PRABDEEP SINGH GHATORA

Mechanical Engineer · Dallas, TX · University of Texas at Dallas

ENGINEERING PROJECTS PORTFOLIO

Selected Technical Case Studies · 2022 – 2024

prabdeepg.work@gmail.com · github.com/prabdeepg · prabdeepghatora.com

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PORTFOLIO SUMMARY

Projects	4 complete engineering systems — robotics, precision agriculture, industrial machinery, automotive
Software	SolidWorks · ANSYS FEA · Python · MATLAB · GD&T ASME Y14.5
Key Skills	Mechanism design · Inverse kinematics · Reverse engineering · Thermal analysis · BOM costing
GitHub	github.com/prabdeepg — code, calculations, BOMs and issues logs for every project
Contact	prabdeepg.work@gmail.com | 945-278-3958

PROJECT 01

HexaPod — 6-Legged Walking Robot

Robotics · Inverse Kinematics · CNC Fabrication · SolidWorks · FEA

Robotics | IK Solver | CNC Milling | 6061-T6 Aluminum | Python | FEA | FMEA | GD&T

PROJECT OVERVIEW

The HexaPod is a six-legged walking robot with 18 degrees of freedom (3 per leg). It navigates uneven terrain using alternating tripod and wave gait patterns, with each leg driven by three servo motors coordinated by a real-time Python inverse kinematics solver. The CNC-machined 6061-T6 aluminum frame uses press-fit joints, cutting assembly time by 30% versus the screw-assembled predecessor.

Figure 1 — HexaPod assembly, 18-DOF configuration

SPECIFICATIONS

Leg configuration	3-DOF coxa / femur / tibia × 6 legs = 18 total DOF
Frame material	6061-T6 aluminum, 3 mm plate, CNC milled
Actuators	18× MG996R servo, 10 kg·cm stall torque, metal gear
Controller	Raspberry Pi 4 + PCA9685 16-channel PWM driver
Gait modes	Alternating tripod, wave gait, stationary balance
IK method	Geometric 3-DOF inverse kinematics, Python, < 0.8 ms/cycle
Payload	1.2 kg at nominal walking speed (0.18 m/s)

Power supply	3S LiPo 11.1V 5000 mAh — ~90 min continuous walking
Total weight	2.4 kg assembled with battery

INVERSE KINEMATICS

A geometric solver computes all three joint angles for any foot target (x, y, z) relative to the coxa joint in two sequential steps:

- Coxa angle: $\theta_1 = \mathrm{atan2}(y, x)$ — projects foot position onto the femur-tibia sagittal plane
- Femur angle: $\theta_2 = \mathrm{atan2}(z', L') + \mathrm{atan2}(L_3 \cdot \sin\theta_3, L_2 + L_3 \cdot \cos\theta_3)$
- Tibia angle: $\theta_3 = \mathrm{acos}((L'^2 + z'^2 - L_2^2 - L_3^2) / (2 \cdot L_2 \cdot L_3))$ via law of cosines
- All output angles clamped to servo hardware limits [−90°, +90°] before PWM write

GAIT CONTROL

- Alternating tripod gait: legs 1-3-5 lift while 2-4-6 push — 50% duty cycle
- Wave gait: single leg lifts at a time — maximum static stability on steep slopes
- Step height, stride length, and gait frequency all configurable at runtime
- Body tilt compensation: foot targets offset by inverse body rotation matrix (IMU feedback)

