

Problem Statement

Campus robots need reliable person tracking without depending on internet or cloud services. Commercial camera systems can introduce privacy, connectivity, and integration limitations. This project develops an offline onboard AI camera system for BillyBOT to provide local, low-latency target tracking.

- Internet & cloud dependency:** single point of failure in campus environments
- Wi-Fi jamming vulnerability:** Wi-Fi deauthentication attacks can disrupt wireless cameras
- Privacy & data sovereignty:** off-device storage exposes footage to third parties
- Limited robot integration:** commercial PTZ systems lack clean BillyBOT ROS2 integration

An offline, onboard AI system eliminates all network dependencies: enabling robust, low-latency person tracking with no internet required.

Objectives & Requirements

- Offline AI processing:** no internet required during operation
- Local data storage:** video, logs, and telemetry remain on-device
- Visual target detection:** person-level tracking with face-based fallback
- Safe servo envelope:** software-enforced angle limits every cycle
- Stable tracking behavior:** state-machine reduces jitter and overreaction
- Modular design:** 3D-printed mount; field-serviceable components
- BillyBOT integration:** physical mount and ROS2/Nav2 expansion path

Final System Overview

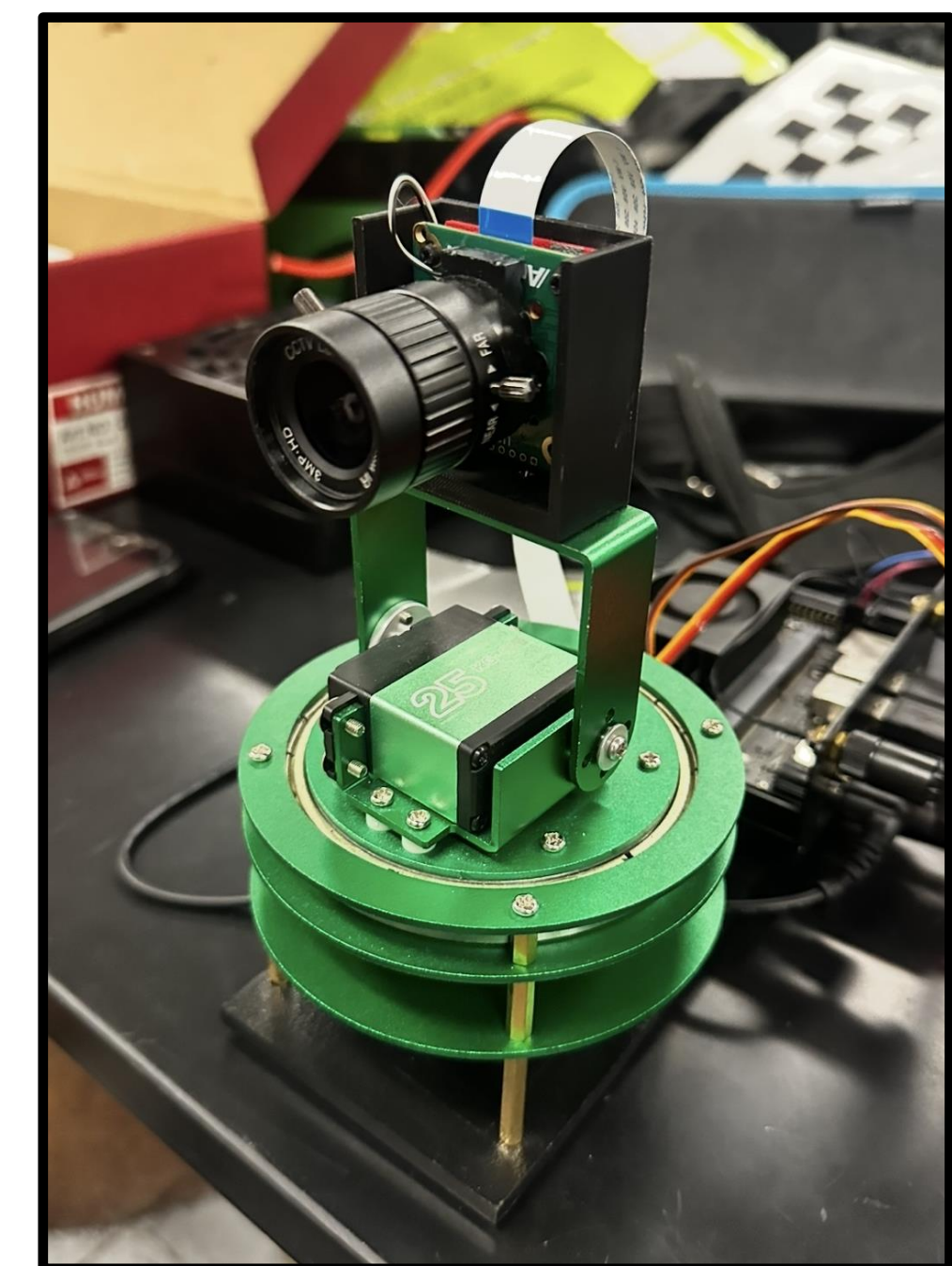


Fig. 1. Assembled camera head without faceplate.

