 V port feeds its servo; pressed, both servo lines open from the PCB and are tied to ground.

Requirement	Verification and pass condition
Servo supply 4.75–5.25 V during motion	With the hood, hose and 0.50 kg end load installed, power the board from a USB-C source advertising 3 A and run both joints through repeated workspace reversals for 5 min. Scope both servo connectors and log USB input current with a USB power meter. Every sample must stay within 4.75–5.25 V, input current must stay ≤ 3 A and the controller must not reset.
Logic rail within limits	During the same run and ten E-stop presses, probe 3.3 V at the PCB and at the sensor connector. The PCB rail must stay within 3.20–3.40 V and the sensor supply at or above 3.10 V, with no controller reset.
E-stop removes servo power ≤ 100 ms	With firmware halted and both servos moving, press the E-stop ten times at different poses. Scope both servo supply lines and film the inlet from above and from the side against a scale. Each line must fall below 0.5 V within 100 ms, and inlet travel after the press must be ≤ 10 mm horizontally and ≤ 2 mm vertically.

E-stop never shorts the PCB 5 V

With the servos disconnected, press and release the E-stop 20 times while scoping the PCB 5 V ports. The rail must not fall below 4.75 V and the e-fuse must not trip.

2.4 Sensing subsystem

The MLx90640 on an Adafruit 4407 breakout provides 32 x 24 thermal pixels over a 55° x 35° field of view [3], [4]. At 100 mm above the work plane, its footprint is about 104 x 63 mm. Firmware pairs complementary subpages at a 16 Hz subpage rate to produce a nominal eight complete frames per second. It segments regions above max(80 °C, image median + 40 °C) and applies a calibrated endpoint offset to estimate the working tip for HLR1. Ambiguous, edge-clipped and occluded targets are rejected.

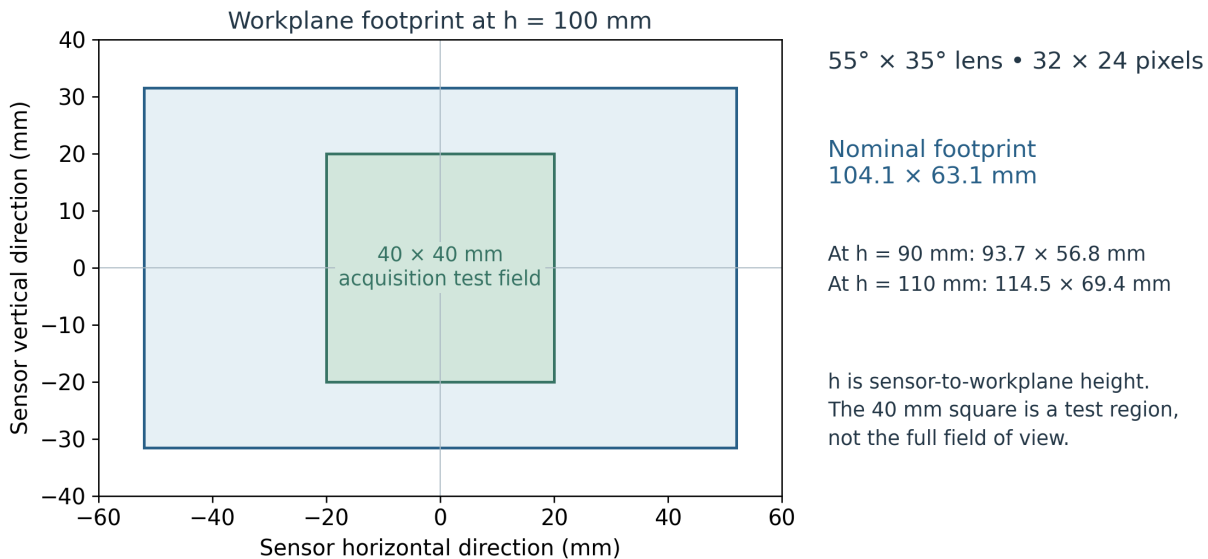
Thermal sensing detects the heated iron without visible illumination. The 55° lens provides finer spatial sampling than the 110° version, and mounting it on the hood keeps the target near the image center. Ambiguous hot objects are rejected; C2 checks target-loss behavior. The sensor's calibrated temperature range ends at 300 °C [3], so S2 verifies localization at iron settings of 250–350 °C without treating the readings as accurate tip temperatures.