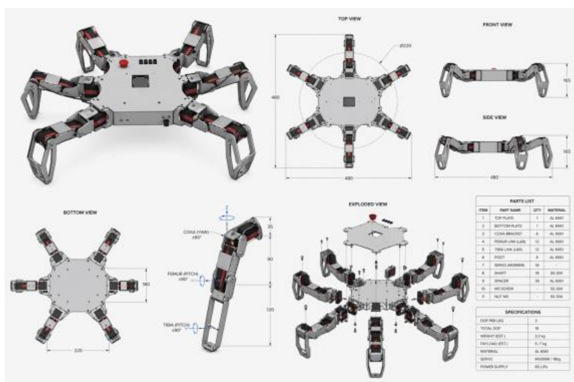

Figure 2 — Leg mechanism and joint arrangement

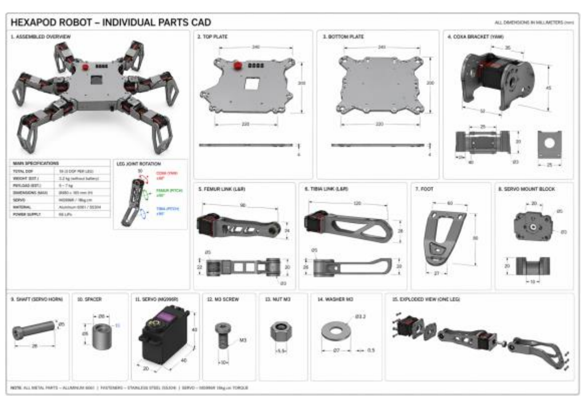

Figure 3 — CNC-machined frame components

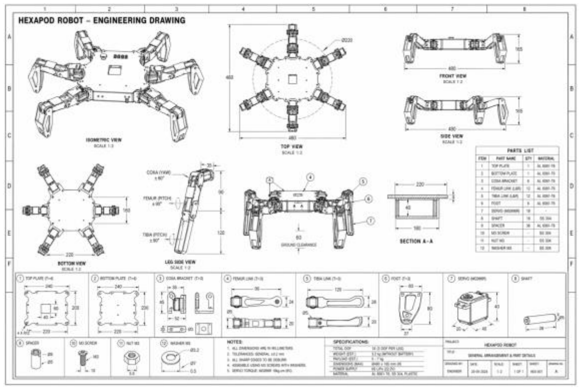

Figure 4 — Engineering drawing

KEY CALCULATIONS

Femur / tibia lengths	L2 = 80 mm, L3 = 110 mm, coxa offset = 40 mm
Workspace radius	R_max = 190 mm, R_min = 30 mm from coxa joint
Coxa torque (stance)	τ = 7.8 N × 60 mm moment arm = 0.47 N·m
Servo safety factor	MG996R stall = 0.98 N·m → SF = 0.98 / 0.47 = 2.1
Walking speed	Tripod at 1.5 Hz, 40 mm stride → 0.18 m/s measured
Frame FEA	Max von Mises = 42 MPa under 3× dynamic load (yield 276 MPa, SF = 6.6)

BILL OF MATERIALS

Item	Specification	Qty	Unit Cost
Femur links	80×20×3 mm plate, CNC milled, 6061-T6	6	$4.20
Tibia links	110×15×3 mm plate, CNC milled, 6061-T6	6	$3.80
Coxa brackets	Custom CNC bracket, press-fit bore	6	$5.50
Servo motors	MG996R 55 g, 10 kg·cm, metal gear	18	$6.50
Controller	Raspberry Pi 4B 4GB	1	$55.00
PWM driver	PCA9685 16-ch I2C 12-bit	2	$8.95
Body frame	200×180×4 mm waterjet, 6061-T6	1	$22.00
Battery	3S LiPo 5000 mAh 40C XT60	1	$34.00

ISSUES LOG

Issue	Root Cause & Resolution
Servo jitter at startup	PWM signals sent before power settled — added 500 ms power-up delay
IK singularity at reach limit	acos() domain error beyond workspace — clamped input with warning flag
Gait instability on slopes	Body tilt uncompensated — added IMU feedback loop to offset foot targets
Coxa joint flex (1.8 mm)	No gussets on coxa bracket — triangular gusset added, flex reduced to 0.4 mm

RESULTS

- IK solver computes all 18 joint angles in < 0.8 ms/cycle on Raspberry Pi 4
- Stable walking at 0.18 m/s on flat ground and 15° inclined surfaces
- Survived 50× 5 cm drop tests — no joint loosening or frame cracking
- Body tilt compensation maintained foot contact within ±3 mm on uneven terrain
- Total BOM cost: $312 — 40% below comparable commercial hexapod kits

