ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

OmniGrasp: VLA-Driven Mobile Manipulator with Custom-Built 7-DOF Arm and Mecanum Chassis

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Team # 41

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Contents

1 Introduction

1.1 Problem Statement

Indoor research workflows still rely on repetitive tabletop sorting for tools, lab components, and test objects. Manual sorting introduces cycle-time variance, operator fatigue, and inconsistent category boundaries across repeated runs. Most low-cost robotic platforms focus on either navigation or manipulation only, creating an integration gap for practical mobile manipulation in supervised lab environments [1], [2].

OmniGrasp addresses this gap with a compact mobile manipulator that can detect objects, execute stable pick-and-place actions, and sort items into predefined bins. The project scope is intentionally practical: structured indoor operation, human-supervised execution, and measurable performance objectives validated through repeated trials.

1.2 Solution Overview & Visual Aid

The system architecture combines four coordinated capabilities:

- **Perception:** camera-based object detection, confidence filtering, and target state estimation.
- **Task and Motion Planning:** target prioritization, grasp pose generation, and retry policy based on confidence and feasibility [3].
- **Manipulation and Mobility:** custom 7-DOF arm for object handling and mecanum base for local repositioning.
- **Embedded Safety Control:** bounded velocity, workspace constraints, watchdog logic, and emergency stop.

Figure 1 summarizes the end-to-end data and control flow from perception to execution and safety fallback, and serves as the visual aid required for rapid system understanding.

Operationally, OmniGrasp runs in a sense-plan-act loop. For each cycle, the system identifies candidate objects, locks one target, computes approach and grasp actions, and verifies completion before moving to the next object. Under low confidence or failed grasp events, the controller switches to retry/abort behavior instead of continuing risky motion.

1.3 High-Level Requirements List

(1) Sorting accuracy shall be at least 90% in controlled tabletop scenes.

(2) Average pick-and-place cycle time shall be no more than 30 seconds per object.

(3) The robot shall trigger retry or abort logic under low confidence without unsafe motion.

