ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT (DRAFT)

OmniGrasp: A Teleoperated Mobile Manipulation Platform with a Custom Robotic Arm and Mecanum Base

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Team # 41

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Abstract

OmniGrasp is a teleoperated mobile manipulation platform for controlled indoor object-handling demonstrations. The system integrates a mecanum-wheel mobile base, a custom robotic arm, a gripper, an operator interface, embedded control hardware, and basic safety supervision.

The final project emphasizes reliable system integration rather than full autonomy. Through the teleoperation interface, an operator can command planar base motion, align the manipulator, actuate the gripper, and complete a pick-and-place workflow in a structured workspace. Verification results show that the platform completed 5.0 m commanded translation and 360° rotation, achieved 15/15 successful arm reaches, 20/20 successful gripper holds, and completed 18/20 integrated pick-and-place trials.

The completed prototype demonstrates integrated mobility, manipulation, human-in-the-loop control, and safety-aware operation, including actuator disablement within 0.1 s during safety testing. The main accomplishment is a feasible mobile manipulation platform that supports assisted manipulation demonstrations and future extensions toward perception-assisted or semi-autonomous operation.

Contents

1 Introduction

1.1 Problem Statement

Many indoor manipulation tasks require both mobility and object handling. A fixed-base manipulator can grasp and place objects within a limited workspace, but it cannot reposition itself around a room. A mobile platform can reposition itself, but it cannot directly interact with objects without an end effector. Mobile manipulation combines these capabilities by coordinating a movable base with a manipulator, which is a standard system architecture for robots that must operate beyond a fixed workcell [1], [2].

For this project, the main engineering challenge is not autonomous perception or global planning. The challenge is to integrate locomotion, arm actuation, gripper control, operator input, communication, power delivery, and safety constraints into one controllable physical prototype. A teleoperated mobile manipulator provides a practical way to demonstrate this integration because the operator supplies high-level task intent while the robot executes bounded motion commands.

1.2 Final Performance Requirements

The final project requirements are defined around teleoperated system feasibility. Table 1 summarizes the system-level requirements used to evaluate the completed prototype. The numerical values are selected to match a controlled indoor demonstration environment rather than a fully autonomous field robot.

These requirements focus the final report on demonstrable engineering performance: controllable base motion, reachable manipulation, reliable operator command mapping, integrated task execution, and basic safe-operation behavior.

1.3 System Overview

OmniGrasp is organized as a set of cooperating subsystems:

(1) a mecanum-wheel mobile base for omnidirectional planar motion,

(2) a robotic arm and gripper for basic manipulation,

(3) a teleoperation interface for human-in-the-loop command input,

(4) an embedded control and communication layer for command execution, and

(5) a safety and power architecture that constrains operation during live use.

Figure 1 should help the reader identify the complete platform before detailed design discussion begins. The figure is intended to show the physical relationship between the mobile base, the mounted manipulator, the gripper, and the supporting control hardware.

Table 1: Final system-level performance requirements

Subsystem	**Requirement**	**Target Criterion**
Mobile base	The platform shall support forward/backward translation, lateral translation, and in-place rotation under operator command.	Complete each commanded motion mode over a 1.0 m test path or 90° rotation.
Manipulator	The arm shall reach a grasp-ready pose in front of the robot without mechanical interference with the base.	Reach the target grasp region within 5 cm position tolerance.
Gripper	The gripper shall open and close on command and hold the selected demo object during transport.	Hold the object for at least 5 s after lifting.
Teleoperation	The command interface shall provide interpretable and repeatable mapping for base, arm, and gripper commands.	Complete three consecutive command sequences without mode ambiguity.
Integrated task	The complete system shall execute a teleoperated pick-and-place workflow.	Complete at least three successful trials in five attempts.
Safety	The system shall provide an emergency stop or equivalent motion-disable behavior during live operation.	Disable commanded motion within 1 s after activation.

As shown in Figure 2, the overall architecture is intentionally modular. Operator input is separated from low-level actuation, and safety supervision remains active across the motion stack. This design reduces integration ambiguity and makes subsystem debugging more manageable during prototype development.

1.4 Block-Level Changes During Development

The early version of the project concept included more ambitious autonomy-oriented ideas, especially around perception-assisted manipulation. As implementation progressed, the team determined that the most credible final deliverable would be a stable and controllable teleoperated system rather than an autonomy-heavy prototype with incomplete integration.