Processor NVIDIA Jetson Orin Nano
Camera Arducam IMX477 HQ 12.3 MP · Auto IR-cut
Servo Driver PCA9685 16C PWM 12-bit · 50 Hz
Actuators 2× DS3218MG Metal-Gear Servos Pan: 20 kg, 270° max · Tilt: 25 kg, 180°
Mount Custom FDM PLA Bracket 3D-printed in-house
Storage 64 GB microSD + 256 GB NVMe SSD
Power BillyBOT Supply + Regulated Rails
Low Light IR Illuminator 850 nm IR, pending integration
Cost ~\$504.44 total

Hardware Architecture

IMX477 Camera	GStreamer NVMM	MobileNet SSD	State Machine	PCA9685 PWM	Pan/Tilt Head
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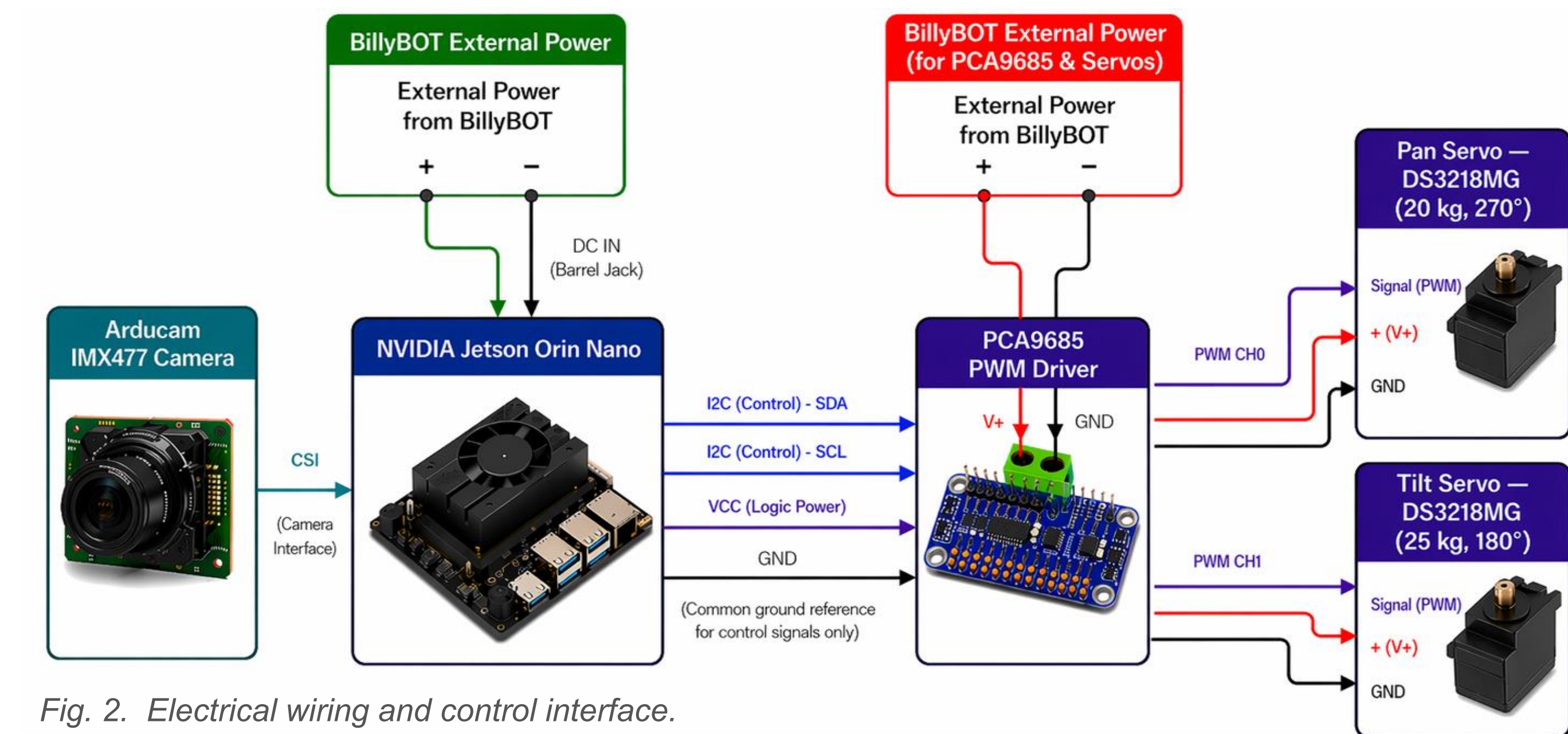


Fig. 2. Electrical wiring and control interface.