The sensor uses 3.3 V (≥ 3.10 V at J6) and connects to GPIO1/SDA and GPIO2/SCL over 400 kHz I²C at address 0x33. The strain-relieved cable is at most 0.6 m long, has a ground conductor alongside each signal and runs away from motor wiring. Calibration maps timestamped pixel coordinates to millimeters relative to the inlet; moving the hood bracket requires recalibration.

At nominal sensor height $h = 100$ mm, the viewing footprint is:

$$W = 2h \tan(27.5^\circ) = 104.1 \text{ mm}$$

$$H = 2h \tan(17.5^\circ) = 63.1 \text{ mm}$$



Unobstructed view required. Pixel-to-inlet calibration includes sensor offset and orientation.

Figure 5. Thermal sensor field of view at a nominal optical height of 100 mm. The sensor is 20 mm above the inlet; the shaded 40 x 40 mm square is the acquisition test region. Dimensions assume a level work plane.

Requirement

Verification

S1 - During arm motion, the sensor shall supply at least 8 complete thermal frames/s on average over 60 s, with no accepted frame older than 250 ms.	Procedure: Log paired subpage IDs, complete-frame timestamps and accepted-frame ages for 60 s while both joints move. Count only complete, nonduplicate pairs. Pass: Save the log and report frame count divided by elapsed time and maximum accepted-frame age. Rate must be ≥ 8 frames/s and age ≤ 250 ms.
S2 - After calibration, tip-localization error shall be ≤ 7 mm in the central 40 x 40 mm field at sensor heights of 90–110 mm.	Procedure: Calibrate the pixel-to-inlet transform, then check nine separate points on a 3 x 3 grid spanning ± 20 mm at 100 mm sensor height and 300 °C. Repeat at varying heights. Pass: Compare each logged estimate with the known tip position, using a photo to confirm placement. Record maximum error and rejected estimates for the 30 conditions. Each condition must yield an estimate within 1 s and error plus placement uncertainty (≤ 1 mm) must be ≤ 7 mm.
S3 - A visible heated tip entering the central 40 x 40 mm acquisition field shall be detected within 1 s (HLR1).	Procedure: With the arm stationary, move the iron into the field from each of four edges. Keep the boundary, tip and LED visible in the recording. Pass: Record the eight entry-to-detection times. Each time, including one video-frame uncertainty, must be ≤ 1 s. Target-loss handling is tested in C2.

2.5 Control subsystem

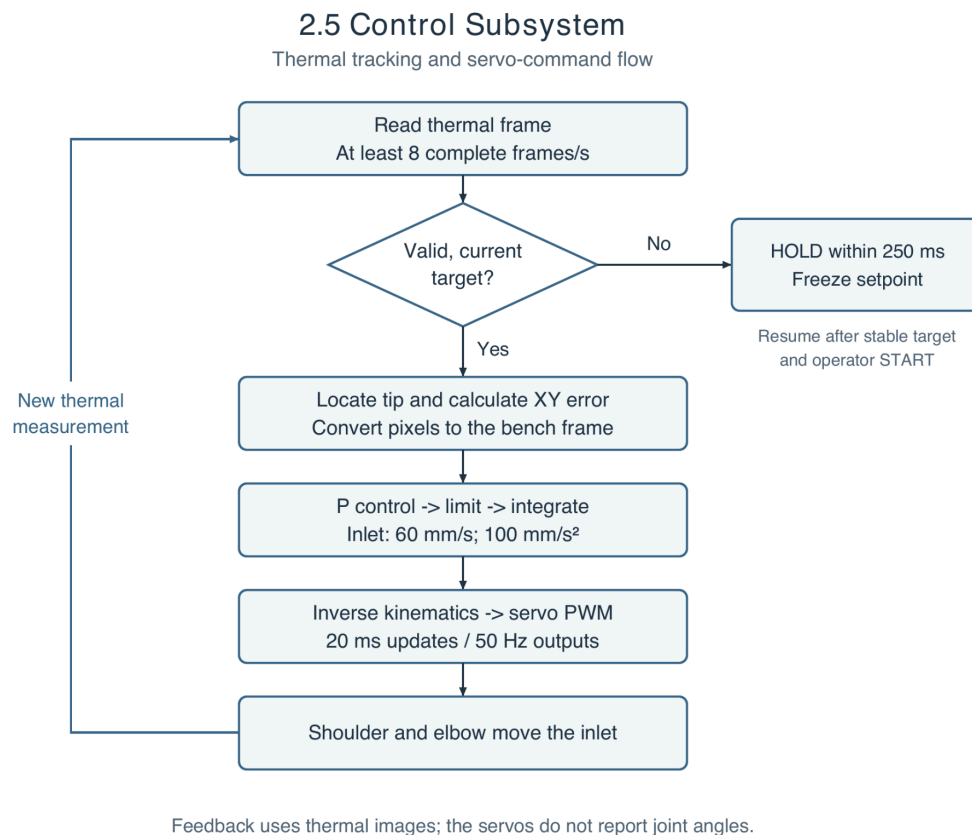


Figure 6. Thermal tracking and servo-command flow. Thermal frames provide position feedback; the servos do not report joint angles.