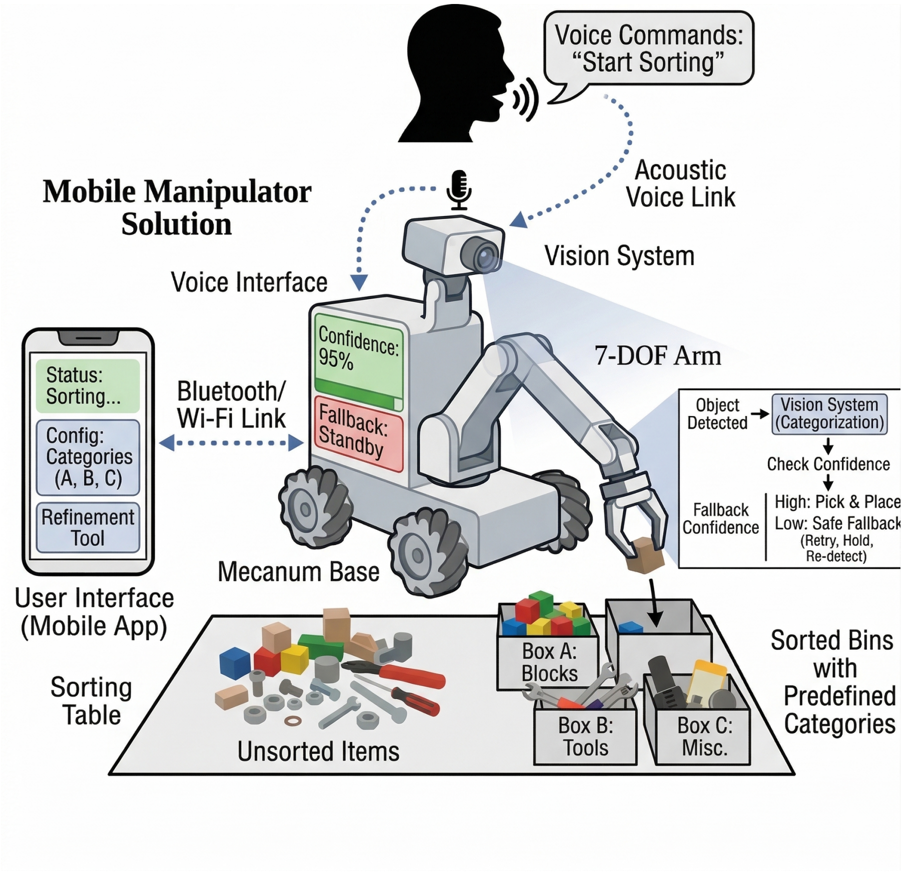

Figure 1: OmniGrasp system concept and end-to-end task flow

(4) Safety interlocks (e-stop, workspace bounds, speed limits) shall remain active in all test modes.

To ensure these goals are testable rather than descriptive, each requirement in Table 1 includes a numerical metric and a repeatable verification method.

Table 1: High-level requirements with validation plan

Req ID	**Requirement**	**Metric**	**Validation Method**
I-1	Category-based sorting correctness	$\geq$ 90% correct placement	5 repeated tabletop trials with mixed object set
I-2	Per-object cycle efficiency	Average $\leq$ 30 s	Timestamp from target lock to successful placement
I-3	Failure-safe behavior	No unsafe motion during retry/abort	Induced low-confidence and failed-grasp test cases
I-4	Protection mechanism availability	E-stop and limits always active	Pre-run checklist and in-run trigger test

2 Design

2.1 Block Diagram

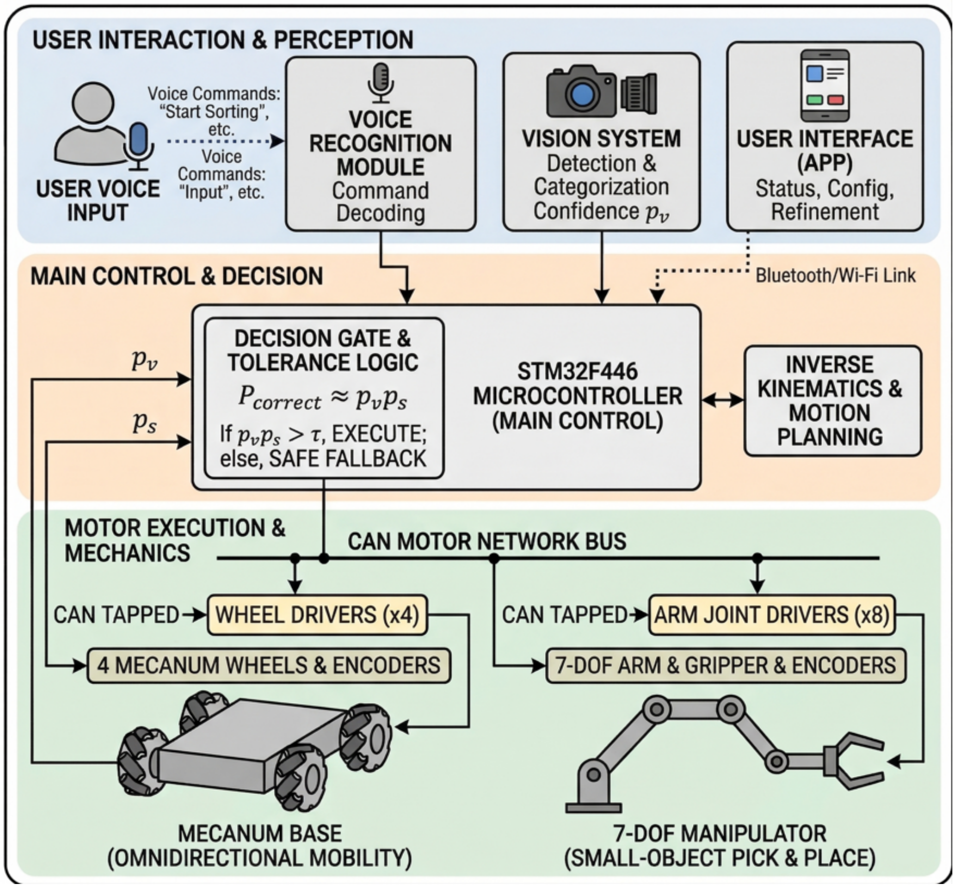

Figure 2: Top-level block diagram of OmniGrasp

The implementation follows a modular architecture: perception outputs target state, planning outputs executable motion intent, embedded control executes bounded commands, and monitoring logic enforces safe fallback transitions. As shown in Figure 2, every subsystem has a single responsibility and a defined interface to reduce integration ambiguity.