Mechanical & Electrical Design

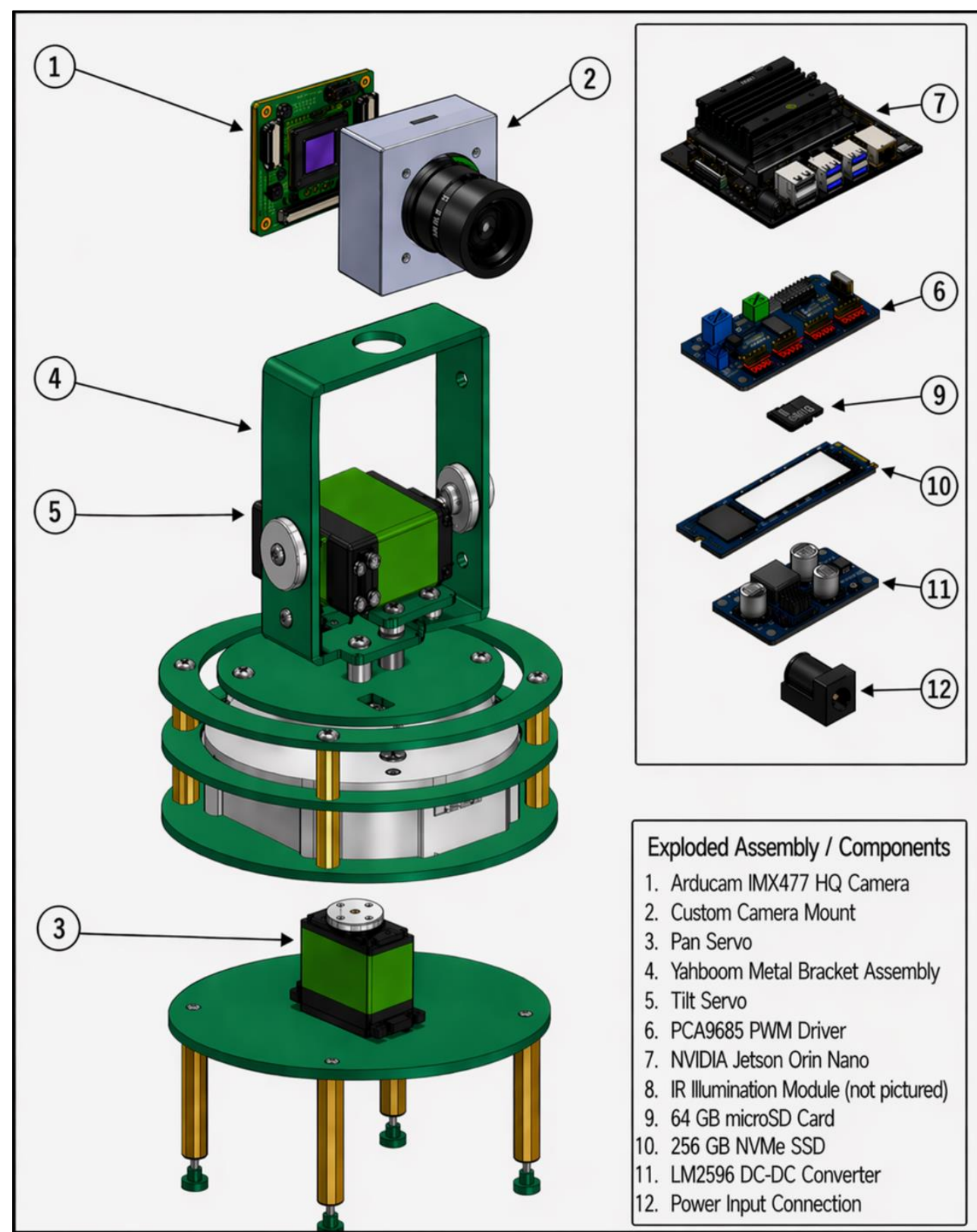


Fig. 3. Exploded assembly of the camera head.