The ESP32-S3-WROOM-1U-N8R8 [5] shares the main PCB with the power and safety circuits. The thermal breakout and E-stop connect by cable; all power enters through the board's USB-C connector. Each accepted thermal frame

gives an inlet-relative error, rotated into bench coordinates. P control requests velocity, limited to 60 mm/s and 100 mm/s² at the inlet and 0.75 rad/s and 1.5 rad/s² at each joint. A 50 Hz motion task integrates this command and uses inverse kinematics to set servo PWM. A supervisor runs at least every 10 ms; the state table defines HOLD and FAULT behavior. The board includes START, a status LED and USB programming/logging. These functions implement HLR1 tracking and HLR3 restart behavior.

The ESP32-S3 has enough RAM for two thermal frames (6,144 bytes) plus calibration data, and provides hardware PWM and native USB. P control with a 3 mm deadband is the baseline because the servos already regulate joint position internally. Start at $K_p = 2 \text{ s}^{-1}$ and increase it while measuring overshoot and oscillation. Add integral action only if repeatable error remains after calibration. The servos do not report joint angles, so the controller tracks commanded angles and starts the arm from its park cradle.

GPIO1/2 connects to the sensor at J6. GPIO4/5 drive J2/J3 at 50 Hz within calibrated 500–2500 μs limits; these headers carry signal and ground only. GPIO12 is motor permit (default LOW), GPIO8 is the buffer enable (default HIGH, disabled), and GPIO13 reads the E-stop. START uses GPIO10, the LED GPIO11 and USB GPIO19/20. Two servo channels are populated.

P control converts the latest valid bench-frame error e into a velocity request. Every $\Delta t = 0.020 \text{ s}$, the motion task applies speed, acceleration and joint limits, then integrates the limited velocity:

$$v_{req} = K_p e$$

$$p_{cmd,k+1} = p_{cmd,k} + \Delta t v_{lim,k}$$

State	Behavior and transition
DISARMED	Motor permit and PWM off. Calibration is checked and the arm is placed in the park cradle before READY.
READY	Park pulse widths are loaded while motor permit and PWM are disabled. With the E-stop released, the arm in its park cradle and a valid target, a fresh START enables the relay and PWM before bounded tracking begins.
TRACK	Accepted frames update the velocity-limited command; inverse kinematics sets both PWM outputs and rejects unreachable points.
HOLD	An invalid, stale or occluded target freezes the setpoint within 250 ms. A stable valid target and START resume tracking.
FAULT	A persistent bus fault, watchdog reset or E-stop disables PWM and removes motor permit. Recovery requires clearing the fault, restoring the park pose and pressing START. Keep the E-stop latched while resetting an unresponsive controller.

Requirement	Verification
C1 - With the inlet and hose installed, horizontal inlet-to-tip error shall remain $\leq 30 \text{ mm}$ while following a target moving at up to 30 mm/s after a 5 s stationary startup (HLR1).	Procedure: Test a line from (175, 0) to (375, 0) mm. Keep the iron orientation fixed and tip 0–5 mm above the work plane. Hold the target stationary for 5 s after START, then follow the path in alternating directions. Use 50 mm distance marks and timed cues; derive actual speed from video. Pass: Track the visible tip and inlet marker throughout each moving portion. Save an error-versus-time plot and maximum for each of six runs. Maximum error plus measurement uncertainty ($\leq 2 \text{ mm}$) must be $\leq 30 \text{ mm}$, with no target-loss HOLD or manual repositioning.

C2 - Missing or invalid target data shall freeze the position command within 250 ms; a persistent sensor-bus fault shall disable PWM and motor permit within 500 ms. Tracking shall require a valid target and a fresh START to resume.

Procedure: While tracking, cover the sensor three times and introduce a second hot object once. Film the obstruction and a status LED that indicates HOLD; measure from the last unobstructed frame to HOLD. Unplug the sensor once to confirm the physical fault reaches FAULT.