2.2 Perception

This module converts RGB frames into stable target states usable by the planner.

2.2.1 Hardware Support

The perception stack uses a fixed-mount RGB camera, an upper-level compute node, and a low-latency communication path to the embedded controller. The camera placement is chosen to cover the primary tabletop workspace while limiting arm self-occlusion. For data-centric improvement, the same hardware interface is mirrored in RoboTwin2.0 simulation so that synthetic trajectories and real logs share a consistent observation/action schema for subsequent supervised fine-tuning (SFT).

2.2.2 Object Detection

The detector outputs class labels, confidence scores, and image-space regions. Current deployment uses category filtering and confidence thresholds to reduce false-positive actuation in cluttered scenes. To improve open-set generalization, the detector is upgraded to a YOLO-World front-end with text-conditioned categories. This allows dynamic vocabulary prompts at inference time and supports long-tail object categories that are not explicitly enumerated in a closed-set classifier.

2.2.3 Target Selection

Candidates are ranked by confidence and grasp feasibility. One target is locked per cycle to avoid mid-action switching. A retry budget prevents repeated failures on one object from blocking total throughput. In the proposed research workflow, target ranking is additionally informed by SFT policy confidence trained from RoboTwin2.0-generated trajectories, and hard failures collected in real deployment are recycled into the next training round.

2.2.4 Pose Estimation

Target pose is estimated from calibrated camera geometry and transformed into planner coordinates. The planner applies conservative offsets before final approach to preserve collision margin. To reduce boundary ambiguity, SAM is used to refine YOLO-World proposals into instance masks before geometric feature extraction. The planner then consumes a unified perception state

$$\mathcal{O}_t = \{(b_i, m_i, s_i, c_i, \mathbf{p}_i)\}_{i=1}^{N_t}, \tag{1}$$

where b_i is a proposal box, m_i is the mask, s_i is confidence, c_i is text-conditioned label, and $\mathbf{p}_i$ is the grasp-relevant pose feature.

2.2.5 Tracking

Temporal smoothing suppresses frame jitter; reacquisition mode is entered when target continuity is lost. If continuity is not recovered within a bounded window, motion is paused and detection restarts. The training strategy behind this tracking module follows a RoboTwin2.0-driven closed loop to improve robustness under clutter, occlusion, and appearance shift:

(1) Generate task episodes in RoboTwin2.0 with randomized scene factors and language/object prompts.

(2) Log multi-modal tuples (I_t, q_t, a_t, y_t) including image, robot state, action, and success/failure labels.

(3) Filter trajectories by safety and execution-quality constraints to remove noisy supervision.

(4) Run SFT on the perception-to-action interface model, then validate on both simulation holdout and real tabletop trials.

(5) Mine hard failures from real deployment and feed them back into the next RoboTwin2.0 generation cycle.

2.2.6 Sim-to-Real Transfer for Real-Robot Deployment

Because the main research risk is transfer degradation from simulation to physical deployment, we explicitly design a staged sim-to-real protocol. Stage A trains on RoboTwin2.0 randomized data; Stage B performs small-scale real-data calibration (camera intrinsics/extrinsics refresh, exposure/white-balance locking, and contact-timing alignment); Stage C runs constrained real-robot adaptation using hard examples collected from failed grasp, missed detection, and unsafe-retry cases.

To reduce domain gap, we use three mechanisms during transfer: (i) visual randomization in simulation (illumination, background texture, clutter level, and object material), (ii) dynamics randomization for friction/contact parameters used by grasp supervision labels, and (iii) feature-level alignment through mixed-batch fine-tuning that combines synthetic and real samples with a fixed real-sample ratio.

Real-robot migration is accepted only when all of the following conditions are met: perception confidence calibration error remains bounded, end-to-end success drop from sim to real is below a preset threshold, and safety-trigger frequency does not increase after adaptation.