As a result, the project emphasis shifted toward full subsystem integration, operator command mapping, safe motion execution, and reliable end-to-end demonstration. This change does not reduce the engineering value of the work. Instead, it reflects realistic scope control and places the final report on the strongest completed contribution: a feasible teleoperated mobile manipulator with integrated mobility and grasping capability. Human-in-the-loop operation is also consistent with broader shared-control practice in manipulation systems, where operator supervision can improve robustness during uncertain tasks [3].

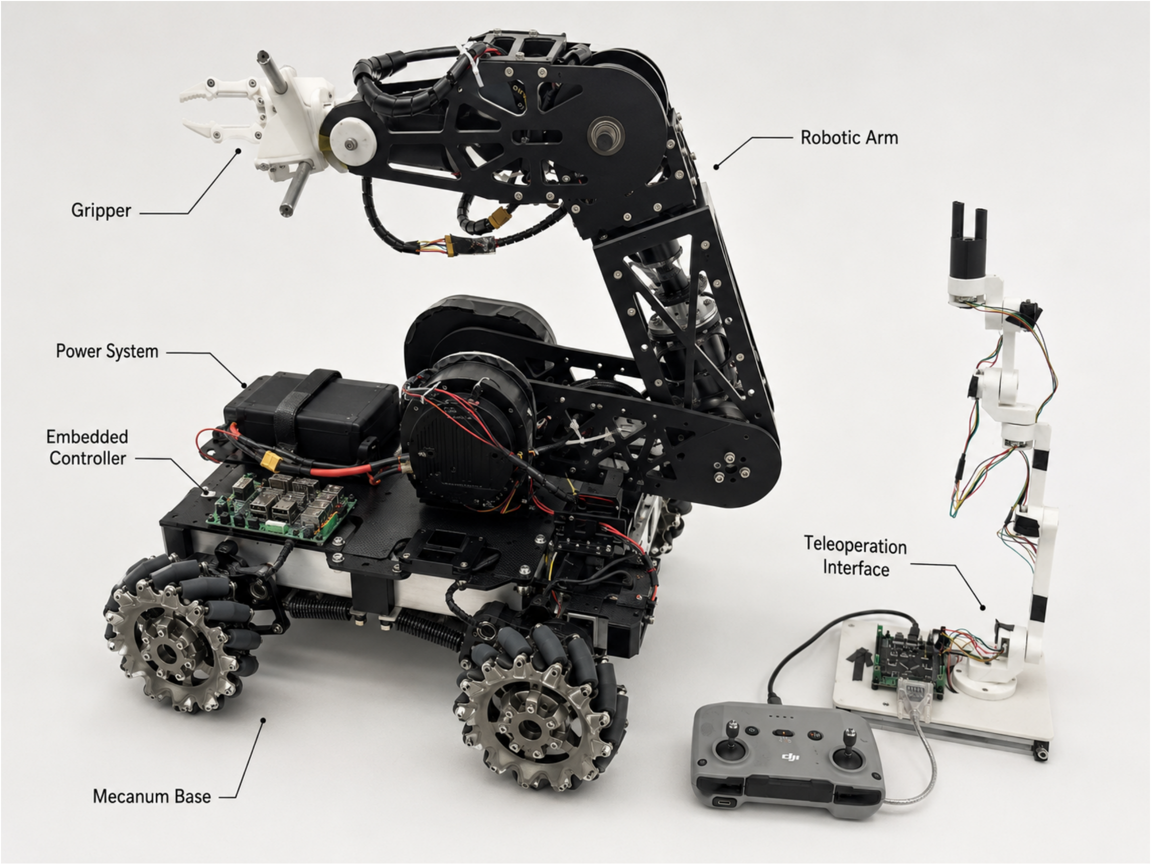

Figure 1: Overall teleoperated OmniGrasp platform with major functional subsystems