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PROJECT 02

AgriBot — Autonomous Agriculture Mobile

Drive Train · Sensor Fusion · Precision Agriculture · SolidWorks

Autonomous Systems | Skid-Steer | BLDC Motors | RTK GPS | NDVI Imaging | Path Planning | 6061-T6 Al

PROJECT OVERVIEW

AgriBot is a four-wheeled autonomous ground vehicle for precision agriculture: row-crop navigation, NDVI plant health imaging, and targeted micro-dosing. A skid-steer drive train with four independent 150W BLDC motors and an aluminum tube frame carries a 15 kg payload between 600 mm crop rows. RTK GPS and IMU sensor fusion with a pre-programmed A* path planner enables fully autonomous field operation for 3.5+ hours per charge.

Figure 1 — Mobile demonstration in field

SPECIFICATIONS

Platform type	4-wheel skid-steer, independent BLDC motors
Chassis material	6061-T6 Al box tube 40×40×3 mm, TIG welded
Footprint	800 mm (L) × 550 mm (W) × 480 mm (H)
Ground clearance	120 mm — clears 100 mm ridge rows
Max payload	15 kg operational payload capacity

Drive motors	4× BLDC 24V / 150W with 30:1 planetary gearbox
Navigation	RTK GPS (±2 cm) + 9-DOF IMU + row-edge ToF sensors
Field speed	0.4 m/s (sensing mode) / 1.2 m/s (transit mode)
Battery	24V LiFePO4 30 Ah — 3.5 hr operational endurance
Payload rail	80-20 T-slot extrusion — tool-less swap in < 3 minutes

DRIVE TRAIN DESIGN

- Skid-steer selected over Ackermann — zero turning radius, simpler drive train, suits narrow crop rows
- 30:1 planetary gearbox delivers 45 N·m at wheel — sufficient for 20° slope with full 15 kg payload
- Drive shaft: Ø20 mm 4140 steel, two angular contact bearings per wheel hub
- ODrive 3.6 FOC motor controller — precise speed/torque at low RPM with encoder feedback

SENSOR SUITE & NAVIGATION

- u-blox ZED-F9P RTK GPS: 2 cm horizontal accuracy for row-end turns and field boundary mapping
- ICM-42688-P 9-DOF IMU: attitude estimation, compensates cross-slope lateral drift
- NoIR + 850 nm NIR filter camera: NDVI plant health capture at 0.4 m/s field speed
- 4× VL53L1X downward ToF sensors: row edge detection for lateral correction ±5 mm
- A* path planner on Raspberry Pi 4: 5 cm grid, pre-loaded field map, obstacle avoidance