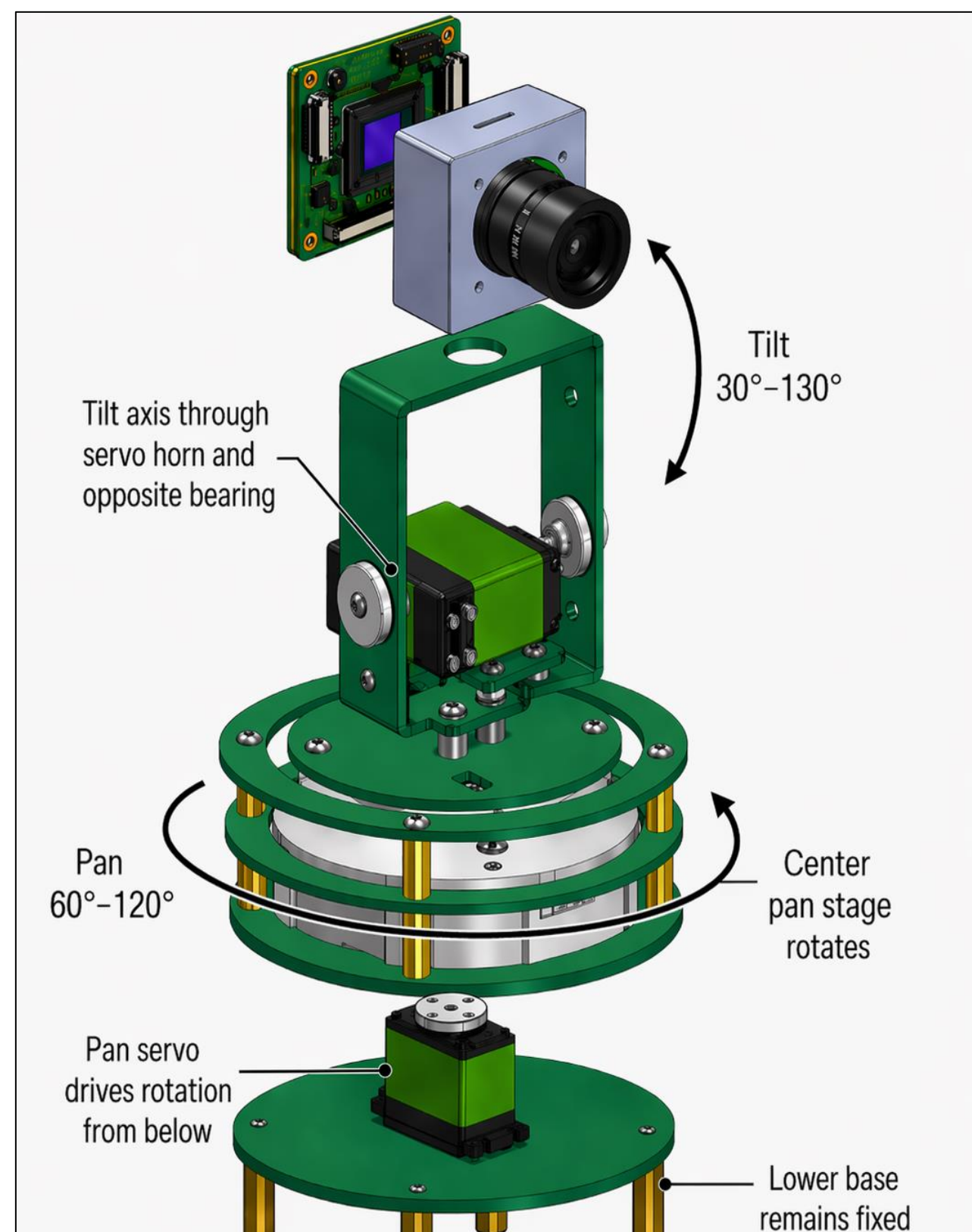


Fig. 4. Pan and tilt axis diagram.

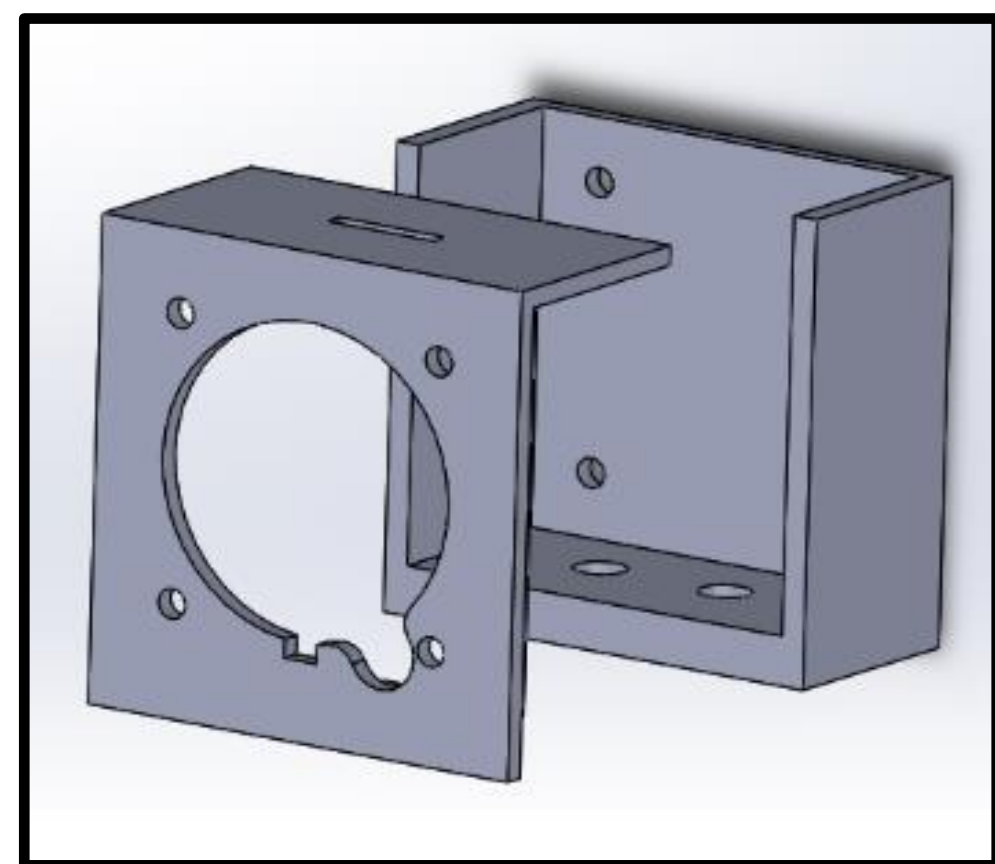


Fig. 5. Custom PLA camera mount.