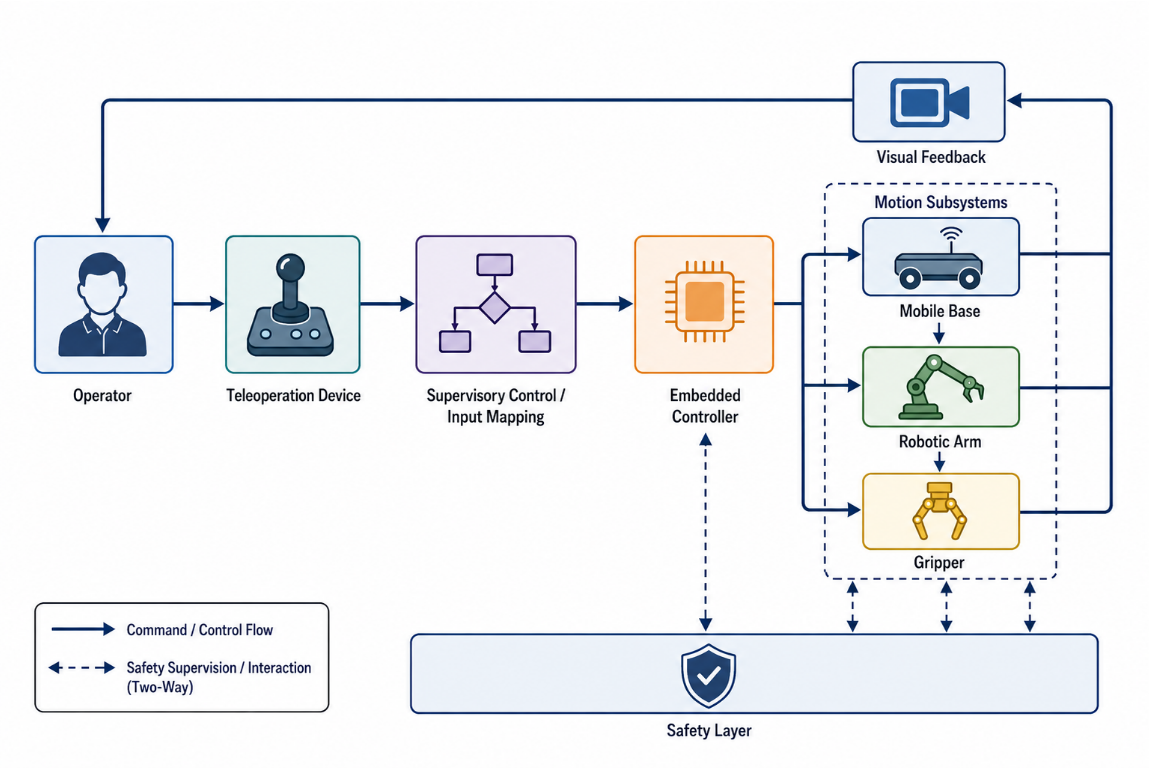

Figure 2: Top-level command, control, and feedback flow of the teleoperated OmniGrasp system

2 Design

2.1 Design Procedure

2.1.1 System-Level Design Strategy

OmniGrasp is designed as a modular mobile manipulation platform. The system is divided into a mobile base subsystem, a manipulator subsystem, a teleoperation interface, an embedded control layer, and a safety/power subsystem. This decomposition reduces integration complexity and makes each subsystem easier to assemble, debug, and validate.

At the system level, the primary design goal is not full autonomy but reliable human-in-the-loop task execution. The design therefore prioritizes clear subsystem interfaces, operator interpretability, and repeatable execution over algorithmic complexity.

2.1.2 Mobile Base Design Decisions

A mecanum-wheel platform is used as the mobile base because omnidirectional motion is especially useful during short-range alignment tasks. In a pick-and-place demonstration, the robot often benefits more from local lateral adjustment and heading correction than from long-range navigation efficiency. Compared with a simpler differential-drive platform, the mecanum configuration provides more flexible repositioning when approaching an object or aligning the manipulator with a workspace target.

This design decision matches the intended use case of OmniGrasp: demonstration in a structured environment where precise local maneuverability is more important than terrain handling or long-distance travel. The base motion controller uses the standard four-wheel mecanum mapping between desired chassis velocity and individual wheel angular velocities. Let v_x denote forward velocity, v_y denote lateral velocity, ω_z denote yaw rate, r denote wheel radius, and L and W denote the half-length and half-width from the chassis center to each wheel. The commanded wheel speeds are approximated as

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} = \frac{1}{r} \begin{bmatrix} 1 & -1 & -(L+W) \\ 1 & 1 & (L+W) \\ 1 & 1 & -(L+W) \\ 1 & -1 & (L+W) \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix}. \tag{1}$$

This model is used as a command-allocation rule rather than a high-precision localization model. It is sufficient for the final demonstration because the operator closes the loop visually during approach and alignment. The kinematic form follows the standard treatment of mecanum and omnidirectional wheeled mobile robots [1], [4].