Pass: Save a timing table and scope traces. Target-loss-to-HOLD, including one video frame, must be ≤ 250 ms; injected bus-fault-to-output-disable must be ≤ 500 ms. The second hot object must not cause a jump to a false target. Unplugging must produce FAULT, and recovery must require a valid target and START.

2.6 Arm subsystem

2.6 Arm Subsystem

Two 250 mm links with manually set inlet height

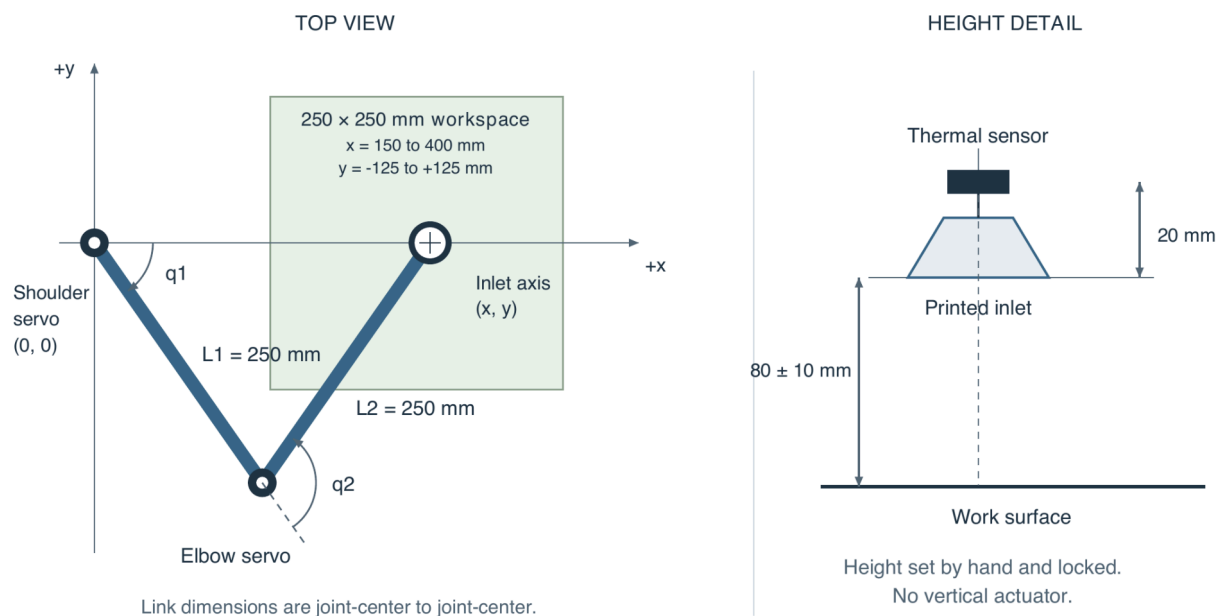


Figure 7. Planar arm geometry and manually set inlet height. Link lengths are measured between joint centers. The sensor sits 20 mm above the inlet; its bracket must leave the field of view clear.

Two HPS-4518SG servos directly drive the arm carrying the inlet, sensor and supported hose end (≤ 0.50 kg total). The 250 mm links cover the HLR2 workspace at a manually locked inlet height of 80 ± 10 mm. The positive-elbow solution requires $q_1 = -106.8^\circ$ to -15.7° and $q_2 = 66.1^\circ$ to 145.1° . The assembly offsets below map these angles into servo travel. Arm accuracy contributes to HLR1.

Bearings and thrust supports carry the weight; the servos supply yaw torque for motion, hose drag, friction and base tilt. Direct drive avoids belts and their adjustment. Section 2.7 estimates shoulder torque at 0.813 N·m and PVC bending deflection at 2.24 mm. Manual height adjustment removes the need for a vertical actuator.

Each servo receives 5 V USB power from a dedicated PCB terminal, routed through the E-stop, plus a 50 Hz PWM signal. The nominal 500–2500 μ s pulse range maps to 0–180°; per-joint calibration replaces this map. Expected command ranges are 43–134° at the shoulder and 46–125° at the elbow. The nominal 100 mm inlet connects to an overhead-supported hose with restoring force ≤ 0.50 N.