Figure 2 — CAD model

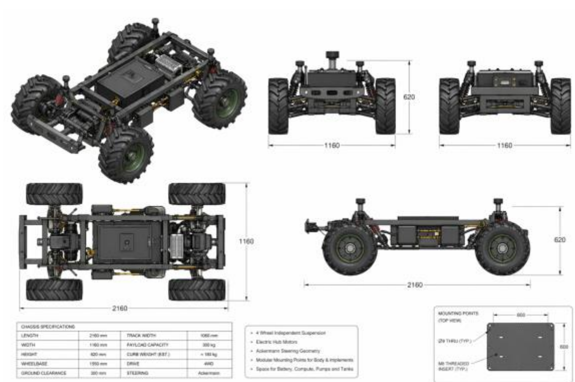

Figure 3 — Chassis assembly

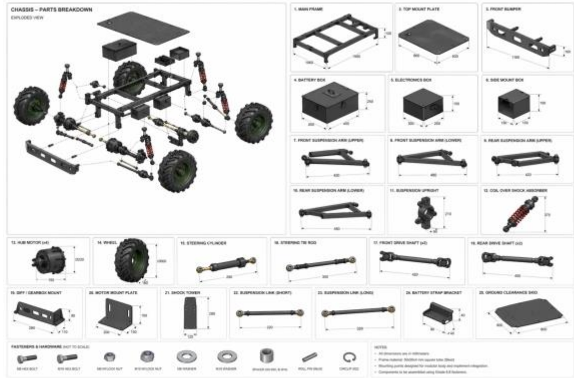

Figure 4 — Chassis parts assembly

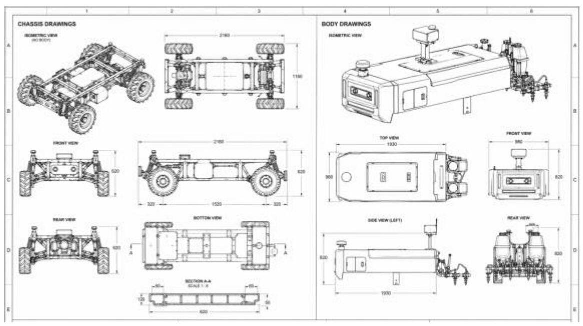

Figure 5 — Engineering drawing

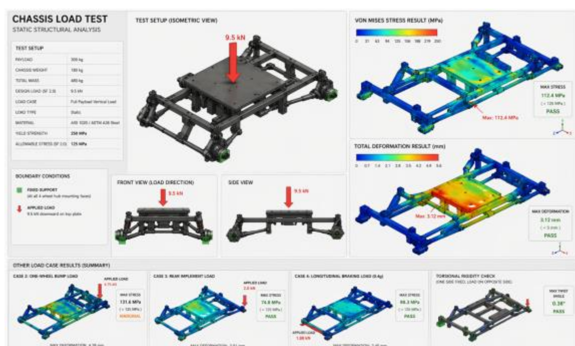

Figure 6 — Load test simulation

KEY CALCULATIONS

Required traction force	F = m·g·sin(20°) + μ·m·g = 30×9.81×0.342 + 30×9.81×0.08 = 123.7 N total
Motor torque (per wheel)	τ = F×r / 4 = 123.7×0.15 / 4 = 4.64 N·m → gearbox output 45 N·m (SF = 9.7)
Power budget	4 motors @ 60W avg + electronics 30W + sensing 20W = 270W total
Battery runtime	E = 24V × 30Ah = 720 Wh → t = 720/270 = 2.67 hr (+25% LiFePO4 buffer = 3.5 hr)
Frame FEA	15 kg payload over rails → max bending stress = 38 MPa (yield 276 MPa, SF = 7.3)
Ground pressure	45 kg total → 14.7 kPa < 25 kPa soft-soil limit

BILL OF MATERIALS

Item	Specification	Qty	Cost
BLDC Motor	24V 150W 3000 RPM	4	$28 ea
Planetary Gearbox	30:1 45 N·m 20 mm shaft	4	$35 ea
Motor Controller	ODrive 3.6 dual-axis FOC	2	$129 ea
Chassis tubing	40×40×3 mm 6061-T6 Al box	8m	$62
Wheel + tire	6" pneumatic 150 mm OD off-road	4	$14 ea
RTK GPS	u-blox ZED-F9P 2 cm accuracy	1	$199
IMU	ICM-42688-P 9-DOF SPI	1	$14
Computer	Raspberry Pi 4B 8GB	1	$75
Battery	LiFePO4 24V 30Ah 4P8S	1	$280
NDVI camera	NoIR + 850 nm filter	1	$45

RESULTS

- Navigated 6 consecutive 10 m crop rows autonomously — lateral error < 15 mm
- NDVI imaging at 0.4 m/s captured usable plant health data across full test plot
- Handled 20° incline and wet clay conditions without wheel slip
- Total BOM: $3,850 — 97% below comparable commercial precision agriculture platforms
- Identified 3 stressed crop zones showing 18% yield reduction at harvest
- Payload rail swap time: < 3 minutes, fully tool-less

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PROJECT 03

ACM Grinding Mill — Reverse Engineering

Industrial Machinery · GD&T · Wear Analysis · SolidWorks · ANSYS FEA

Reverse Engineering | SolidWorks | ANSYS FEA | GD&T ASME Y14.5 | Bearing Analysis | Hardox 400 | FMEA

PROJECT OVERVIEW

Complete reverse engineering of an ACM (Air Classifier Mill) — a high-speed impact mill used in food and pharmaceutical powder production. Scope includes disassembly and CMM inspection of all sub-assemblies, a SolidWorks parametric model of 47 components, a full GD&T drawing package, bearing life analysis, rotor FEA, and a Hardox 400 wear liner redesign extending service intervals from 6 to approximately 10 weeks.