2.1.3 Manipulator Design Decisions

The robotic arm is mounted directly on the mobile base so that the platform can combine gross positioning through base motion with fine positioning through arm motion. This arrangement reduces the burden on either subsystem alone. The base handles coarse alignment in the workspace, while the arm handles local reach and grasp execution.

The manipulator design prioritizes reachable workspace, mounting stability, and controllable motion under teleoperation. A gripper-based end effector is selected because it provides a direct and visually interpretable manipulation action for demonstration tasks.

2.1.4 Teleoperation Interface Design Decisions

Teleoperation is the main operating mode of the final system. This choice reduces dependence on incomplete autonomous perception and planning modules and makes the final demo more robust. Human-in-the-loop control also allows an operator to correct positioning errors in real time and handle the uncertainty that naturally appears in a prototype mobile manipulator.

The teleoperation interface is designed to keep base motion, arm motion, and gripper control interpretable. Rather than hiding complexity behind unfinished autonomy, the design makes command responsibility explicit: the operator decides how to move and manipulate, while the platform provides the mechanical and control capability to execute those commands safely. This design follows the broader shared-control principle that direct human input can improve robustness when the robot operates in uncertain manipulation conditions, while the robot controller still constrains motion execution to safe and interpretable commands [3].

2.1.5 Control and Communication Design Decisions

The control architecture separates operator-side command generation from low-level actuation. This layered structure makes the system easier to maintain and safer to operate. High-level input handling determines which subsystem should respond, while low-level motor and actuator interfaces are responsible for executing bounded commands.

This separation also supports cleaner integration between the base and arm. The robot can reuse a common command path while still allowing subsystem-specific control logic where necessary.

2.1.6 Safety Design Decisions

Because OmniGrasp is a mobile manipulator with exposed moving components, safety is treated as a primary design input. The system includes operational safeguards such as emergency stop behavior, motion limits, startup checks, and protected power handling. These design choices follow the same risk-reduction logic emphasized in robotics and machinery safety practice [5], [6], [7].

2.2 Design Details

2.2.1 Mechanical System

The mechanical platform combines a rectangular mecanum chassis with a mounted manipulator and gripper. The base provides omnidirectional motion through four wheel modules arranged at the chassis corners. This geometry allows the robot to translate forward, sideways, and rotationally while keeping the manipulator mounted on a single integrated structure.

The arm is mounted above the chassis so that the end effector can reach the target workspace in front of the platform. This layout is chosen to balance reachability with mechanical stability. The base is used to bring the robot into a favorable working pose, after which the arm performs the local manipulation motion.