From a paper perspective, this yields three publishable claims: (i) open-vocabulary perception improves long-tail object handling, (ii) mask-refined geometry improves grasp stability in clutter, and (iii) simulation-driven SFT narrows the sim-to-real drop when failure mining is enabled.

Table 2 defines the minimum ablation/evaluation set needed for a conference-style empirical section.

Table 3 defines quantitative pass/fail criteria so perception verification can be repeated by another team.

2.3 Manipulation Alignment

This module aligns arm orientation and base position to maximize reachable, collision-safe grasps.

Table 2: Planned experimental protocol for YOLO-World + SAM + RoboTwin2.0 SFT

Study	Compared Settings	Primary Metrics	Expected Insight
E-1	Closed-set detector vs. YOLO-World open-vocabulary detector	Novel-class success rate, mAP@0.5	Semantic generalization gain on unseen objects
E-2	Box-only grasping vs. YOLO-World + SAM mask-guided grasping	Grasp success, collision rate, placement error	Benefit of mask-level geometry for manipulation
E-3	No-SFT vs. RoboTwin2.0 SFT vs. SFT + hard-failure mining	End-to-end task success, recovery rate, cycle time	Data-engine value and sim-to-real transfer effectiveness
E-4	Low-randomization vs. high-randomization data generation	Robustness under lighting/clutter shift	Domain randomization sensitivity and optimal training mix
E-5	Sim-only training vs. mixed synthetic+real adaptation	Sim-to-real success drop, calibration error, safety-trigger rate	Effectiveness of real-robot transfer pipeline

Table 3: Perception requirements and verification

Req ID	Test Setup	Pass Threshold	Verification Procedure
P-1	200-frame mixed tabletop dataset	mAP@0.5 $\geq$ 0.85 for trained categories	Compute detection metrics over 5 repeated runs
P-2	30 pick cycles with clutter	Lock-switch rate $\leq$ 5% (excluding true loss)	Log target ID sequence during each cycle
P-3	Calibration board at sampled poses	Mean position error $\leq$ 12 mm	Compare estimated pose against reference points
P-4	Controlled short occlusion injection	Reacquisition within 2 s in $\geq$ 90% trials	Measure recovery time and retry count
P-5	Sim-to-real deployment set (same task, different scenes)	End-to-end success drop $\leq$ 10 percentage points	Compare success rate between simulation holdout and real-robot trials

2.3.1 End-Effector Orientation

Approach orientation is selected from object geometry and local collision constraints, then mapped to joint-space targets. Candidate orientations are filtered by workspace limits and kinematic singularity risk before execution [4], [5].

2.3.2 Local Base Repositioning

When arm-only reach is insufficient, the mecanum base performs short corrective motions before replanning. Repositioning is intentionally small to preserve perception consistency and avoid unnecessary navigation latency.