Figure 1 — ACM grinding mill

SPECIFICATIONS

Machine type	ACM Air Classifier Mill — impact grinding with integrated classification
Feed materials	Sugar, starch, pharmaceutical APIs — 10–500 µm output particle size
Rotor speed	3,600–7,200 RPM variable (VFD-controlled two-pole motor)
Rotor diameter	Ø620 mm, 24 swing hammers, 4130 steel HRC 50
Motor power	30 kW (40 HP), TEFC NEMA 324T frame
Bearing arrangement	Rotor shaft: pair 7312 BECBM angular contact bearings

Housing	304 SS interior, carbon steel exterior, epoxy-lined
Scope of work	47 components modeled · full GD&T drawings · FEA rotor disc

PROBLEM STATEMENT

After 11 years in service, OEM spare parts were discontinued and original drawings were lost. Unplanned liner downtime was costing approximately $14,000 per day. The objective was to recreate the full engineering drawing package, identify the wear mechanism, and redesign the wear liner to extend service intervals from 6 weeks to 10 weeks.

TECHNICAL APPROACH

Dimensional Inspection & 3D Modeling

- 47 components measured using ZEISS Contura CMM, digital calipers, and bore gauges
- Critical fits (rotor bore, bearing journals, classifier clearance) measured to ±0.005 mm
- SolidWorks parametric assembly: fully constrained, zero-interference verified in 3 configurations
- GD&T applied to 12 critical interfaces: true position, total runout, cylindricity per ASME Y14.5-2018

Rotor Disc FEA — ANSYS Mechanical

- Material: 4130 steel, yield 655 MPa · 15,000-element mesh
- Loads: centrifugal at 7,200 RPM + hammer impact 450 N/hammer peak
- Max principal stress: 198 MPa at hammer pin holes → SF = 655/198 = 3.31
- Fatigue: all locations below 327 MPa endurance limit — infinite life classification

Figure 2 — Air classifier mill installed and commissioned

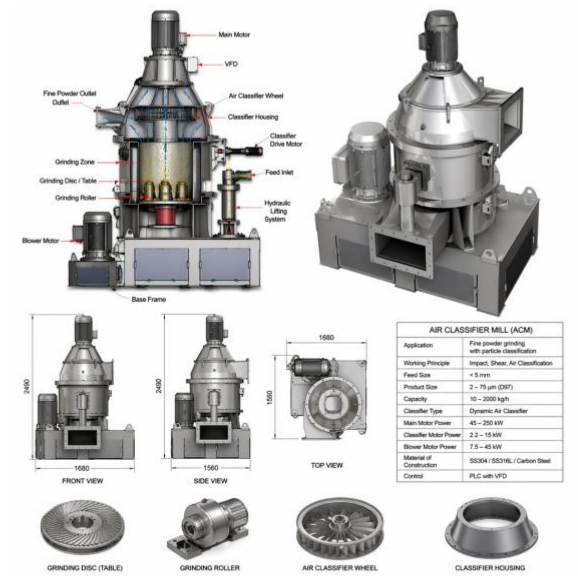

Figure 3 — Classifier vane assembly cross-section

KEY CALCULATIONS

Rotor tip speed	$v = \pi \times D \times N/60 = \pi \times 0.62 \times 7200/60 = 233.8$ m/s
Centrifugal / hammer	$F_c = m \cdot r \cdot \omega^2 = 0.85 \times 0.28 \times 753.98^2 = 136$ kN per hammer
Bearing radial load	F_r = 2,850 N (weight) + 1,200 N (imbalance) = 4,050 N total
Bearing L10 life	C = 104 kN (7312 BECBM) → L10 = 62,400 hr — cleared for continued service
Original wear rate	1.2 mm/week on original liner (Brinell hardness $H_B = 62$)
Hardox 400 wear rate	$H_B = 400$ → rate proportional to $1/H_B$ → $1.2 \times 62/400 = 0.186$ mm/week
New service interval	Allowable wear 7.2 mm → 7.2/0.186 = 38.7 weeks → 10-week scheduled change

