ECE 445

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

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

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Team # TBD

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Abstract

OmniGrasp is a mobile manipulation project for supervised indoor *table sorting*. The system combines a custom 7-DOF robotic arm, a mecanum-wheel mobile base, and an STM32F446-based CAN control network to perform reliable tabletop pick-and-place operations. To reduce integration risk and improve engineering interpretability, the software follows a modular perception-to-action pipeline: vision provides object and category cues, voice handles start/stop interaction, and a decision layer gates motion execution before inverse-kinematics and low-level control.

Instead of fixing one object type at the proposal stage, the project defines a general sorting framework and iteratively refines the target object set during the senior design process. Early milestones focus on controlled-scene robustness, while later iterations update object categories according to grasp success, perception confidence, and observed failure modes. This strategy balances generality and deliverability by keeping requirements measurable throughout development.

Target outcomes include at least 90% sorting accuracy across repeated runs, average handling time within 30 seconds per item, and safe fallback behavior when perception confidence is low. Safety is enforced through confidence-based rejection, bounded motion profiles, workspace constraints, and physical/software stop mechanisms. The result is a practical and scalable foundation for future ROS 2/MoveIt integration.

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1 Introduction

1.1 Problem

Tabletop object sorting is a common but repetitive workflow in many indoor service and research settings. Human operators often spend significant time on repeated pick-and-place operations, and performance can drop when object layouts become cluttered or when task volume increases.

Existing consumer robots are usually optimized for navigation or cleaning rather than reliable tabletop manipulation. Industrial sorting systems can achieve high throughput, but they are often costly and oversized for compact indoor environments. Therefore, we target a lightweight and affordable mobile manipulation solution for a constrained but practical task: *table sorting* [1], [2].

1.2 Solution

We define the project task as a supervised tabletop sorting pipeline instead of binding the system to one fixed object type at the proposal stage. The robot receives a simple command (e.g., "start sorting"), detects sortable items on a table, and places them into predefined categories using the mecanum base and 7-DOF arm.

To keep development feasible, the system is implemented with a modular architecture: vision for object/category cues, voice for interaction commands, and motion/control modules for stable pick-and-place execution. A confidence-gating policy is used to reject uncertain decisions and trigger safe fallback actions (hold, re-detect, or retry) before motion.

The specific object set will be iteratively refined during the senior design process. Early milestones focus on robust operation in controlled scenes; later iterations will update object categories based on graspability, perception reliability, and failure analysis. This approach keeps the platform general while ensuring measurable progress toward a stable final demo.

1.3 Visual Aid

Figure 1 illustrates the planned end-to-end workflow for supervised tabletop sorting, from multimodal perception to gated manipulation execution.

1.4 High-level Requirements List

- *Sorting accuracy:* In a controlled tabletop test with predefined categories, the system shall achieve at least 90% correct placement over 5 consecutive runs.
- *Task efficiency:* The average handling time shall be no more than 30 seconds per item, measured from successful detection to completed placement.

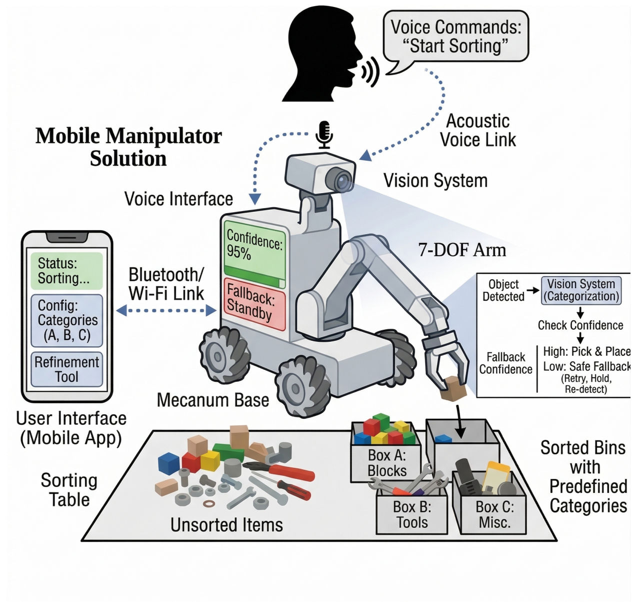

Figure 1: System visual aid for the supervised tabletop sorting workflow

- *Iterative object scope:* The target object set shall be revised across design iterations, and each revision shall be documented with rationale based on perception confidence, grasp success rate, and safety constraints.
- *Safe fallback behavior:* Under low-confidence perception, the robot shall execute a non-destructive fallback action (retry or hold/re-detect) and maintain zero unsafe collisions during demos.

2 Design

2.1 Block Diagram

The control topology follows a perception-to-action pipeline: navigation, voice, and vision modules provide multimodal inputs; a decision module and inverse-kinematics module generate motion targets; and the low-level controller executes motor commands [3].

