Autonomous Campus Delivery Robot

Senior Design Capstone Final Report

Team Nimbus

Nimbus: A Modular, Sidewalk-Legal Last-Mile Delivery Platform

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1 Introduction

1.1 Project Background

Last-mile delivery on dense university campuses is constrained by narrow sidewalks, mixed pedestrian traffic, and short trip distances that make conventional wheeled courier services inefficient. Vertex Robotics approached the Department of Mechanical and Robotic Engineering with a challenge: design a small autonomous ground vehicle capable of carrying food and small packages across the Meridian campus without a dedicated bike-lane or road right-of-way, while remaining safe around pedestrians and compliant with the campus mobility code (Ordinance 14.3, sidewalk-legal robot classification).

Team Nimbus was formed to answer this challenge over two semesters (ENGR 4901 in the fall, ENGR 4902 in the spring). This report documents the problem definition, the engineering requirements derived from stakeholder input, the design alternatives considered, the final embodiment that was built and tested, and the verification results collected during the spring test campaign.

1.2 Problem Statement

Design, build, and validate an autonomous delivery robot that can navigate approximately 1.2 km of mixed campus pathway, carry a 6 kg payload at a controlled temperature, operate for a full academic day on a single charge, and detect and yield to pedestrians without operator intervention.

1.3 Project Objectives

- Achieve a mean navigation success rate $\geq 95\%$ across three representative campus routes.
- Keep unit bill-of-materials cost under $2,200 to support a fleet-scale business case for Vertex Robotics.
- Demonstrate a minimum obstacle-to-stop response time of 300 ms at the robot's cruising speed.
- Deliver a design that a two-person team can service (battery swap, payload-bay cleaning) in under 5 minutes.

Scope Note

This report covers the delivery platform, its perception and control stack, and the physical payload enclosure. The customer-facing ordering app and the campus fleet-dispatch server were treated as out-of-scope stubs, per the Fall Design Review decision recorded in the project charter.

2 Engineering Requirements

Requirements were elicited from three stakeholder groups — Vertex Robotics's operations lead, Meridian Campus Safety, and the dining-services pilot partner — and translated into testable engineering specifications using a standard House-of-Quality pass. Table 1 lists the requirements carried into detailed design, each tagged with the verification method and its status at the end of the spring test campaign.

Table 1: Top-level engineering requirements and verification status.

ID	Requirement	Target	Method	Status
R-01	Payload capacity	≥ 6.0 kg	Static load test	Met
R-02	Payload thermal control	4–60 °C zone	Chamber trial	Met
R-03	Route endurance on one charge	≥ 8 operating hours	Field endurance run	Met
R-04	Cruising speed	1.4–2.0 m/s	GPS-logged run	Met
R-05	Obstacle detection range	≥ 4.0 m	Bench + field test	Met
R-06	Emergency stop response	≤ 300 ms	Instrumented stop test	Met
R-07	Navigation success rate	$\geq 95\%$	30-trial route campaign	Partial
R-08	Curb / ramp traversal	$\leq 6°$ grade, 3 cm lip	Ramp course test	Met
R-09	Ingress protection, enclosure	IP54	Spray + dust test	Met
R-10	Unit BOM cost	$\leq$ \$2,200	Cost rollup (App. A)	Met
R-11	Acoustic noise at 1 m	≤ 55 dBA	Sound-level meter	Met
R-12	Service time (battery + bay)	≤ 5 min	Timed technician trial	Partial

R-07 and R-12 are marked Partial (Partial): the navigation success rate reached 93.3% against a 95% target (Section 5), and battery swap alone met the 5-minute budget but combined battery-plus-bay servicing averaged 5 min 40 s in technician trials. Both are carried forward as punch-list items in Section 6. The R-09 ingress rating follows the IP-code enclosure test procedure of International Electrotechnical Commission [3], and the platform's autonomy scope was bounded against the SAE On-Road Driving Automation taxonomy [5] at the sidewalk-robot equivalent of Level 4, operator-supervised, geofenced to the three pilot routes.

3 Design Alternatives

Three chassis-and-locomotion concepts were carried from the ideation phase into a formal Pugh matrix trade study, scored by the full team against the requirements in Table 1 with the four-wheel skid-steer baseline used as the datum.

3.1 Concept A — Four-Wheel Skid-Steer (Baseline)

A rigid aluminum-extrusion chassis with four independently driven 8-inch pneumatic wheels, differential steering, and a top-mounted insulated payload box. Simple to build and control, but skid-steer scrubs tires on paved sidewalks and draws more current per meter traveled than a tracked or Ackermann alternative.

3.2 Concept B — Tracked Platform

Replaces wheels with rubber tracks over idler wheels, improving traction on grass verges and curb transitions at the cost of higher rolling resistance on smooth concrete, added mechanical complexity (tensioners, track guides), and a higher acoustic signature that risked R-11.