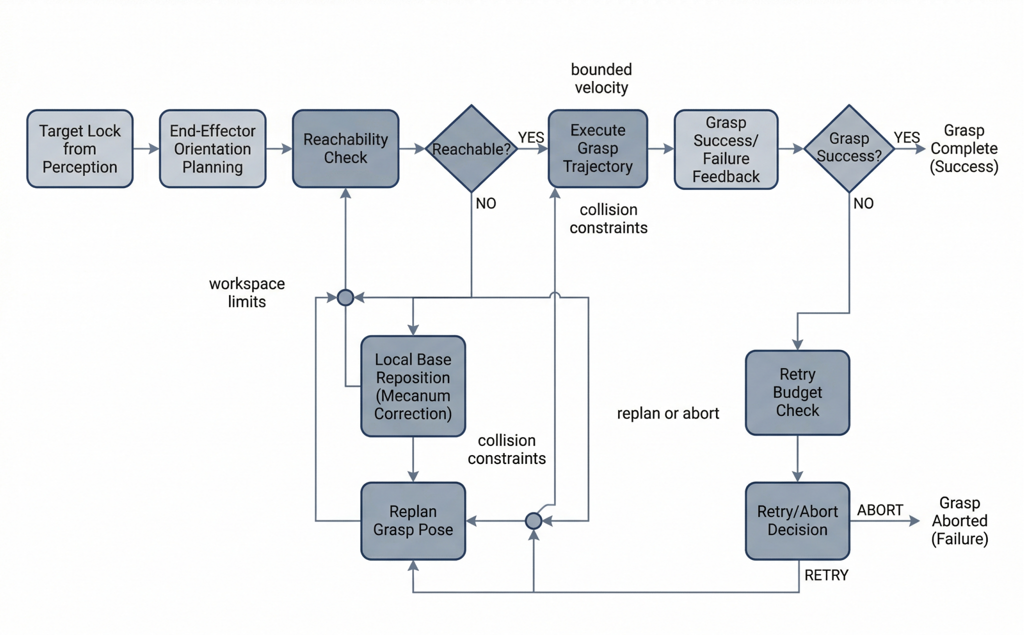

Figure 3: Manipulation alignment control flow

Figure 3 shows the alignment logic used before each grasp attempt.

2.4 Power

Power architecture separates compute/control and actuation domains to improve stability and fault isolation.

2.4.1 Power Domains

Compute and control loads run on regulated low-power rails, while arm/base actuation uses a dedicated high-current rail. This separation prevents motor transients from destabilizing perception and communication modules.

Table 4: Manipulation requirements and verification

Req ID	**Test Setup**	**Pass Threshold**	**Verification Procedure**
M-1	Representative objects and angles	Collision-free plans in $\geq 95\%$ attempts	Validate planner output against collision checks
M-2	Boundary targets	Success gain from base correction ≥ 20 percentage points	Compare success with and without base correction
M-3	30 repeated pick-and-place cycles	Unsafe contact events = 0; retries ≤ 2 per object	Record cycle outcomes and retry count distribution

2.4.2 Protection

Protection strategy includes overcurrent limits, undervoltage detection, and thermal-aware operation constraints. Fault events trigger controlled degradation or safe stop rather than abrupt reset.

Table 5: Power budget and validation conditions

Domain	**Primary Loads**	**Budget (W)**	**Validation Condition**
Compute	Vision and planning node	45	Continuous run under perception workload
Control	MCU and communication interfaces	18	Runtime telemetry and fault monitor active
Actuation	Arm and mecanum motors	280	Peak-load motion profile without brownout

2.5 Control

Control logic bridges high-level planning and low-level actuation while enforcing safety policies.

2.5.1 Motion Controller

The embedded controller executes bounded motor commands, tracks actuator states, and triggers stop behavior on faults. Hard limits on speed and acceleration are enforced independently of high-level requests.

2.5.2 CAN Network

CAN is the primary deterministic bus for synchronized command and telemetry transfer. Prioritized frames are used for safety-critical updates, and timeout/error events are monitored continuously.

2.5.3 UART Channel

UART is retained for bring-up diagnostics, parameter updates, and integration logging. It is isolated from motion-critical pathways to avoid loop jitter.

Table 6: Control requirements and verification

Req ID	**Test Setup**	**Pass Threshold**	**Verification Procedure**
C-1	Timestamped command/feedback stream	95th-percentile loop latency ≤ 50 ms	Compute latency distribution over stress interval
C-2	Inject communication interruption	Safe-stop response time ≤ 150 ms	Measure stop response after injected fault
C-3	Multi-mode runtime logging	Log packet loss $\leq 1\%$ over 20 min run	Validate log schema completeness per mode