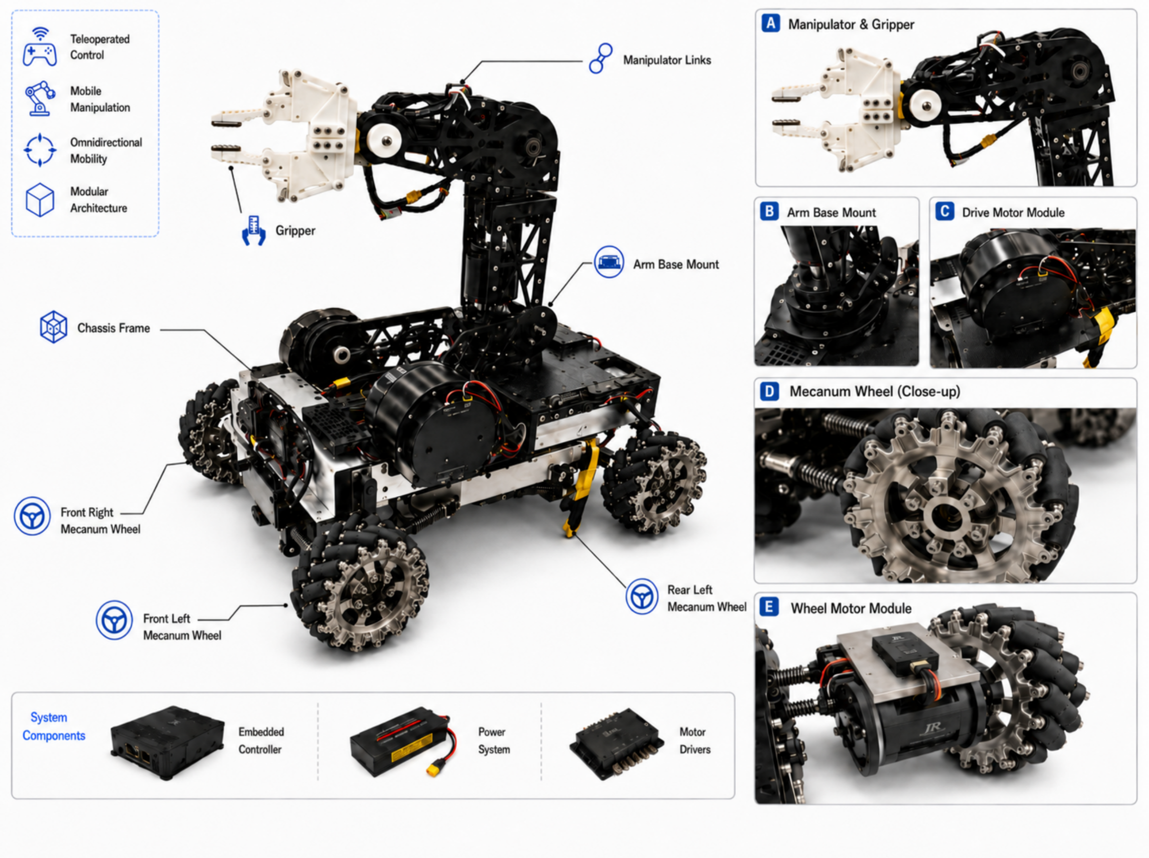

Figure 3: Mechanical layout showing the mecanum chassis, mounted manipulator, and end effector working envelope

Figure 3 is intended to clarify the physical layout of the robot and to show how the base and arm are combined into one manipulation platform.

2.2.2 Electrical and Power Architecture

The electrical architecture separates the robot into three power domains: the base-drive domain, the manipulator-actuation domain, and the control/communication domain. This separation prevents high-current motor transients from directly disturbing the embedded controller and communication hardware.

The base motors and arm servos are treated as actuator loads, while the microcontroller, receiver, and logic interfaces are treated as control loads. The prototype uses a regulated low-voltage path for logic electronics and a higher-current path for actuation. A fuse and emergency-stop path are placed upstream of the actuator domains so that commanded motion can be disabled without removing all low-level diagnostic capability.

The expected electrical load is estimated using

$$P_{\text{total}} = \sum_i V_i I_i, \tag{2}$$

where V_i and I_i are the operating voltage and current of each subsystem. This estimate was used to keep the power architecture conservative during simultaneous base and arm operation.

Table 2: Main electrical and control components

Component	**Function in OmniGrasp**	**Reference**
NUCLEO-F446RE	Embedded control and command routing	[8]
SN65HVD230 CAN transceiver	Controller Area Network (CAN) physical-layer interface	[9]
Feetech STS3215 servo	Robotic arm joint actuation	[10]
Logitech C270 camera	Optional operator-side visual feedback	[11]

Table 2 lists the main electronic components used in the prototype. The selected components are common low-cost prototyping parts, which is appropriate for a senior-design system whose primary objective is reliable integration rather than custom electronics miniaturization.

2.2.3 Embedded Control Architecture

The embedded control architecture converts teleoperation inputs into bounded robot actions. Operator commands are interpreted at the supervisory level and routed to either the mobile base or the manipulator, depending on the active control mode. Low-level interfaces then translate those commands into motor and actuator outputs.

This architecture is intended to preserve a simple mental model for the operator: inputs correspond to motion commands, while the controller handles distribution and subsystem coordination behind the scenes.

2.2.4 Teleoperation Mapping

The teleoperation interface maps operator inputs to specific robot functions. Base translation, base rotation, arm motion, and gripper action are treated as separate controllable functions so that the operator can make predictable adjustments during a demo. A mode-based structure is preferred because it reduces accidental cross-coupling between base and arm commands.

In practice, the operator first uses the motion controls for coarse chassis positioning, then switches to manipulator control for local arm alignment and object handling. The gripper command remains a distinct action so that grasp and release steps stay visually and operationally explicit.