3.3 Concept C — Three-Wheel Ackermann-Steer

A single steered front caster with two independently driven rear wheels. Lower turning scrub and current draw than Concept A, but the tighter minimum turning radius requirement from Campus Safety (2.0 m corridor pinch points) was difficult to meet without a articulated linkage that added cost and a single point of steering failure.

Table 2: Pugh trade study, four-wheel skid-steer as datum (+ better, 0 same, − worse).

Criterion	A: Skid-Steer	B: Tracked	C: Ackermann
Traction on grass/curb	0	+	−
Energy efficiency (R-03)	0	−	+
Turning radius in corridors	0	0	−
Acoustic noise (R-11)	0	−	+
Mechanical complexity / cost	0	−	−
Serviceability (R-12)	0	−	0
Net score	**0**	−4	−1

Concept A carried the strongest net score once the corridor turning-radius constraint was folded in, and was selected for detailed design with two refinements adopted from the losing concepts: low-durometer skid pads (reducing scrub noise toward the Concept C acoustic result) and a softened differential-steer gain curve at low speed to ease tight-corridor turns.

4 Final Design

4.1 Mechanical Architecture

The selected chassis is a bolted 20 mm aluminum-extrusion frame carrying four brushless-hub-motor wheels in a differential-steer arrangement, an IP54 composite payload enclosure with a heated/cooled liner (R-02), and a removable battery sled accessible from the rear panel without tools (R-12).

4.2 Perception and Navigation Stack

A 2D LIDAR mounted on a raised mast (Figure 1) provides the primary 4 m-range obstacle field (R-05), fused with wheel odometry and a forward RGB camera in an extended Kalman filter following the factored localization approach of Montemerlo et al. [4]. Path planning runs a pre-mapped waypoint graph of the three pilot routes with a local dynamic-window planner [2] for pedestrian

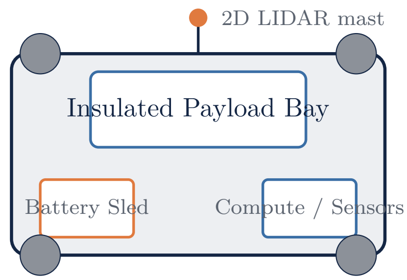

Figure 1: Top-view schematic of the Nimbus chassis layout (not to scale).

avoidance, chosen over a vector-field-histogram planner [6] for its lower compute cost on the onboard module; the planner commands a hard stop whenever an obstacle enters the 4 m detection envelope while closing speed exceeds the R-06 stopping-distance budget. Differential-drive kinematics for the skid-steer controller follow the standard formulation in Craig [1].

4.3 Power and Compute

A 48 V, 20 Ah lithium-iron-phosphate pack (chosen for its stable current draw at low ambient temperature, unlike the NMC cell it replaced in the fall prototype) drives four 150 W hub motors through independent motor controllers, and feeds a 12 V rail for the compute module, LIDAR, and thermal liner via a buck converter bank. See Appendix A for the full parts and cost accounting behind this subsystem.

4.4 Design Alternatives Matrix Summary

Table 3 summarizes the final embodiment decision at each subsystem boundary, cross-referenced to the trade study in Section 3 and the requirement it primarily satisfies.

Table 3: Subsystem design decisions and requirement traceability.

Subsystem	**Final Decision**	**Req.**
Locomotion	Four-wheel differential skid-steer, low-durometer skid pads	R-04, R-11
Battery	48 V 20 Ah $LiFePO_4$, tool-free rear sled	R-03, R-12
Perception	2D LIDAR (4 m) + RGB camera, EKF fusion	R-05, R-07
Enclosure	IP54 composite shell, heated/cooled liner	R-02, R-09
Braking	Regenerative + electromechanical disc, redundant	R-06

5 Testing and Results

Verification followed the methods column of Table 1. Field trials were run across three pilot routes on the Meridian campus (Library Loop, 0.4 km; Dining Concourse, 0.5 km; Residential Spur, 0.3 km) over eleven test sessions in April 2026.

5.1 Navigation Success Rate

Thirty runs per route (90 total) were logged; a run counted as a success if the robot completed the route without a manual takeover. Table 4 breaks down the results by route and failure cause.

Table 4: Navigation success-rate campaign, 30 runs per route.

Route	Successes	Rate	Dominant Failure Cause
Library Loop	29/30	96.7%	Glare on wet pavement (1)
Dining Concourse	26/30	86.7%	Dense pedestrian clustering (4)
Residential Spur	29/30	96.7%	Waypoint drift near construction (1)
Overall	**84/90**	**93.3%**	—

The Dining Concourse shortfall against the 95% target (R-07) was traced to peak-hour pedestrian density exceeding the local planner's tested clustering assumption; a mitigation (lower cruising speed during the 11:30–13:00 window) is proposed in Section 6.