For joint angles q_1 and q_2 and link lengths $L_1 = L_2 = 250$ mm, the inlet position and inverse kinematics are:

$$x = L_1 \cos q_1 + L_2 \cos(q_1 + q_2)$$

$$y = L_1 \sin q_1 + L_2 \sin(q_1 + q_2)$$

$$c_2 = \frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1 L_2}$$

$$q_2 = \arccos(c_2)$$

$$q_1 = \text{atan2}(y, x) - \text{atan2}(L_2 \sin q_2, L_1 + L_2 \cos q_2)$$

Initial assembly offsets and the nominal pulse map are:

$$\alpha_1 = q_1 + 150^\circ, \quad \alpha_2 = q_2 - 20^\circ$$

$$u = (500 + \frac{2000}{180}\alpha) \mu s \quad (\alpha \text{ in degrees})$$

Parameter	HPS-4518SG value [2]	Design use
Supply range	5–8.4 V	Operated from the USB 5 V rail, 4.75–5.25 V at the connector
Stall torque	35 kgf·cm (3.43 N·m) at 5 V; 45 kgf·cm at 7.4 V	Lower value used; shoulder demand estimated at 0.813 N·m
Stall current	3.5–5.8 A	Combined stall exceeds the 3 A USB budget; the e-fuse limits input current
Travel and command	180°; 500–2500 μ s; 2 μ s control accuracy	0.09°/ μ s nominal map, replaced by per-joint calibration
Size, mass and cost	40 x 20 x 40.5 mm; 60 g; \$28.99	One at the shoulder and one at the elbow, direct drive

Requirement	Verification
M1 - With a 0.50 kg end load and the final hose, the arm shall cover the 250 x 250 mm workspace while maintaining 70–90 mm inlet clearance, without collisions, cable tension, hose detachment or kinking (HLR2).	Procedure: Check inverse kinematics on a 10 mm software grid. Physically command the four corners, four edge midpoints and center, then move along the boundary and both diagonals. Set the height once before testing. At the nine points, measure clearance and inspect the hose, cables and joints. Pass: Save the software range check and a nine-position clearance/pass-fail table. All points must be reachable, all clearances within 70–90 mm, and all movements free of the listed interference.
M2 - After calibration, loaded static inlet-position error shall be ≤ 8 mm at representative workspace positions.	Procedure: With the final hood and hose installed, command the nine M1 positions. Read the inlet-axis projection against the grid after settling. Pass: Record the xY errors. Maximum radial error plus measurement uncertainty (≤ 1 mm) must be ≤ 8 mm. Use these measurements to check the arm-tolerance assumptions.
M3 - The loaded arm shall complete 5 min of repeated motion without structural slip, controller resets or loss of function. Inlet clearance shall remain	Procedure: Run a repeating path through the M1 positions for 5 min with the final load and hose. Check the center and two far corners before and after: record position and clearance and inspect witness marks, fasteners and printed parts.

70–90 mm, and unpowered vertical movement shall be ≤ 2 mm over 60 s.	Pass: Record before/after measurements and inspection results. There must be no slip, cracks, loosening or resets; the three static positions must still meet M2 and clearance limits. Maximum unpowered drop plus scale-reading uncertainty (≤ 0.5 mm) must be ≤ 2 mm.
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2.7 Tolerance analysis

2.7.1 Arm positioning tolerance

Joint-angle and link-length errors determine whether the arm can meet its 8 mm static-position allocation [12]. S2 and M2 check localization and static positioning; C1 verifies the total 30 mm tracking limit, including lag and drift, and is repeated after M3.

Using $L_1 = L_2 = 250$ mm and the kinematics in Section 2.6, shoulder sensitivity is $r \leq 500$ mm and elbow sensitivity is $L_2 = 250$ mm. The conservative angular-error bound is:

$$\delta p = J \delta q$$

$$\|\delta p\| \leq 500|\delta q_1| + 250|\delta q_2| \quad (mm; \delta q_i \text{ in radians})$$

The calculation assumes $\pm 0.5^\circ$ loaded error at each joint and ± 0.5 mm uncertainty in each calibrated joint-center spacing. Joint error includes offset, backlash and repeatability. Measure joint-center spacing with calipers during assembly. M2 checks the resulting endpoint error directly, avoiding separate precision angle measurements.

The angular bound is 6.55 mm. Adding 1 mm for both link-length errors gives 7.55 mm, within the 8 mm allocation. Replacing $r|\delta q|$ with the exact chord bound $2r \sin(|\delta q|/2)$ gives the same rounded result and bounds errors between sampled poses.

A nonlinear sweep used a 5 mm workspace grid (2,601 poses) and all 16 sign combinations of joint and link errors. With link errors fixed at ± 0.5 mm, joint limits of $\pm 0.25^\circ$, $\pm 0.50^\circ$, $\pm 0.75^\circ$ and $\pm 1.00^\circ$ produced maximum sampled errors of 3.34, 6.15, 8.96 and 11.78 mm. The corresponding conservative bounds are 4.27, 7.55, 10.82 and 14.09 mm.