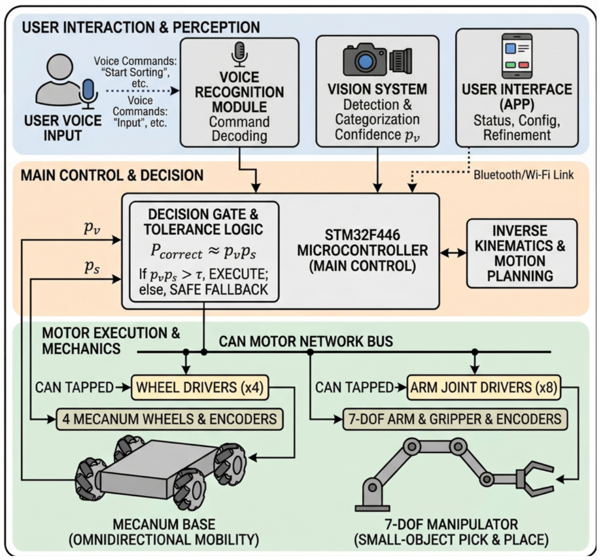

Figure 2: System-level topology from multimodal perception to motor execution

2.2 Subsystem Overview

Mechanical subsystem. The robot uses a carbon-fiber plate body to balance structural stiffness and weight. A mecanum-wheel chassis provides omnidirectional mobility in constrained indoor sorting scenes. A custom 7-DOF arm is mounted on the mobile base, and the gripper performs pickup/place operations for tabletop target objects.

Embedded control subsystem. The current low-level controller is STM32F446. All drive and joint motors are controlled over a unified CAN network, which simplifies wiring and supports deterministic command distribution for multi-axis coordination. The low-level motion stack is operable without an upper computer; however, full multimodal operation (vision and voice interaction) is intended to run with an upper-level compute module during integrated demonstrations.

Perception and interaction subsystem (planned). Instead of an end-to-end VLA pipeline, the project adopts a modular and engineering-oriented approach: (1) a vision module for object/category identification, (2) a voice module for command input (e.g., start sorting, stop, place to target area A/B), (3) a motion module for base navigation and arm manipulation. This decomposition reduces integration risk while preserving practical intelligence for iterative tabletop sorting tasks [1].

2.3 Subsystem Requirements

To support a supervised tabletop-sorting workflow, the following design requirements are defined.

- *Mobility:* The mecanum base shall support forward/backward/lateral translation and in-place rotation for narrow indoor environments.
- *Manipulation:* The 7-DOF arm and gripper shall complete stable grasp and place actions for small-to-medium tabletop objects in the target workspace.
- *Embedded control:* STM32F446 shall generate real-time motor commands and receive feedback through CAN with bounded communication latency.
- *System modularity:* Vision, voice, and motion modules shall use clear interfaces so each module can be developed and validated independently.
- *Future scalability:* The software stack shall remain compatible with ROS 2 Humble + MoveIt for future inverse kinematics and motion planning integration [4].

2.4 Requirement Verification Plan

Each high-level requirement is verified with a repeatable tabletop protocol [3]. Sorting accuracy is evaluated over consecutive multi-item runs in a controlled scene, task efficiency is measured as end-to-end handling time per item, and fallback safety is evaluated by injecting low-confidence perception cases to confirm hold/re-detect behavior without unsafe contact. For each iteration of the object set, the team records grasp success rate, recognition confidence distribution, and failure categories to guide the next design update.

2.5 Tolerance Analysis

A key design risk is decision reliability when vision and voice inputs are fused for sorting actions.

Let the vision module output a target class with confidence p_v, and the voice module output an operation intent with confidence p_s. Under an independence approximation, the probability that both cues are simultaneously correct is

$$P_{\text{correct}} \approx p_v p_s. \tag{1}$$

To avoid unsafe pick-and-place operations, the system enforces a decision gate

$$p_v p_s > \tau, \tag{2}$$

where τ is a task-level confidence threshold [5]. Equations (1) and (2) define the confidence gate used to decide whether motion execution is allowed. If the condition is not satisfied, the robot transitions to a safe fallback state (hold position, request repeat command, or trigger re-detection) instead of executing motion.

This analysis shows a direct trade-off: increasing τ improves decision precision but reduces task throughput due to more re-tries. During integration, τ can be tuned to meet sorting accuracy and cycle-time targets across iterative object-set revisions, providing a practical and testable path to robust multimodal behavior.

3 Ethics and Safety

3.1 Ethical Issues During Development and Use

This project combines a VLA model, a 7-DOF manipulator, and a mecanum base, so ethical risks appear in both development and deployment. During development, key risks are privacy leakage from camera data, overstatement of model capability, and unsafe testing behavior. During use, accidental misuse includes operation in crowded spaces; intentional misuse includes surveillance or unsafe manipulation.

We reduce these risks by limiting deployment to supervised indoor research settings, minimizing retained video data, and clearly documenting operational limits (payload, speed, environment, and prohibited uses).

3.2 IEEE/ACM Code of Ethics Alignment

Our approach follows the IEEE and ACM Codes of Ethics [6], [7]: prioritize public safety, communicate system limits honestly, protect privacy, and evaluate fairness across varied users and environments.

