TECHNICAL RESEARCH PAPER

JHON PORK: THE ZOG HOG

A First-Principles Scientific and Engineering Manuscript

Mathematical, Physical, and Robotic Feasibility Analysis of a Heavy-Class Porcine-Form Quadruped

Zog Robotics Research Team

2. ABSTRACT AND SYSTEM DEFINITION

2.1 ABSTRACT

This paper derives the governing mathematics for the Zog Hog, a heavy-class porcine-form quadruped robotic platform. We develop first-principles models for stability, locomotion, actuator sizing, energy budgeting, thermal behavior, acoustic signature, and snout-assisted sensing. A quantitative baseline is established to enable preliminary design trade studies and to bound performance under mission-relevant conditions.

2.2 SYSTEM DEFINITION

Let

m = total robot mass

$g = 9.81\ \mathrm{m/s^2}$

$W = mg$

Baseline case:

$m = 220$ kg

$W = 220 \times 9.81 = 2158.2$ N

Therefore $W \approx 2.16$ kN

Equal load-sharing (static stand):

$$F_{leg} = \frac{W}{4} = 539.55\ \mathrm{N}$$

Peak load case (dynamic impact, nominal 0.45g):

$$F_{peak\ leg} = 0.45mg = 971.19\ \mathrm{N}$$

Therefore each leg should be designed for approximately 1.0 kN peak loading.

TABLE 1. BASELINE PARAMETERS

PARAMETER	SYMBOL	VALUE (BASELINE)	UNITS
Total Mass	m	220	kg
Weight	W	2.16	kN
Static Load per Leg	F_{leg}	539.55	N
Peak Load per Leg	$F_{peak\ leg}$	971.19	N
CoM Height	z_{CoM}	0.46	m
Shoulder Height	h_{sh}	0.78	m
Overall Length	L_{tot}	1.72	m
Stance Length	L_{stance}	0.94	m
Stance Width (nom.)	W_{stance}	0.60	m