2.6 Schematics

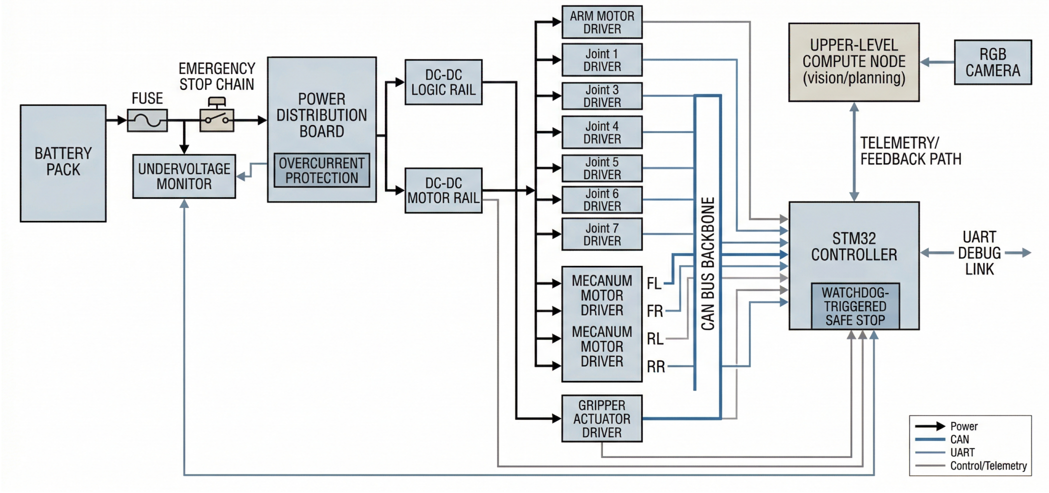

Figure 4: Current wiring and control interface schematic overview

Figure 4 provides the current electrical/control interface schematic used during integration.

2.7 Supporting Matrix

Table 7 traces each high-level requirement to concrete subsystem requirements, satisfying the rubric's requirement-traceability expectation.

Table 7: Requirement traceability supporting matrix

High-Level Req	**Mapped Subsystem Requirements**	**Rationale**
I-1 Sorting accuracy $\geq 90\%$	P-1, P-3, M-1, M-3	Accurate detection and stable grasp are both necessary for correct bin placement
I-2 Cycle time ≤ 30 s	P-2, P-4, C-1, M-2	Fast target lock, reacquisition, and low-latency control reduce per-object time
I-3 Safe retry/abort behavior	P-4, M-3, C-2	Retry logic must remain bounded and transition to safe-stop under failures
I-4 Interlocks always active	C-2, C-3, power protection checks	Safety functions require reliable communication, logging, and protected power

2.8 Tolerance Analysis

For the pose-sensitive operation, placement error is computed as

$$\varepsilon_{\text{place}} = \left\| \mathbf{p}_{\text{actual}} - \mathbf{p}_{\text{target}} \right\|_2 , \tag{2}$$

where $\mathbf{p}_{\text{actual}}$ is measured end placement and $\mathbf{p}_{\text{target}}$ is desired bin location. This equation is used in regression testing to verify tolerance compliance. The acceptance limits listed in Table 8 are derived from bin opening size, grasp repeatability, and closed-loop response constraints.

Table 8: Tolerance analysis with acceptance criteria

Parameter	**Nominal**	**Tolerance**	**Measurement Condition**
Placement error	12 mm	± 5 mm	30 repeated placements on fixed tabletop layout
Perception-to-action latency	180 ms	± 40 ms	200 cycles from image timestamp to first actuator command
Grasp repeatability	88% success rate	± 5%	Mixed-object supervised trials under fixed gripper setup

3 Cost

3.1 Labor Cost Analysis

For each team member, labor is estimated using the required model:

$$\text{Labor Cost} = (\text{hourly salary}) \times 2.5 \times (\text{hours worked}). \tag{3}$$

A conservative labor estimate is set to 25 RMB/hour for each team member.

Table 9: Labor cost estimate by partner

Partner	**Hours**	**Salary (RMB/h)**	**Multiplier**	**Labor Cost (RMB)**	
Yaofang Ji	120	25	2.5	7500	
Shurong Wang	115	25	2.5	7187.5	
Dayu Xia	118	25	2.5	7375	
Tongning Zhang	112	25	2.5	7000	
Total Labor Cost				**29062.5**	

3.2 Parts, Equipment, and Shop Services

Table 10 lists non-standard parts, lab equipment usage, and machine shop services needed for the project, including manufacturer/part identifiers and estimated costs.

3.3 Grand Total

The overall project estimate is:

$$\text{Grand Total} = \text{Total Labor Cost} + \text{Total Parts + Services Cost} = 29062.5 + 991 = 30053.5 \text{ RMB}. \tag{4}$$

This total reflects full engineering labor valuation plus prototype build and shop costs, and follows the required ECE 445 cost-analysis format.