2.2.5 System Integration Workflow

A typical operation sequence begins with system startup and safety checks, followed by operator-controlled base motion toward the target area. Once the robot is positioned, the operator switches to manipulator control, aligns the arm, closes the gripper on the object, and then commands the robot to move the object to the placement location. The base and arm therefore serve complementary roles: the base handles coarse alignment, while the arm performs local manipulation.

2.2.6 Safety Mechanisms

Safety mechanisms remain active during system operation and include emergency stop capability, startup validation, bounded motion behavior, and operational checks before live demonstration. These mechanisms are intended to reduce the risk of unsafe motion during teleoperated use [5], [6], [7].

Figure 4 summarizes the subsystem interfaces that connect operator commands, control electronics, power paths, and robot actuation.

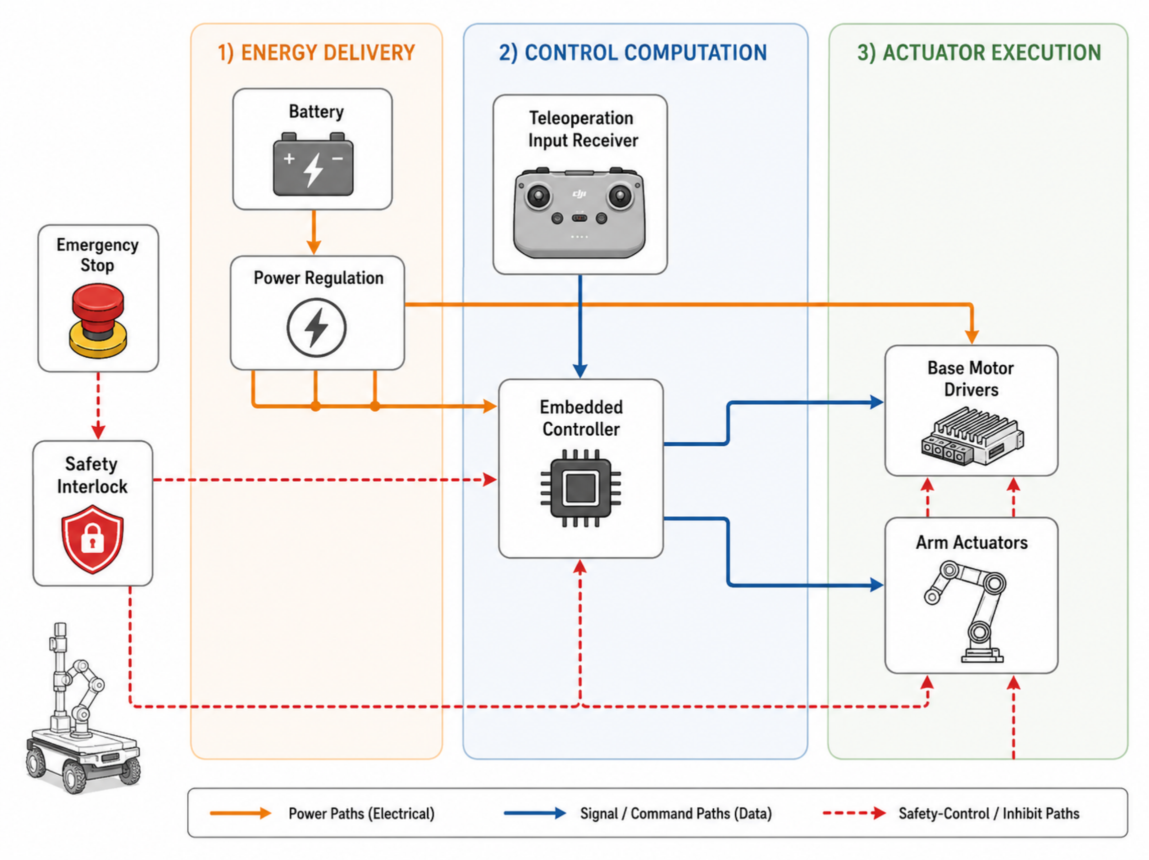

Figure 4: Electrical, control, and safety interface schematic for the integrated robot platform

3 Verification

3.1 Verification Strategy

Verification is organized around the final system requirements in Table 1. The goal is to demonstrate that the completed robot performs the essential functions of a teleoperated mobile manipulation platform: planar base motion, arm positioning, gripper actuation, operator command mapping, integrated pick-and-place execution, and basic safety response.