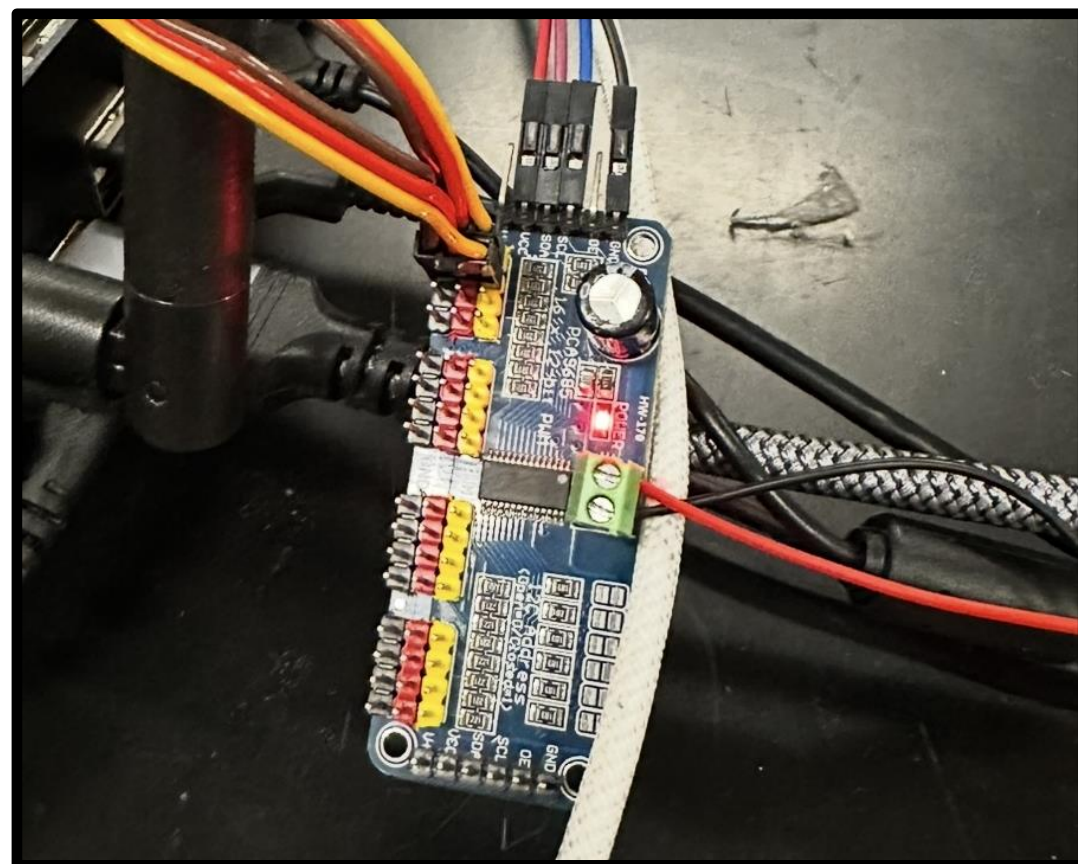


Fig. 6. PCA9685 servo harness.

Software: State-Machine Tracker

A five-state tracker stabilizes camera motion using proportional angle correction, predictive hold, local reacquisition, and automatic return-to-center after extended target loss. Face-based detection is used for target confirmation, with fallback logic used when needed.

SCAN Sweeps pan $\pm 1.4^\circ$ /frame to search for a person	TRACK Proportional error-to-angle; smooth step commands	HOLD Predictive hold while target is briefly occluded
LOCAL REACQUIRE Searches nearby area before issuing a full reset	RETURN TO CENTER Returns pan/tilt to 90/90° after extended loss	TARGET SELECT Face-preferred; head-biased centroid as fallback

- Servo limits enforced every cycle:** pan 60°-120°, tilt 30°-130°
- Step clamped at 5°/frame max:** prevents mechanical shock and overrun
- All state transitions logged:** structured timestamped CSV records

BillyBOT Integration

The camera head was mounted onto BillyBOT's aluminum frame to provide onboard person-sensing capability. The system operates fully offline from BillyBOT's onboard power and supports future ROS2-based person-follow navigation.