Table 10: Parts and services cost breakdown

Description	**Manufacturer**	**Part # / Service**	**Qty / Hours**	**Cost (RMB)**
Digital servo motors for 7-DOF arm	Feetech	STS3215	7	175
Mecanum wheel set with DC motors	Generic robotics vendor	60 mm mecanum kit	1 set	120
Microcontroller development board	ST	NUCLEO-F446RE	1	85
CAN transceivers and interface boards	Waveshare / TI-based modules	SN65HVD230 modules	2	36
USB RGB camera module	Logitech	C270	1	95
Battery + DC-DC + fuse protection components	Generic power modules	3S pack + buck converters	1 set	110
3D printing filament and consumables	Bambu Lab / equivalent	PLA/PETG consumables	1 set	60
Fasteners, couplers, harness, connectors	Generic hardware vendor	Mixed mechanical/electrical kit	1 set	70
Lab equipment usage (oscilloscope, PSU, soldering station)	ECE 445 Lab	Internal lab usage	1 set	0
Machine shop service (cutting, drilling, finishing)	ECE Machine Shop	Quoted service	4 hours	240
			Total Parts + Services Cost	**991**

4 Schedule

Table 11: Phase-level schedule aligned with course calendar

Phase	Primary Tasks	Target Window	Status Gate
Phase 1 (Completed)	Architecture definition, requirement freeze, subsystem interface mapping	Jan 20 – Feb 16, 2026	Interface review checklist approved
Phase 2 (Completed)	Chassis/arm bring-up, CAN baseline, camera pipeline setup	Feb 17 – Mar 29, 2026	Subsystem bring-up logs stable
Phase 3 (Completed)	Design execution, safety agreement, and first report update cycle	Mar 30 – Apr 5, 2026	Weekly report update submitted
Phase 4 (In Progress)	Design document delivery/revision, teamwork reflection, and weekly report updates	Apr 6 – May 10, 2026	Design document milestones and weekly updates complete
Phase 5 (Planned)	Final report draft integration, validation reruns, and demo script freeze	May 11 – May 17, 2026	Final report draft submitted
Phase 6 (Planned)	Final demo, final presentation, and report closeout package	May 18 – May 29, 2026	Final demo and presentation complete; final report submitted

Figure 5 summarizes the milestone sequence and is used as the baseline during weekly reviews. The dates in Tables 11 and 12 are synchronized to the course calendar milestones (weekly report updates, document checkpoints, final draft, and final demo period).

Schedule Risk and Mitigation

To satisfy schedule realism criteria, each critical path item has a fallback:

- If document deliverables slip before the April 27, 2026 revision checkpoint, non-critical feature text is moved to appendix and core verification results are prioritized.

Table 12: Weekly task allocation by team member (calendar-synchronized)

Week	**Owner**	**Assigned Task**	**Deliverable**
W1 (Apr 6–Apr 12)	Yaofang Ji	Finalize design document package and submit teamwork reflection artifacts	Design document submission + reflection proof
W2 (Apr 13–Apr 19)	Shurong Wang	Grasp retry strategy and cycle-time optimization for weekly checkpoint	Updated planner parameters + weekly report update
W3 (Apr 20–Apr 26)	Dayu Xia	Individual progress review materials and CAN/watchdog stress validation	Progress review package + fault-response dataset
W4 (Apr 27–May 3)	Tongning Zhang	Design document revision and end-to-end benchmark rerun	Revised document + benchmark summary plots
W5 (May 4–May 10)	Team Integration	Reliability regression and weekly checkpoint closeout	Integration checklist + weekly report update
W6 (May 11–May 17)	Team Integration	Final report drafting and evidence consolidation	Final report draft submission
W7 (May 18–May 24)	Team Integration	Final demonstration and presentation rehearsal/execution	Demo completion + presentation materials
W8 (May 25–May 29)	Team Integration	Final report closeout and post-demo archive cleanup	Final report submission + archive package

- If integration metrics are below target before the May 11, 2026 final-draft week, object-class scope is reduced to stabilize repeatability.
- If control fault-response tests fail after May 18, 2026, final demo operation is restricted to low-speed mode with an expanded safety exclusion zone.