The 8 mm bound allows equal joint errors up to about $\pm 0.535^\circ$ with 1 mm reserved for link uncertainty. Thus $\pm 0.5^\circ$ passes, but $\pm 0.75^\circ$ does not. Shoulder error has twice the full-reach sensitivity of elbow error. If M2 fails, check calibration, horn/shaft rigidity and bearing fits before considering different servos.

The manufacturer's 2 μ s control specification [2] does not establish loaded mechanical accuracy. M2 verifies the 8 mm static-position requirement with the hood and hose installed.

The 7.5 mm planning allowance for dynamic error corresponds to the following effective lag at constant speed:

$$\tau_{effective} \leq \frac{7.5 \text{ mm}}{30 \text{ mm/s}} = 0.25 \text{ s}$$

At $K_p = 10 \text{ s}^{-1}$, the ideal P model has a 0.10 s time constant. The nominal 0.125 s frame interval leaves little of the 0.25 s planning allowance for processing and servo response. Tune the gain against C1's measured total error; the frame rate and ideal model alone do not establish tracking performance.

2.7.2 Height and optical scale

The ± 10 mm clearance budget comprises ± 3 mm manual setting, ± 4 mm sag and ± 3 mm surface/fixture variation. Clamp slip is a failure. At a nominal 100 mm sensor height, ± 10 mm changes optical scale by about $\pm 10\%$, or ± 3 mm at a 30 mm offset. S2 includes this effect by testing the full height range.

2.7.3 Torque and structural feasibility

Vertical joint axes transfer weight to the bearings and structure. Servo torque covers acceleration, hose drag, friction and base tilt. The calculation uses the lower published stall torque, 3.43 N·m at 5 V [2]; continuous-load capability requires testing.

Assumed masses are 0.50 kg at the inlet, 0.15 kg per link assembly and 0.06 kg for the elbow servo. At full extension, the inertia terms are $M_{11}=0.1538$, $M_{12}=0.0703$ and $M_{22}=0.0344$ kg·m². The shoulder load comprises 0.336 N·m from acceleration at 1.5 rad/s², 0.061 N·m from velocity coupling at 0.75 rad/s, 0.250 N·m from 0.50 N hose drag, 0.116 N·m from 2° base tilt and 0.050 N·m friction. Assembly measurements will check the assumed masses.

Total estimated torque is 0.813 N·m at the shoulder and 0.371 N·m at the elbow. A screening allowance of 25% of stall torque gives 0.858 N·m, only 1.06 times shoulder demand. This fraction is an assumption, not a continuous rating; the loaded tracking and endurance tests determine whether the servos are adequate.

At 1.0 N hose drag, shoulder demand rises to 1.063 N·m. At the original 0.50 N drag with acceleration reduced to 1.0 rad/s², demand falls to 0.701 N·m. Hose support is therefore important; revised motion limits must still pass C1.

Structural checks

At full extension, the assumed payload, links and elbow servo produce about 3.34 N·m shoulder bending moment. Bearings spaced 40 mm apart react a force couple of about 84 N, before shock and assembly factors. Housings, fasteners and shaft fits must withstand this load without slip or excessive deformation.

For a preliminary beam estimate, use PVC diameters of 33.4 mm outside and 26.6 mm inside, $E = 2.5$ GPa, and a 0.50 m cantilever carrying 4.91 N:

$$I = \frac{\pi(D_o^4 - D_i^4)}{64} \approx 3.65 \times 10^{-8} \text{ m}^4$$
$$\delta_{tip} = \frac{FL^3}{3EI} \approx 2.24 \text{ mm}$$

This estimate omits joint compliance, creep, clearances, distributed mass and stock variation. M1 and M3 check actual sag and drift.

3 Cost and schedule

3.1 Cost analysis

3.1.1 Parts costs

Costs are line totals. Entries marked “est.” are planning allowances rather than vendor quotes. Lab-stock wiring and fasteners are assumed available at no charge. The listed-parts subtotal excludes relay/protection hardware, the USB-C power adapter and PCB fabrication; any purchases in these categories must be added to the project cost.