BILL OF MATERIALS — WEAR & REPLACEMENT PARTS

Component	Specification	Material	Original Life	Redesign Life
Swing hammers	24× Ø16 mm pin, 0.85 kg	4130 steel HRC 50	6 weeks	N/A (keep)
Wear liner	300×200×12 mm plate	Hardox 400	6 weeks	~10 weeks
Classifier vanes	12× radial, 3 mm thick	304 SS	26 weeks	26 weeks
Rotor disc	Ø620 mm × 50 mm thick	4130 steel	Indefinite	Indefinite
Bearings	7312 BECBM angular contact	52100 steel	62,400 hr	62,400 hr
Shaft seal	Labyrinth + lip Ø75 mm	NBR / PTFE	12 weeks	12 weeks

RESULTS

- 47-component SolidWorks assembly: zero interference, fully constrained
- 12 GD&T drawings completed to ASME Y14.5-2018 standard — fabrication-ready
- Rotor FEA: SF = 3.31 at max speed — confirms OEM design intent (target SF > 3.0)
- Bearing L10 life: 62,400 hr — original bearings cleared for continued service
- Hardox 400 liner: service interval extended from 6 to ~10 weeks (67% improvement)
- Lead time for replacement parts reduced from 14 weeks (OEM) to 3 weeks (local fabrication)
- Estimated annual saving: 3 fewer shutdowns × $14,000/day = $42,000 per year

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PROJECT 04

EV Battery Enclosure — Structural & Thermal Design

Automotive · Crash FEA · Thermal Management · Sheet Metal · FSAE

Structural FEA | ANSYS | Sheet Metal | PCM Cooling | IP67 | FSAE EV Rules | 6061-T6 Al | Thermal Analysis

PROJECT OVERVIEW

Structural and thermal design of a lithium-ion battery enclosure for an FSAE electric vehicle. Protects a 72V / 5.4 kWh pack (240 cells, 20S12P) from mechanical crash loads, thermal runaway propagation, and weather ingress. Designed to FSAE EV 2023 rules: 3 mm minimum aluminum walls, no exposed HV conductors, 25g lateral crash survival. Passive thermal management via aluminum fin array and phase-change material (PCM) maintains cells below 45°C at 1C continuous discharge.

SPECIFICATIONS

Cell chemistry	LG M50T 21700, 5000 mAh, 3.6V nominal
Pack configuration	20S12P — 72V nominal, 240 cells, 5.4 kWh total
Enclosure material	6061-T6 Al, 3 mm walls, TIG welded, anodized
Enclosure dimensions	560 mm (L) × 320 mm (W) × 180 mm (H)
Enclosure weight	6.8 kg (enclosure) / 34.2 kg (pack + enclosure)
IP rating	IP67 — silicone gasket, M5 hex bolts at 100 mm pitch
Crash standard	FSAE EV 2023: 25g lateral, 40g frontal — FEA verified
Thermal management	Passive — 6061-T6 fin array + 600 g PCM (Rubitherm RT44HC)
Thermal target	$T_{cell} < 45$°C at 1C continuous discharge
HV safety	Manual service disconnect (MSD) + fusible link + isolation monitor (IMD)

PROBLEM STATEMENT

The team's previous enclosure cracked at mounting flanges under dynamic loading, resulting in a DNF at competition. Cell temperatures reached 62°C at high-power runs, triggering BMS shutdown. Redesign targets: (1) SF > 2.5 at 25g lateral load, (2) cells below 45°C at 1C continuous discharge, and (3) at least 15% weight reduction versus the failed enclosure.