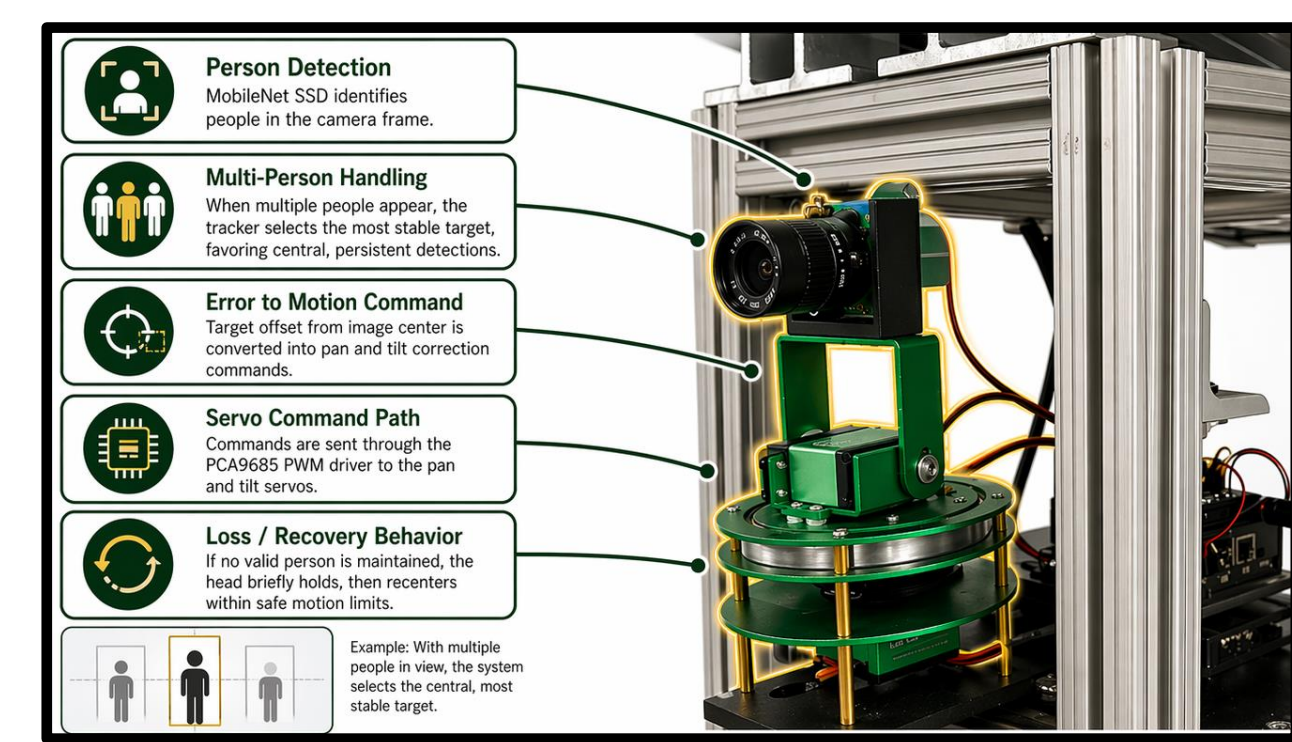


Fig. 7. Close-up of camera installed on BillyBOT.

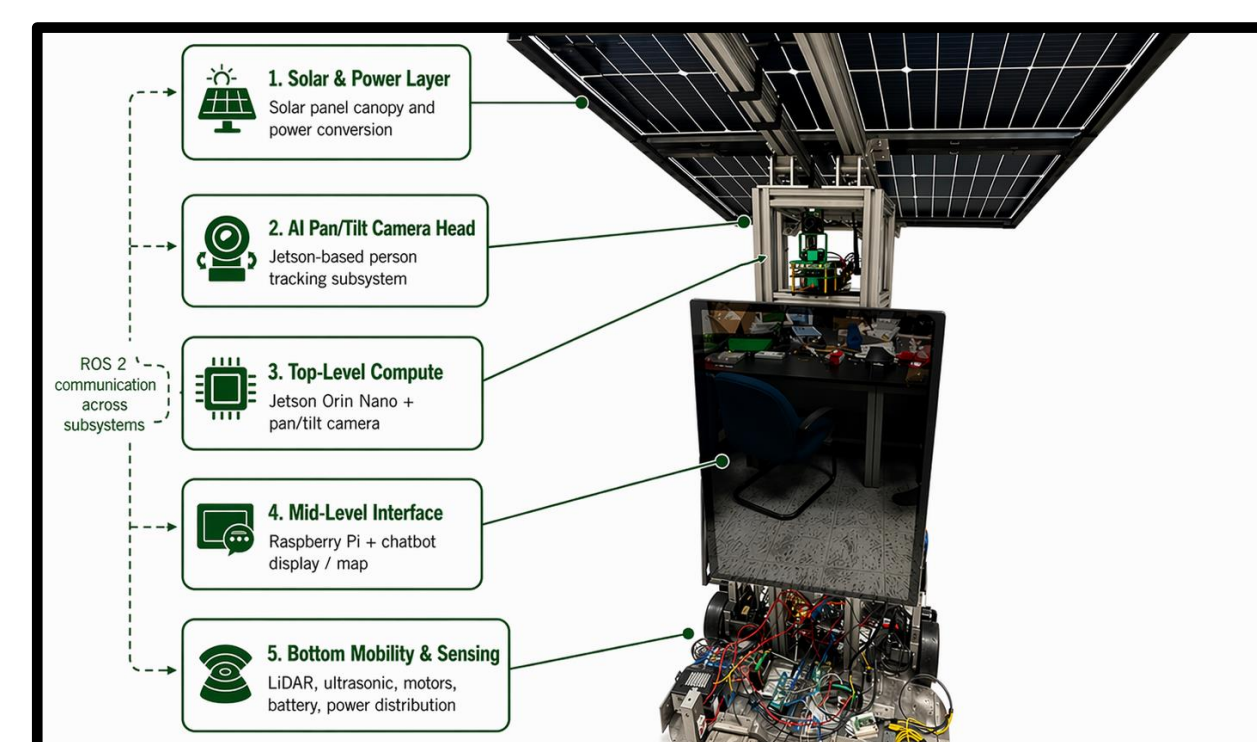


Fig. 8. Layered BillyBOT integration overview.