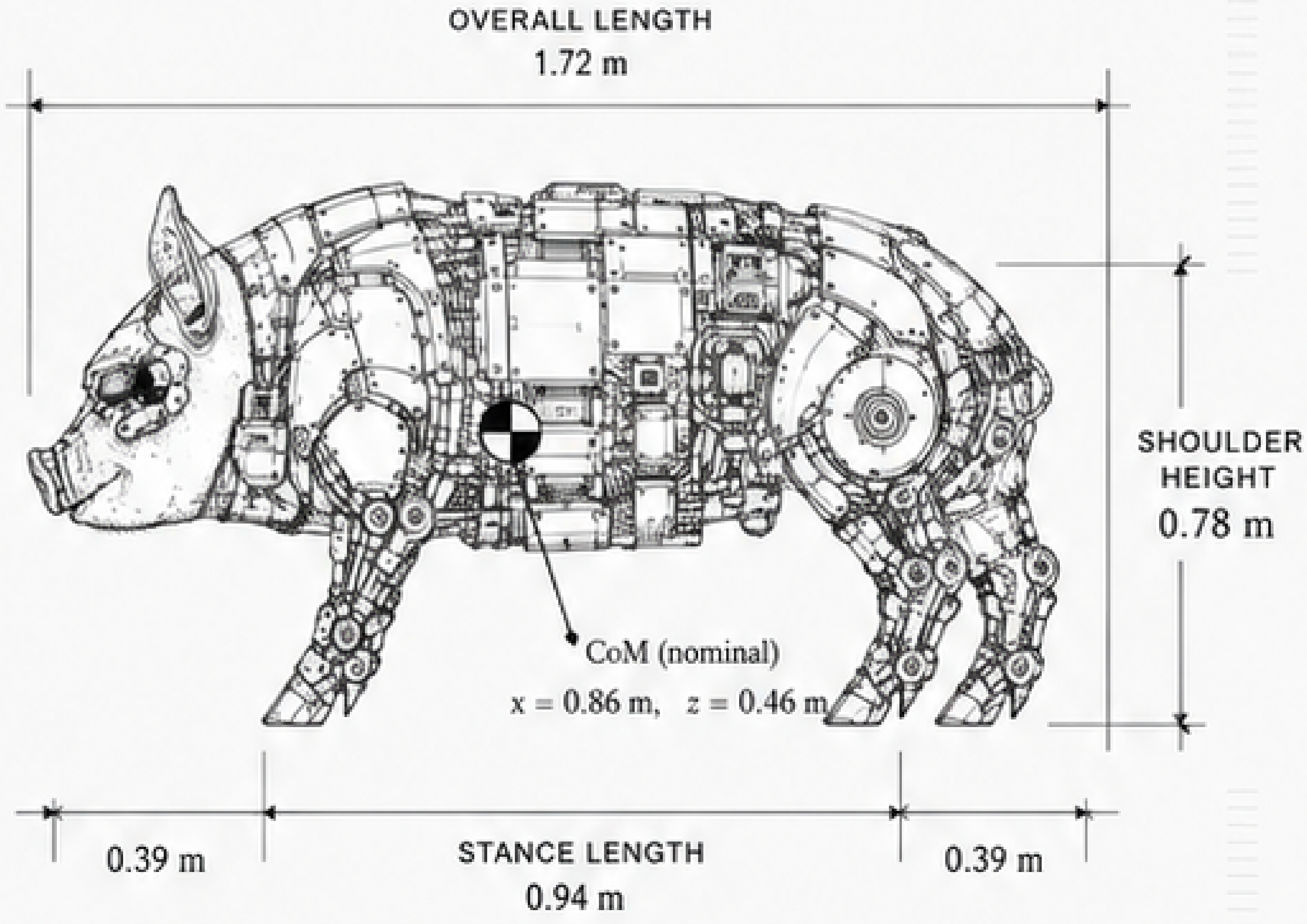


Figure 2. Side view schematic and key dimensions (baseline configuration).

EQUATION BLOCK SUMMARY

$$W = mg \tag{1}$$

$$F_{leg} = \frac{W}{4} \tag{2}$$

$$F_{peak\ leg} = 0.45mg \tag{3}$$

Units: m [kg], g [m/s²], W [N], F [N]

SYSTEM ASSUMPTIONS

Mass envelope	180–280 kg
Payload	60–100 kg
Cruise speed	1.2 m/s
Battery (LFP) energy capacity	5.8 kWh
Battery endurance target	94 min
Hybrid (fuel + battery) endurance target	6.4 h
Slope (continuous) target	±35°
Step height (vertical) target	0.48 m
Buried-sensing depth (soil) target	0.55 m
Acoustic signature target	49 dB(A) at 7 m

3. GEOMETRY AND STATIC STABILITY

3.1 OVERVIEW

The porcine form provides a mechanically advantageous geometry for heavy-class quadrupeds. Its wide body, low center of mass, and short, stout limbs yield a large, stable support polygon and high resistance to lateral tipping. The anatomy also enables efficient internal packaging and robust frontal structures for environmental interaction. These traits directly enhance payload carriage, energy efficiency, and mission survivability in rough terrain.

3.2 WHY THE PORCINE FORM IS MECHANICALLY USEFUL

- Wide body increases support polygon width.
- Low center of mass reduces overturning moments.
- Short, robust limbs lower the CoM and resist impact loads.
- Large internal volume supports high-capacity payloads.
- High roll stability from wide stance and low height.
- Strong payload placement along the longitudinal axis.
- Strong front probing structure for sensing and impact tolerance.

3.3 LATERAL TIPPING RESISTANCE

The lateral tipping angle is approximated by:

$$\theta_{tip} = \tan^{-1}\left(\frac{b/2}{h}\right) \quad [1]$$

Porcine form (Zog Hog):

$$b = 0.82\ \text{m},\ h = 0.42\ \text{m},\ \theta_{tip} \approx 44.3^\circ \quad [2]$$

Dog-form comparison:

$$b = 0.55\ \text{m},\ h = 0.58\ \text{m},\ \theta_{tip} \approx 25.4^\circ \quad [3]$$

Improvement ratio:

$$R = \frac{44.3}{25.4} \approx 1.74 \quad [4]$$

Units: b, h [m], θ_{tip} [deg], R [−]

The porcine geometry provides a lateral tipping angle of approximately 44.3°, compared with 25.4° for a dog-form of similar mass. This yields an improvement ratio of $R \approx 1.74$, corresponding to roughly 74% greater lateral tipping resistance, substantially improving traversal safety, payload stability, and resilience to side impacts.