Item/Description	Manufacturer	Qty	Link	Cost
HPS-4518SG servo [2]	Hiwonder	2	Link	\$57.98
MLx90640 IR Thermal Camera Breakout - 55 Degree [4]	Adafruit	1	Link	\$74.95
E-Stop Button	Mxuteuk	1	Link	\$9.99
1 kg PETG for structural fittings, inlet hood and enclosure	SUNLU	1	Link	\$20.00 (est.)
Servo/logic/misc. wiring and sensor cable(s)	Lab stock	1	ECE wire kit	\$0.00
M3/M4/M5 bolts, nuts and washers for printed fittings	Lab stock	1	ECE Supply Center	\$0.00
ESP32-S3-WROOM-1U-N8R8 module U1	Espressif	1	Link	\$6.32
AP7361C-33E-13, 3.3 V regulator, SOT-223 U2	Diodes Incorporated	1	Link	\$0.52
SN74AHCT1G125DBVR PWM buffers, U4–U5; two channels	Texas Instruments	2	Link	\$1.00 (est.)
TUSB320LAIRWBR USB-C controller, x2QFN-12 - U7	Texas Instruments	1	Link	\$1.83

TPS259530DSGR electronic fuse, WSON-8 - U9	Texas Instruments	1	Link	\$1.04
MMBT3904LT1G NPN transistor, SOT-23 - Q2	onsemi	1	Link	\$0.14
LTST-C170KGKT green LED, 0805 - D3	Lite-On	1	Link	\$0.19
USB4085-GF-A USB-C receptacle - J9	GCT	1	Link	\$0.91
SM04B-SRSS-TB, 4-pin JST-SH sensor connector - J6	JST	1	ECE445 Lab	\$0.00
PREC003SAAN-RC, 3-pin servo signal headers - J2, J3	Sullins	2	ECE445 Lab	\$0.00
PREC006SAAN-RC, 6-pin male header, 2.54 mm pitch - J10, J11	Sullins	2	ECE445 Lab	\$0.00
TL3305AF160QG momentary pushbutton - SW1–SW3	E-Switch	3	Link	\$0.63
470 μ F, 10 V SMD electrolytic capacitor, 8 x 10.2 mm - C1	Panasonic	1	Link	\$1.07
100 μ F, 16 V SMD electrolytic capacitor, 6.3 x 5.8 mm - C13	Panasonic	1	Link	\$0.61
4.7 μ F, 16 V x7R ceramic capacitor, 0805 - C2	Samsung Electro-Mechanics	1	Link	\$0.25
10 μ F, 10 V x7R ceramic capacitor, 0805 - C3, C4	Samsung Electro-Mechanics	2	Link	\$0.48
100 nF, 50 V x7R ceramic capacitor, 0805 - C5, C7, C9–C11, C14–C18	Yageo	10	Link	\$0.98

1 μ F, 50 V x7R ceramic capacitor, 0805 - C6	Samsung Electro-Mechanics	1	Link	\$0.14
10 nF, 50 V x7R ceramic capacitor, 0805 - C12	Yageo	1	Link	\$0.14
100 Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R1–R3	Yageo	3	ECE445 Lab	\$0.00
10 k Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R4–R8, R15, R17, R20	Yageo	8	ECE445 Lab	\$0.00
22 Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R9, R10	Yageo	2	ECE445 Lab	\$0.00
4.7 k Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R11, R12, R16, R24, R25	Yageo	5	ECE445 Lab	\$0.00
100 k Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R18, R19, R28	Yageo	3	ECE445 Lab	\$0.00
1 k Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R21	Yageo	1	ECE445 Lab	\$0.00
100 Ω , 1%, $\frac{1}{2}$ W resistor, 1210 - R22	Yageo	1	ECE445 Lab	\$0.00
499 Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R23	Yageo	1	ECE445 Lab	\$0.00
887 k Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R26	Yageo	1	ECE445 Lab	\$0.00
1.02 k Ω , 1%, $\frac{1}{8}$ W resistor, 0805 - R27	Yageo	1	ECE445 Lab	\$0.00
1-inch Schedule 40 PVC, two 250 mm joint-center links	Commercial PVC stock	2	Hardware allowance	\$6.00 (est.)
608-size radial bearings (4), 8 mm shafts (2), thrust supports and servo hubs	Various	2	Hardware allowance	\$24.00 (est.)
Base mast, bench clamp, height lock and retaining collar	Various	1	Hardware allowance	\$20.00 (est.)

Flexible hose, nominal 100 mm inlet adapter and overhead support	Various	1	Hardware allowance	\$12.00 (est.)
Listed-parts subtotal:		\$241.17		

3.1.2 Labor and economic total

Labor is estimated at \$22.50 per hour, using the UIUC student wage guidance for graduate work [11], with 120 hours per team member:

$$\text{Salary/person} = 22.50 * 2.5 * 120 = \$6750$$

3.1.3 Grand total cost

For three members at \$6,750 per person, estimated labor is \$20,250. Adding the \$241.17 listed-parts subtotal gives \$20,491.17, excluding tax, shipping and the unpriced items noted above.

$$\text{Total} = 3\text{persons} * \$6750/\text{person} + \$241.17 = \$20,491.17$$

3.2 Weekly schedule and responsibilities

The proposed nine-week schedule assigns primary responsibility for each task and reserves time for integration, testing and revisions.