Design Verification

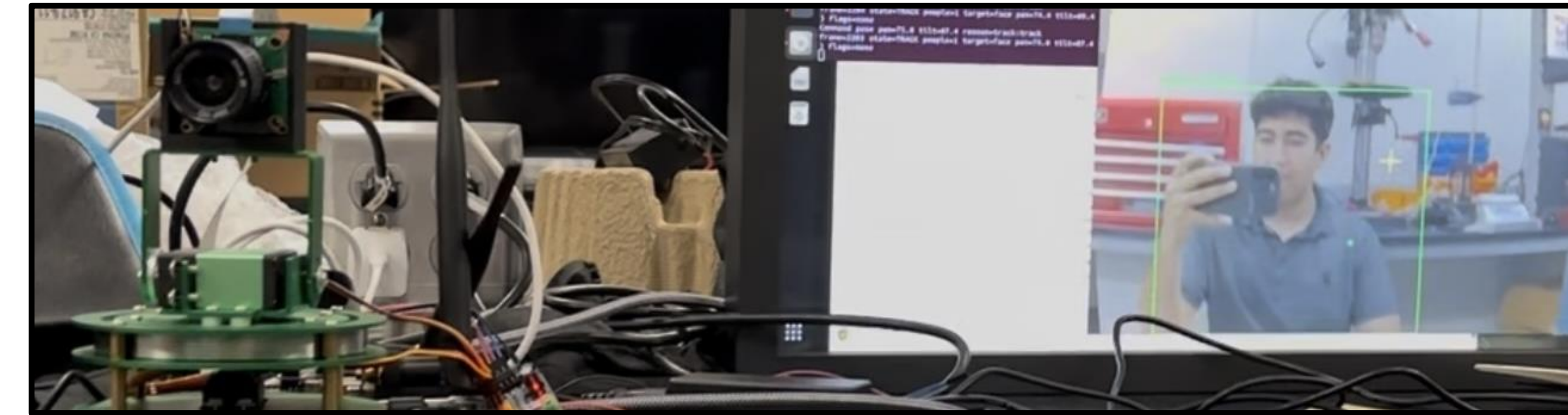


Fig. 9. Live bench test with person tracking.

Bench Validation Summary

7/7 Servo Tests Passed	8.38 Avg FPS (Scan Run)	0.068 ms Avg Software Dispatch Time	0 Out-of-Bounds Commands
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Measured Results

Baseline Validation : Live Hardware [April 18, 2026]

Validation Check	Result
Camera opened via repaired nvarguscamerasrc path	PASS
MobileNetSSD Caffe detector loaded	PASS
Haar cascade face detector loaded	PASS
Startup-center command (pan 90, tilt 90)	PASS
GST_ARGUS: 1920x1080 @ 60 fps confirmed	PASS
SCAN-state pan commands at ~8 Hz	PASS
Full live human-in-the-loop testing	PENDING

Servo Command Latency : Command Path Only

Motion Type	Interval	Dispatch
Pan small step (n=3 runs)	152.5 ms	0.063 ms
Pan medium step	101.6 ms	0.075 ms
Tilt small step	120.4 ms	0.069 ms
Return to center	120.4 ms	0.073 ms
Repeat left / right	99.8 ms	0.097 ms

Command-path timing only. No encoder feedback : mechanical servo latency is not independently confirmed.

Simulation & Scenario Results

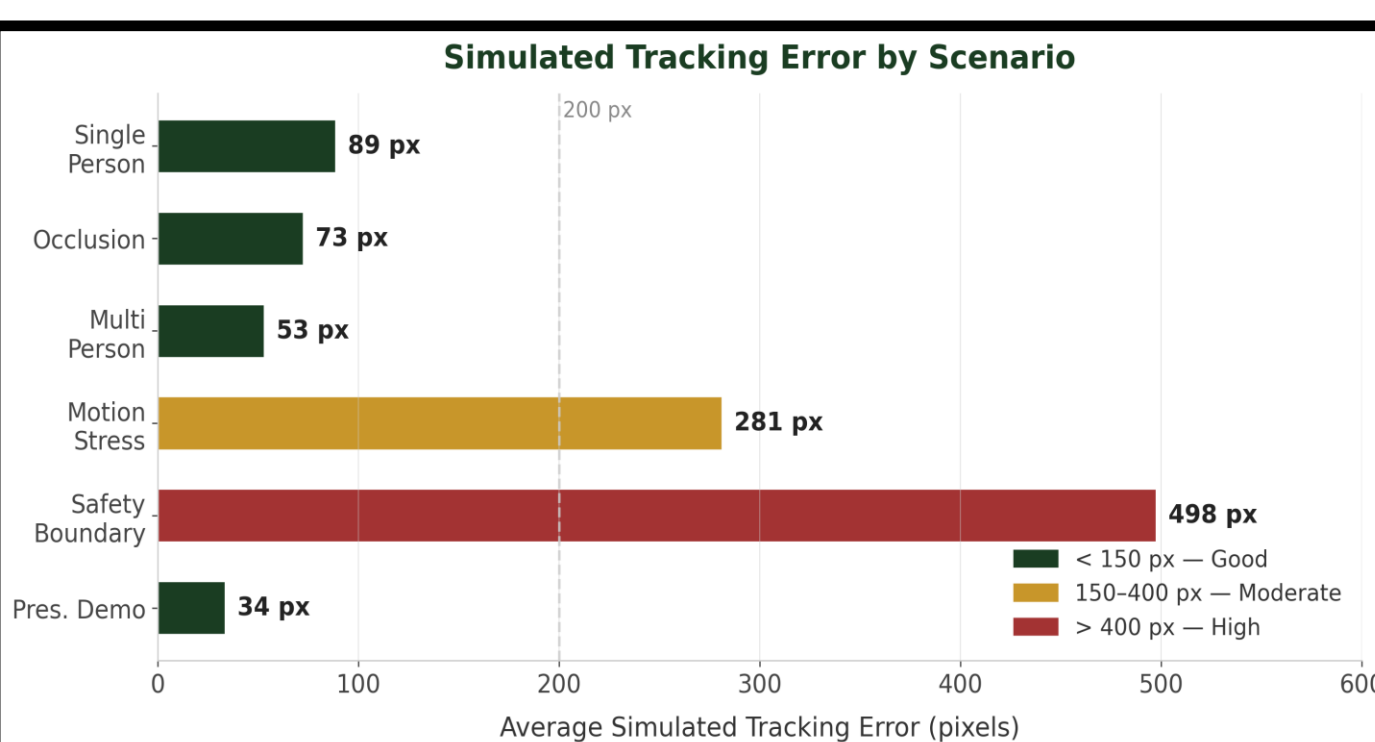


Fig. 10. Simulated tracking comparison graph.