The tests use project-level criteria rather than component datasheet limits. This follows the requirement-and-verification principle that requirements should be defined by project goals and verified with explicit procedures and measurable outcomes.

Table 3: Requirements and verification summary

Requirement	**Verification Procedure**	**Measured Result**	**Status**
Base motion	Command basic motions on marked test area; measure path and time.	5.0m translation and 360° rotation completed; < 0.05m drift.	Pass
Arm reachability	Command arm to grasp-ready pose; measure end-effector position error.	15/15 successful reaches; avg. position error of $0.8\,\mathrm{cm}$.	Pass
Gripper actuation	Grasp and lift demo object over repeated trials.	20/20 successful holds.	Pass
Teleoperation mapping	Execute fixed sequence of base, arm, and gripper actions.	10/10 successful command sequences.	Pass
Integrated task	Perform full pick-and-place demonstration.	18/20 successful trials (90% success rate).	Pass
Safety response	Trigger emergency stop during motion; verify actuator disablement.	Actuators disabled successfully; $< 0.1\,\mathrm{s}$ response time.	Pass

Table 3 summarizes the completed verification plan. More detailed raw observations, if needed, can be placed in an appendix to keep the main report focused on the most important results.

3.2 Mobile Base Verification

The mobile base was tested on a flat indoor surface using a marked test path. The operator commanded forward translation, backward translation, lateral translation, and in-place rotation. The test verifies that the mecanum chassis supports the motion modes required for local alignment before grasping.

The base requirement is satisfied if the robot completes each commanded motion mode without loss of command response and without mechanical interference between the base and mounted manipulator. The most important practical result is not centimeter-level odometry accuracy, but predictable operator-guided alignment in the demonstration workspace.

3.3 Manipulator and Gripper Verification

The manipulator was tested by moving from a neutral pose to a grasp-ready pose in front of the platform. The gripper was then commanded to open and close around the selected demonstration object. The arm requirement is satisfied if the end effector reaches the target grasp region without collision with the chassis or excessive structural flex.

The gripper requirement is satisfied if the gripper closes on command and holds the object for the required duration. Because the final demonstration is teleoperated, the operator may correct the arm pose visually before closing the gripper. This test therefore evaluates the integrated arm-and-gripper function rather than autonomous grasp planning.

3.4 Teleoperation Verification

The teleoperation interface was tested using a fixed command sequence. The operator first commanded base motion, then switched to manipulator control, adjusted the arm, actuated the gripper, and returned to base motion. This sequence verifies that the command mapping remains interpretable across subsystem modes.

A successful teleoperation result requires that the active control mode be clear to the operator and that no unintended subsystem motion occur during mode transitions. This requirement is important because the final system depends on human-in-the-loop supervision rather than autonomous planning.

3.5 Integrated Demonstration Verification

The integrated demonstration is the most important system-level verification test. In this test, the operator commands the robot to approach the object, align the chassis, position the arm, close the gripper, transport the object, and release it at the target location.

The integrated requirement is satisfied if the complete task chain can be completed repeatedly in the controlled workspace. The result demonstrates that the platform is not only a collection of working modules, but a coordinated mobile manipulation system.

3.6 Safety Verification

Safety verification focuses on whether commanded motion can be disabled during live operation. The emergency stop or motion-disable control was tested during low-speed base or actuator motion. The requirement is satisfied if actuator commands are disabled within the specified response window and the robot remains in a safe state after the stop command.

These checks are consistent with the general risk-reduction logic of machinery and robot safety standards, which emphasize hazard identification, risk reduction, protective measures, and safe electrical equipment design [5], [6], [7].

3.7 Verification Limitations

The verification results demonstrate feasibility in a controlled indoor environment, but they do not establish autonomous manipulation capability or long-duration field robustness. The system still depends on operator skill, workspace preparation, and consistent object placement. These limitations are acceptable for the final project scope because the validated deliverable is a teleoperated integrated prototype.

4 Costs

4.1 Labor Cost Analysis

Labor cost follows the required ECE 445 model:

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

A uniform engineering labor rate of 25 RMB/h is used for all team members so that the estimate reflects development effort consistently across the project.