To avoid ethical breaches, we require pre-test safety checklists, peer review before major control changes, and incident logging for failures and near-misses. Any team member can stop testing when unsafe behavior appears.

3.3 Safety and Regulatory Standards

Although this is a course prototype, we align design choices with applicable regulations and standards.

Federal and state considerations include FCC Part 15 for RF devices, OSHA workplace safety expectations, and Illinois BIPA when biometric data may be captured [8], [9], [10].

Industry guidance includes ISO 12100 (risk assessment), ISO 10218 and ANSI/RIA R15.06 (robot safety), plus IEC 60204-1 and UL 1740 (electrical and robotic equipment safety) [11], [12], [13], [14], [15]. Campus work follows UIUC lab safety and training policy [16].

3.4 Project Safety Concerns and Mitigations

Collision/pinch risk: Limit speed and acceleration, enforce workspace boundaries, and require a spotter.

Dropped loads/overload: Enforce payload limits and validate gripper force before tests.

Electrical/battery risk: Use fuses, insulation, strain relief, and safe charging/storage procedures.

Software/control faults: Use watchdogs, timeout-based fail-safe stop, and a physical emergency-stop.

Cybersecurity/privacy risk: Disable unnecessary network services, require authenticated control, post recording notices, and restrict log access.

Before each session, we verify clear workspace, e-stop function, communication health, and payload limits to reduce injury and misuse risk.

References

[1] M. Sereinig, W. Werth, and L.-M. Faller, "A review of the challenges in mobile manipulation: Systems design and robocup challenges," *e & i Elektrotechnik und Informationstechnik*, vol. 137, pp. 297–308, 2020. DOI: 10.1007/s00502-020-00823-8

[2] C. A. Contreras, A. Rastegarpanah, M. Chiou, and R. Stolkin, "A mini-review on mobile manipulators with variable autonomy," *Frontiers in Robotics and AI*, vol. 12, p. 1 540 476, 2025. DOI: 10.3389/frobt.2025.1540476

[3] I. A. Şucan, M. Moll, and L. E. Kavraki, "The open motion planning library," *IEEE Robotics & Automation Magazine*, vol. 19, no. 4, pp. 72–82, 2012. DOI: 10.1109/MRA.2012.2205651

[4] J. Malvido et al., "Extending the motion planning framework — moveit with advanced manipulation functions for industrial applications," *Robotics and Computer-Integrated Manufacturing*, vol. 83, p. 102 559, 2023. DOI: 10.1016/j.rcim.2023.102559

[5] H. Saeidi, J. D. Opfermann, M. Kam, S. Raghunathan, S. Leonard, and A. Krieger, "A confidence-based shared control strategy for the smart tissue autonomous robot (star)," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 1268–1275. DOI: 10.1109/IROS.2018.8594290

[6] IEEE. ""IEEE Code of Ethics"," Accessed: Mar. 24, 2026. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html

[7] Association for Computing Machinery. "ACM Code of Ethics and Professional Conduct," Accessed: Mar. 24, 2026. [Online]. Available: https://www.acm.org/code-of-ethics

[8] U.S. Government Publishing Office. "47 CFR Part 15 — Radio Frequency Devices," Accessed: Mar. 24, 2026. [Online]. Available: https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-15

[9] Occupational Safety and Health Administration. "Occupational Safety and Health Act, Section 5(a)(1)," Accessed: Mar. 24, 2026. [Online]. Available: https://www.osha.gov/laws-regs/oshact/section5-duties

[10] Illinois General Assembly. "Biometric Information Privacy Act (740 ILCS 14)," Accessed: Mar. 24, 2026. [Online]. Available: https://www.ilga.gov/legislation/ilcs/ilcs3.asp?ActID=3004&ChapterID=57

[11] International Organization for Standardization. "ISO 12100:2010 Safety of machinery — General principles for design — Risk assessment and risk reduction," Accessed: Mar. 24, 2026. [Online]. Available: https://www.iso.org/standard/51528.html

[12] International Organization for Standardization. "ISO 10218-1:2011 Robots and robotic devices — Safety requirements for industrial robots — Part 1," Accessed: Mar. 24, 2026. [Online]. Available: https://www.iso.org/standard/51330.html

[13] Robotic Industries Association. "ANSI/RIA R15.06 Industrial Robots and Robot Systems — Safety Requirements," Accessed: Mar. 24, 2026. [Online]. Available: https://www.automate.org/industry-insights/industrial-robot-safety-standard-r15-06

[14] International Electrotechnical Commission. “IEC 60204-1 Safety of machinery — Electrical equipment of machines — Part 1,” Accessed: Mar. 24, 2026. [Online]. Available: https://webstore.iec.ch/en/publication/26037

[15] UL Standards. “UL 1740 Standard for Safety for Robots and Robotic Equipment,” Accessed: Mar. 24, 2026. [Online]. Available: https://www.shopulstandards.com/ProductDetail.aspx?productId=UL1740

[16] University of Illinois Urbana-Champaign, Division of Research Safety. “Laboratory Safety at Illinois,” Accessed: Mar. 24, 2026. [Online]. Available: https://drs.illinois.edu/