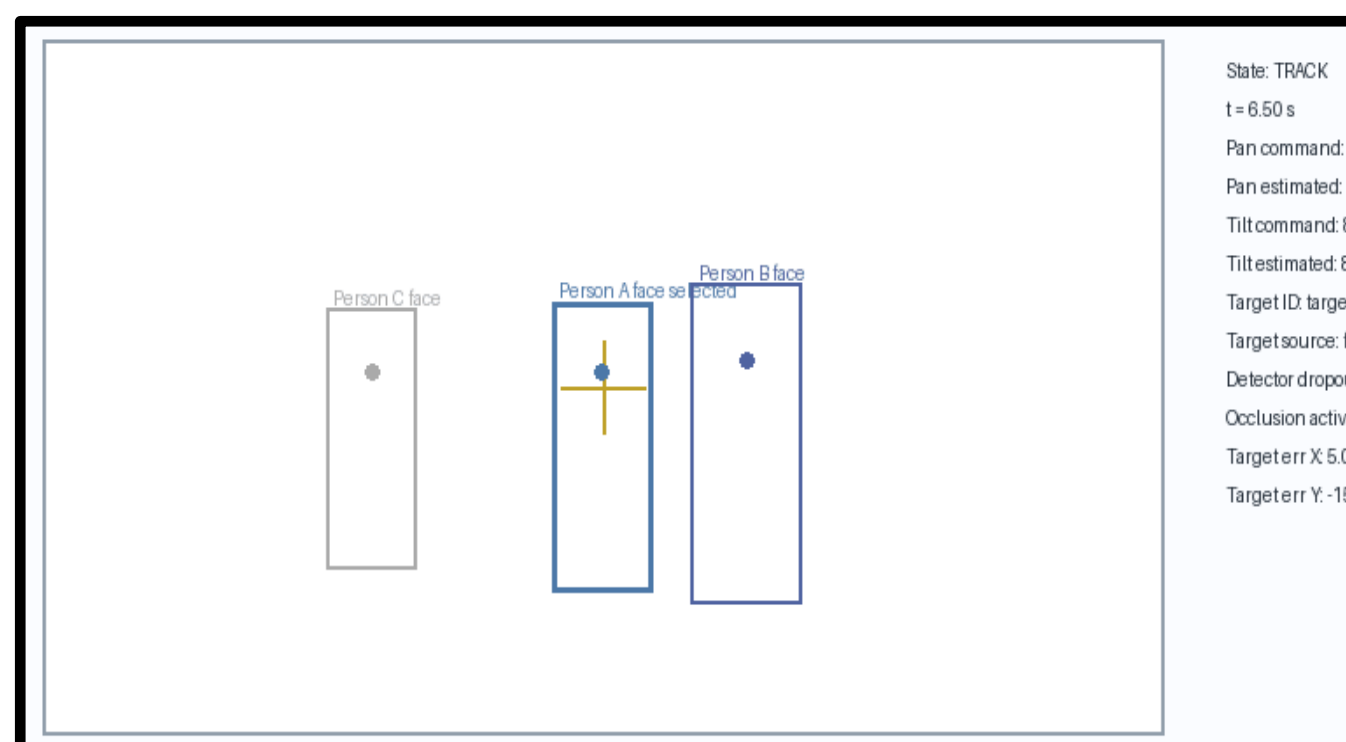


Fig. 11. Simulation screenshot of multi-person tracking.

Simulation Support Only: not closed-loop hardware proof

Limitations

- Live testing incomplete :** structured human-in-the-loop scenarios not yet complete
- Command-path timing only :** no encoder-confirmed mechanical servo latency
- Scenario data is simulated :** not closed-loop hardware proof
- Lighting & occlusion :** broader characterization remains future work

Conclusions & Next Steps

This project designed, built, and bench-integrated an offline AI camera tracking prototype using Jetson Orin Nano. The camera was mounted on BillyBOT and demonstrated live target-tracking behavior, establishing a foundation for future person-following campus tours.

- Complete** structured live human-in-the-loop validation across all scenarios
- Add** encoder or vision-based feedback for servo latency characterization
- Implement** ROS2/Nav2 bridge for full BillyBOT person-follow integration
- Extend** tracker with person re-ID and multi-target engagement

KEY TECHNOLOGIES

NVIDIA Jetson Orin Nano · Arducam IMX477 HQ · PCA9685 16C PWM
MobileNetSSD (Caffe) · OpenCV + GStreamer · Yahboom 2-DoF
2× DS3218MG Servos · Python 3 / Ubuntu · FDM PLA

REFERENCES

- [1] Howard et al., MobileNets: Efficient CNNs, arXiv:1704.04861, 2017
- [2] NVIDIA, Jetson Orin Nano Developer Kit Datasheet, 2023
- [3] Arducam, IMX477 HQ Camera Module Product Docs, 2023
- [4] Adafruit, PCA9685 16-Ch 12-bit PWM Driver Guide, 2022

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