Week	Yubo Wu	Noah Zhang	Franklin Liu
6	Finalize initial v0 PCB schematic and power delivery design	Design initial 3D printable arm brackets and CAD geometry Order parts for breadboard prototype and initial PCB design	Finalize initial PCB schematic and power delivery design
7	Breadboard prototype setup and debug with thermal camera	Print initial structure prototype and check mechanical fit	Breadboard prototype setup and debug with servo control
8	Revise and reorder the PCB if needed	Develop tip localization algorithm on breadboard system	Assemble and test PVC links, bearing supports, and base mast
9	Test thermal localization accuracy and frame rate limits	Assemble and solder the v1 PCB	Finalize 3D prints for hood, brackets, and joint covers
10	Implement kinematic motion control and speed profiles	Debug v1 hardware; identify revisions to PCB design	Assemble physical arm links, mounts, and hose harness
11	Integrate closed-loop tracking firmware with visual feedback	Submit new PCB design order with fixes and start v2 build	Mount emergency stop circuit and perform power tests
12	Test thermal-to-bench calibration	Continue board assembly for v2 PCB and test power rails	Perform mechanical verification and workspace tests
13	Fix remaining bugs in tracking and safety state logic	Run integration tests for tracking, hood/hose loading and safety	Finalize assembly and mount the hose and guards
14	Demonstration	Demonstration	Demonstration

4 Societal impact, standards, ethics and safety

4.1 Ethics

IEEE Code of Ethics I.1 and the course guidelines require attention to public safety [8], [13]. The design must address pinch, collision and thermal hazards created by moving hardware near the operator.

IEEE Code of Ethics I.5 requires claims supported by evidence [13]. The demonstration measures positioning and stopping, not fume-removal effectiveness or exposure reduction.

The team will cite borrowed software, datasheets and mechanical designs, and report test failures as well as successful results [8].

4.2 Safety

Operating the arm near a hot iron introduces pinch, collision, thermal and electrical hazards. Follow course training and laboratory procedures [1], [9]. Before each session, inspect clamps, guards, hose support and wiring, then test the E-stop with a cold fixture. Adjust height only while supported and disarmed; begin hot-target testing only after cold-motion and stop tests pass.

4.2.1 Electrical safety

All power comes from one 5 V, 3 A USB-C input. The TPS259530 e-fuse limits input current, including during a servo stall [2], and rated wiring and PCB copper carry servo current. Logic and servo circuits share ground; separate return routing and decoupling reduce noise. P1 checks voltage stability and resets.

4.2.2 Mechanical and thermal safety

Joint covers shield pinch points. Software limits inlet speed to 60 mm/s and bounds acceleration; HLR3 requires the latching E-stop to cut motor power within 100 ms. Metal standoffs and shielding prevent iron contact with the PETG hood. Maintain the specified clearance and inspect the plastic and joints during loaded operation.

4.3 Standards

The following standards and guidance inform specific design choices; these references do not constitute certification of the prototype.

- ISO 13850 (Emergency Stop Function): Informs the latching stop actuator and deliberate restart procedure [7]. The E-stop interrupts relay-coil current independently of firmware; firmware handles normal restart inhibition. The prototype is not a certified safety control system.
- OSHA 1910.212 (Machine Guarding): Its guidance on guarding rotating parts and securing fixed machinery informs joint covers and bench anchoring [14].
- NXP UM10204 (I²C Bus Specification): Defines the Fast-mode timing and electrical limits used for the 400 kHz sensor interface ; S1 checks usable frame delivery during motion [6].

4.4 Societal impact

Automatic positioning may reduce interruptions during soldering and improve capture when used with a suitable extractor. The demonstration tests positioning only.

- Economic factors: PVC, printed fittings and hobby servos limit cost. Budget for the unpriced relay/protection hardware, supply and PCB fabrication before purchasing.

- Environmental and global factors: Common, replaceable parts simplify repair. Minimize print waste and follow campus disposal procedures for solder waste and contaminated consumables [1].

Social and cultural factors: Clearly labeled controls, a status LED and text logs show system status. Controls remain outside the arm's motion envelope.

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