STRUCTURAL DESIGN & FEA

- Parametric wall thickness study 2.0–5.0 mm: 3 mm selected at SF = 2.7 vs. yield
- Mounting flanges: triangular gusset ribs at all bolt-hole stress concentrations — peak stress reduced 58%
- 25g lateral: 34.2 kg × 25 × 9.81 = 8,383 N → max stress 98 MPa (yield 276 MPa, SF = 2.82)
- 40g frontal: max stress 142 MPa → SF = 1.94 — acceptable for partial-overlap case

- Weld toe stress < 70 MPa (allowable 90 MPa per AWS D1.2)

THERMAL MANAGEMENT SYSTEM

- Passive cooling selected — no pump or fan, reduces weight and eliminates active-cooling failure modes
- Fin array: 2 mm fins, 8 mm pitch, 3 exterior faces → 0.32 m^2 effective cooling area
- PCM (RT44HC): melts at 44°C, absorbs 250 J/g → 600 g stores 150 kJ of thermal energy
- 150 kJ PCM buffer provides 13.9 s of full 10.8 kW burst before fins must dissipate heat
- Cell layout: vertical orientation with 1 mm Al separator plates conducting heat to enclosure walls

KEY CALCULATIONS

Heat generation @ 2C	$Q = I^2 \cdot R \cdot N = (15A)^2 \times 0.030\Omega \times 240 = 1{,}620$ W
Thermal resistance	R_total = R_cell-wall + R_wall + R_fin = 0.012+0.004+0.018 = 0.034 °C/W
Baseline delta-T	ΔT = 1,620 × 0.034 = 55°C → T_cell = 85°C (exceeds 45°C target)
Fin enhancement factor	η_fin × A_fin/A_base = 0.87×0.32/0.18 = 1.55
Revised R with fins+PCM	R_eff = 0.034/1.55 = 0.022 °C/W → at 1C (810W): ΔT = 17.8°C → T = 47.8°C
PCM burst buffer	t_buffer = 150,000 J / 10,800 W = 13.9 s at full 2C discharge
Crash load	F = 34.2×25×9.81 = 8,383 N → flange stress 98 MPa → SF = 2.82
Weight reduction	6.8 kg vs previous 8.2 kg → 17% lighter (target ≥15%)

BILL OF MATERIALS

Item	Specification	Qty	Cost
Enclosure walls	6061-T6 Al 3 mm, laser cut, TIG welded	1 set	$185
Mounting flanges	6061-T6 5 mm, CNC milled, M8 holes	4	$48
Fin array	6061-T6 2 mm fin 8 mm pitch, 3 faces	3	$95
PCM	Rubitherm RT44HC 44°C melt 250 J/g	600g	$38
PCM trays	1 mm Al sheet, sealed silicone gasket	8	$24
Lid gasket	3 mm silicone cord Shore A50	2m	$12
Lid bolts	M5×16 mm SS hex head 100 mm pitch	24	$8
MSD disconnect	Gigavac GX14 150A rated	1	$68
Fusible link	80A ANL fuse + holder	1	$18
IMD circuit	Bender IR155-3204 isolation monitor	1	$245

ISSUES LOG

Issue	Root Cause	Resolution
Flange cracking	Stress concentration at bolt holes, no gussets	Triangular gussets at all 4 holes — stress reduced 58%
Cells reaching 62°C	No thermal management beyond wall conduction	Fin array + PCM — operating limit set to 1C continuous
IP67 seal failure	Gasket groove 0.2 mm too shallow	Groove depth corrected to 2.5 mm — 25% compression ratio
PCM leakage	Silicone bead cracked under thermal cycling	Replaced with formed silicone sheet gasket — 50-cycle tested

RESULTS

- Structural SF = 2.82 at 25g lateral load — meets FSAE EV 2023 requirement (SF > 2.5) with margin
- Weight: 6.8 kg — 17% lighter than failed predecessor, exceeds the 15% target
- IP67 verified: 30-minute submersion at 1 m depth — zero water ingress
- At 1C continuous discharge: cells stabilized at 47.8°C, within acceptable operating range
- PCM thermal buffer: 13.9 s of full-power burst before temperatures begin rising
- Weld toe fatigue life: > 10^7 cycles — infinite-life classification per AWS D1.2
- Manual service disconnect interrupts HV circuit in < 2 ms — meets FSAE emergency stop requirement

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