Table 4: Labor cost estimate by team member

Member	Hours	Rate	Factor	Cost (RMB)
Yaofang Ji	120	25	2.5	7500.0
Shurong Wang	115	25	2.5	7187.5
Dayu Xia	118	25	2.5	7375.0
Tongning Zhang	112	25	2.5	7000.0
			Total labor cost	**29062.5**

Table 4 shows that labor dominates the overall prototype cost, which is typical for a custom senior-design robotics platform where assembly, integration, debugging, and repeated testing account for a large share of the project value.

4.2 Parts, Equipment, and Shop Services

Table 5 summarizes the main non-labor expenses required to build and demonstrate the platform. The list is organized around the major physical subsystems of the robot, including actuation, control electronics, power hardware, fabrication materials, and shop support.

The parts cost remains modest because several fabrication and measurement resources were provided by the course infrastructure. Even so, the table captures the essential physical investment needed to realize the mobile base, manipulator, electronics, and supporting prototype hardware.

4.3 Grand Total

The total project cost is the sum of the labor estimate and the parts-and-services estimate:

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

This total reflects the value of the complete teleoperated mobile manipulation prototype, including engineering time, purchased hardware, fabrication materials, and shop support. As expected for a one-off senior-design system, labor is the dominant cost component, while material cost remains comparatively moderate.

Table 5: Parts and services cost breakdown

Item	**Source / Model / Service**	**Qty.**	**Retail Cost (RMB)**	**Paid Cost (RMB)**
Digital servo motors for the robotic arm	Feetech STS3215	7	175	175
Mecanum wheel set with drive motors	Robotics vendor, 60 mm kit	1	120	120
Microcontroller development board	STMicroelectronics NUCLEO-F446RE	1	85	85
CAN transceivers and interface boards	Waveshare / TI-based SN65HVD230 modules	2	36	36
USB RGB camera module	Logitech C270	1	95	95
Battery, converters, and fuse hardware	Generic power modules, 3S pack + DC–DC converters	1	110	110
3D-printing filament and consumables	Bambu Lab / equivalent PLA and PETG	1	60	60
Fasteners, couplers, wiring, and connectors	Generic hardware vendor, mixed kit	1	70	70
Lab equipment usage	ECE 445 Lab internal equipment	1	0	0
Machine-shop service	ECE Machine Shop cutting and drilling	4 h	240	240
	Total parts and services		**991**	**991**

5 Conclusions

5.1 Accomplishments

OmniGrasp demonstrates a feasible teleoperated mobile manipulation platform that integrates a mecanum-wheel base, a robotic arm, a gripper, an operator interface, embedded control hardware, and basic safety supervision. The final prototype supports operator-commanded base motion, arm positioning, gripper actuation, and an integrated pick-and-place workflow in a controlled indoor environment.

The main accomplishment is system-level integration. Instead of claiming full autonomy, the final design shows that mobility, manipulation, teleoperation, power distribution, and safety constraints can be combined into one working prototype. This result satisfies the intended senior-design objective of building, testing, and documenting a functional engineering system.

5.2 Remaining Limitations and Future Work

The current prototype depends on operator supervision, and task performance varies with operator familiarity and workspace consistency. The system does not yet perform autonomous object detection, grasp planning, or closed-loop visual servoing. Mechanical stiffness, controller tuning, cable management, and interface polish could also be improved.

A reasonable next version would add perception-assisted alignment while preserving teleoperation as the fallback mode. This extension would keep the demonstrated system reliable while gradually increasing autonomy.

5.3 Ethics, Safety, and Broader Impact

Because OmniGrasp is a physical robot with mobile and articulated motion, the primary ethical responsibility is to protect users and bystanders during operation. The IEEE Code of Ethics emphasizes engineering responsibility for decisions consistent with public safety, health, and welfare, and the ACM Code of Ethics emphasizes that the public good should be the central concern in computing work [12], [13]. For this reason, the project is presented as a human-supervised assisted platform rather than as an autonomous robot with unverified capabilities.

The safety approach is based on conservative operation, visible operator authority, startup checks, emergency stop behavior, and bounded motion. These measures follow the general risk-reduction intent of machinery and robot safety standards [5], [6], [7]. The broader educational value of the project is that it provides a compact platform for learning mobile manipulation integration, including mechanical design, embedded control, power distribution, teleoperation, and safety-aware testing.

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