A phase is marked complete only when its gate checklist is passed and corresponding test evidence is archived in the team log.

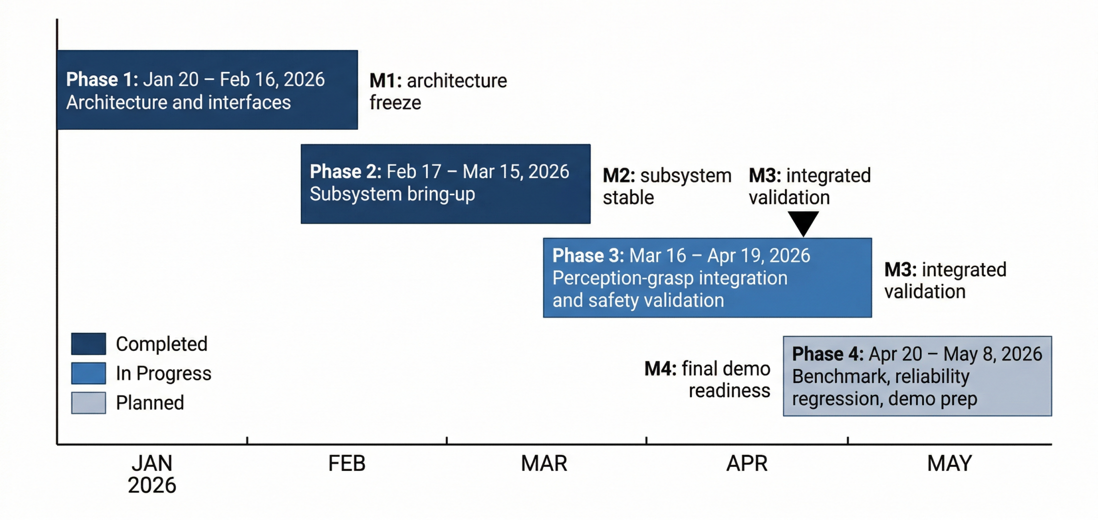

Figure 5: Schedule and milestone overview

5 Ethics and Safety

5.1 Ethics

The project involves vision-based perception and autonomous decision support in a physical workspace. Ethical priorities are transparent capability reporting, privacy-aware data handling, and strict human-supervised operation. Team process is aligned with the IEEE and ACM codes of ethics [6], [7].

The primary ethical conflict is the trade-off between performance data collection and operator privacy. Our policy resolves this conflict by defaulting to non-persistent processing, and only storing short debug clips after explicit team approval and access control logging.

Key commitments include: (1) explicitly reporting uncertainty and known failure modes, (2) retaining human authority for start/stop and override actions, and (3) minimizing retention and access scope of recorded visual data.

5.2 Safety

Primary safety risks include manipulator collision, pinch points, dropped objects, and electrical faults. The control stack enforces layered safeguards: hardware e-stop, software watchdog, workspace limits, and bounded motion profiles. This approach follows risk-reduction principles consistent with robotics and machinery safety standards [8], [9], [10], [11], [12].

Table 13: Safety checklist and execution conditions

Check Item	**Pass Condition**	**Verification Method**
Emergency stop	Immediate actuator disable on trigger	Trigger test before each session
Workspace clearance	No personnel in manipulator hazard zone	Visual confirmation by designated spotter
Power integrity	Battery and wiring in safe operating range	Voltage check + connector inspection
Control health	Telemetry and fault monitor active	Communication and watchdog status check

Table 13 is executed before every integrated run and after any hardware modification.

5.3 Applicable Regulations and Justification

Regulatory references considered for project deployment context include FCC Part 15 (electromagnetic interference constraints), OSHA general-duty safety principles, and Illinois BIPA where biometric data risk may be relevant [13], [14], [15]. These references inform design decisions on shielding, operation procedures, access control, and data minimization.

These regulations are applicable because the prototype combines digital electronics (FCC), workplace physical operation (OSHA), and camera sensing that may capture identifiable individuals in shared lab spaces (BIPA). Therefore, compliance is treated as a design input rather than a post-test checklist.

Safety checklist execution is mandatory before every integrated run; any failed item blocks operation until resolved and logged.

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