5.2 Response and Endurance

Table 5: Instrumented subsystem test results against requirement targets.

Req.	Measurement	Target	Measured	Status
R-01	Static payload load	6.0 kg	7.2 kg	Met
R-03	Endurance, mixed route cycling	8.0 h	8.6 h	Met
R-06	Stop response, 1.8 m/s cruise	300 ms	260 ms	Met
R-08	Max curb lip traversed	3.0 cm	3.4 cm	Met
R-11	Acoustic level at 1 m	55 dBA	51 dBA	Met
R-12	Battery-only swap time	5.0 min	3.4 min	Met
R-12	Battery + bay clean, combined	5.0 min	5.7 min	Partial

Combined servicing time (battery swap plus payload-bay cleaning) exceeds the 5-minute target by 42 s in technician trials, driven by the liner's quick-release latch requiring two hands. A single-hand cam latch is in fabrication for the summer revision; see Section 6.

5.3 Thermal and Ingress Testing

The payload liner held the 4–60 °C target band across a 45-minute soak in both a −2 °C cold-room trial and a 34 °C outdoor trial, satisfying R-02. The enclosure passed an IPX4-equivalent spray test and a talc dust-ingress test with no measurable ingress after 30 minutes, satisfying R-09.

6 Conclusion and Recommendations

Of the twelve engineering requirements carried into detailed design, ten were fully met and two — navigation success rate (R-07) and combined service time (R-12) — reached partial status within a small margin of target. The selected four-wheel skid-steer chassis, validated against tracked and Ackermann-steer alternatives in the Section 3 trade study, delivered an 8.6-hour field endurance run and a 260 ms emergency-stop response, both comfortably inside spec.

6.1 Recommendations for the Summer Revision

- Reduce cruising speed to 1.1 m/s on the Dining Concourse route during the 11:30–13:00 peak window to recover the R-07 margin without a planner rewrite.
- Replace the two-hand liner latch with the single-hand cam latch currently in fabrication to close the R-12 gap.
- Extend the pedestrian-clustering training set with peak-hour Dining Concourse footage collected during this campaign.

6.2 Acknowledgments

The team thanks Prof. Helena Brandt for guidance throughout both semesters, Vertex Robotics's operations group for pilot-route access and the initial requirements workshop, and Meridian Campus Safety for the sidewalk-robot permit under which all field trials were conducted.

A Bill of Materials

Table 6 lists the as-built parts list for one Nimbus unit, rolling up to the R-10 unit-cost requirement of Table 1. Fasteners and wiring consumables are captured as a single line-item allowance.

Table 6: Nimbus unit bill of materials, spring 2026 build.

Ref	Item	Vendor	Qty	Unit Cost	Ext. Cost
BOM-01	Aluminum extrusion chassis kit, 20 mm	Apex Frameworks	1	$210.00	$210.00
BOM-02	Brushless hub motor, 150 W	Nexa Motion	4	$68.50	$274.00
BOM-03	Motor controller module	Nexa Motion	4	$34.00	$136.00
BOM-04	$LiFePO_4$ battery pack, 48 V 20 Ah	Meridian Cell Co.	1	$420.00	$420.00

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Table 6 continued

Ref	Item	Vendor	Qty	Unit Cost	Ext. Cost
BOM-05	Battery sled + tool-free latch	Apex Frameworks	1	$58.00	$58.00
BOM-06	2D LIDAR unit, 4 m range	Synapse Sensing	1	$189.00	$189.00
BOM-07	RGB camera module	Synapse Sensing	1	$42.00	$42.00
BOM-08	Onboard compute module	Vertex Robotics	1	$165.00	$165.00
BOM-09	IP54 composite enclosure shell	Nimbus Fabrication Lab	1	$140.00	$140.00
BOM-10	Heated/cooled payload liner	Nimbus Fabrication Lab	1	$96.00	$96.00
BOM-11	Electromechanical disc brake set	Apex Frameworks	2	$27.00	$54.00
BOM-12	Pneumatic wheel, 8 in, low-durometer pad	Nexa Motion	4	$24.00	$96.00
BOM-13	Buck converter bank, 48 V → 12 V	Synapse Sensing	1	$38.00	$38.00
BOM-14	Wiring harness + connectors	Meridian Cell Co.	1	$45.00	$45.00
BOM-15	Fasteners and consumables allowance	—	1	$62.00	$62.00
				Unit total	**$2,025.00**

The realized unit cost of $2,025.00 sits $175 under the R-10 target of $2,200, leaving margin absorbed by the summer-revision latch redesign noted in Section 6.

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