A. SUPPORT POLYGON (TOP VIEW)

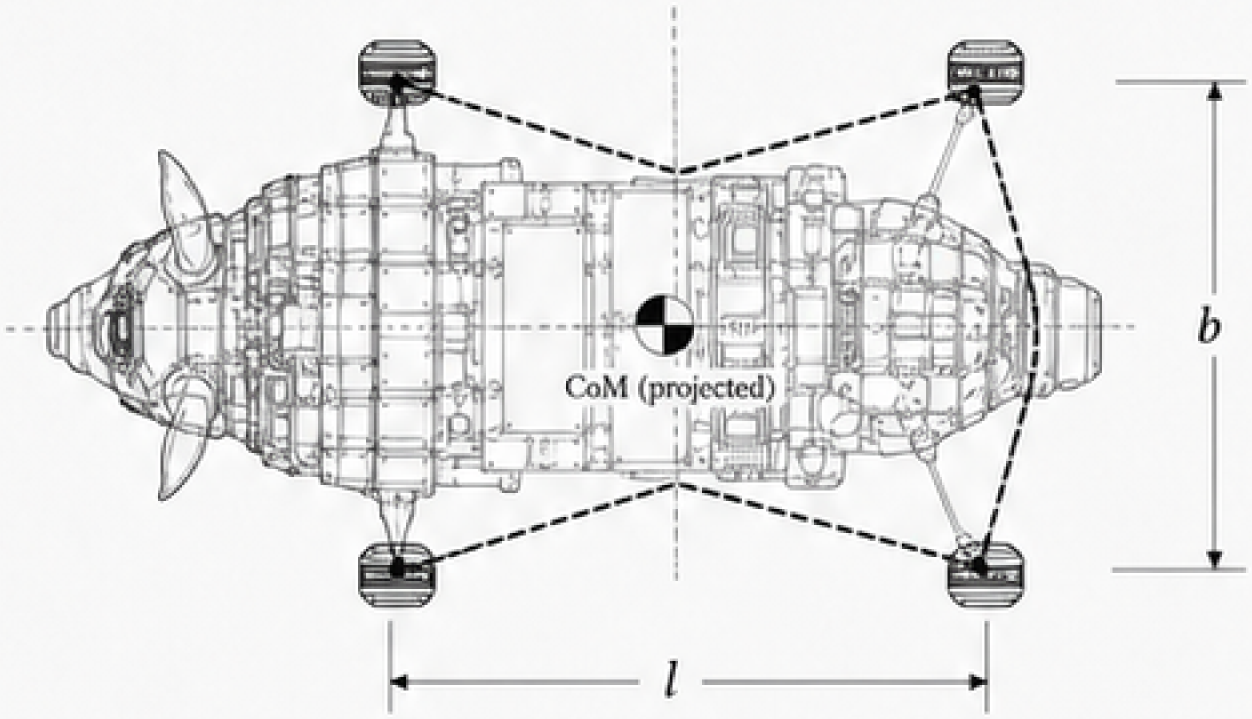


Figure 3. Top view showing the support polygon and projected CoM.

B. LATERAL TIPPING GEOMETRY (FRONT VIEW)

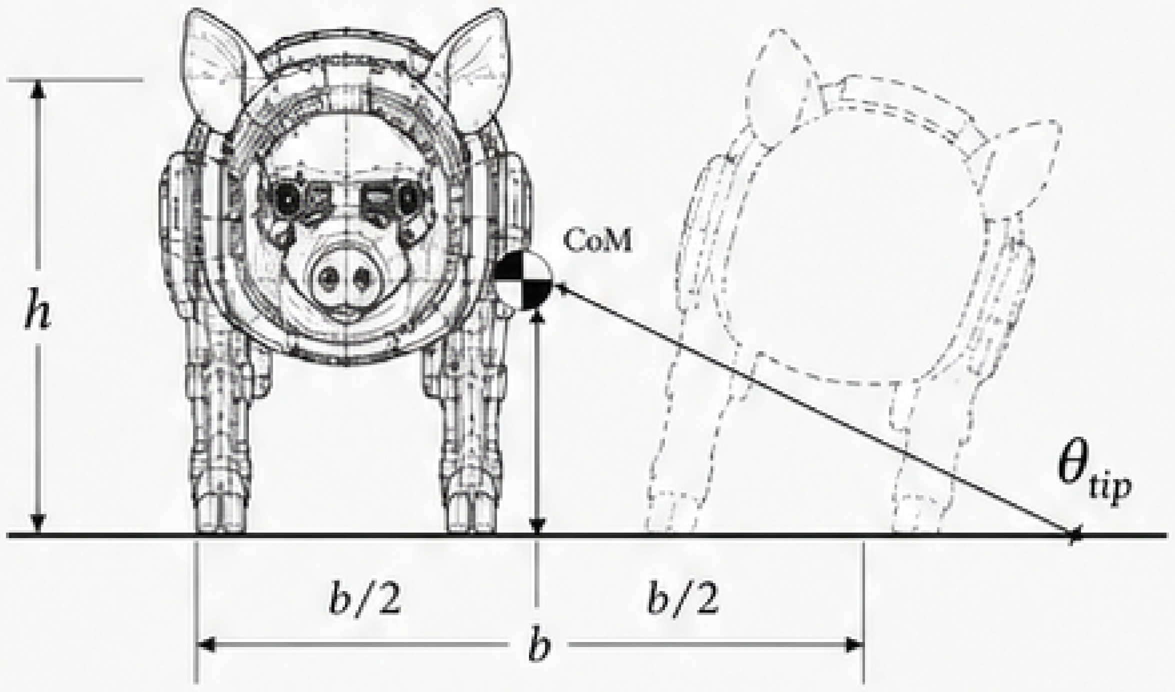


Figure 4. Front view tipping geometry and definition of θ_{tip}.

TABLE 2. PORCINE VS DOG-FORM GEOMETRY

PARAMETER	PORCINE FORM (ZOG HOG)	DOG-FORM (COMPARISON)	IMPROVEMENT (PORCINE / DOG)
Stance Width, b	0.82 m	0.55 m	1.49×
CoM Height, h	0.42 m	0.58 m	0.72×
Lateral Tipping Angle, θ_{tip}	44.3°	25.4°	1.74×
Tipping Resistance Ratio, R	1.74	1.00	1.74×
Body Width / Length	0.48	0.28	1.71×
Support Polygon Area	1.36 m^2	0.69 m^2	1.97×

Note: Dog-form values correspond to a representative heavy-class quadruped with similar mass and overall length.

4. SUPPORT POLYGON AND SLOPE STABILITY

4.1 SUPPORT POLYGON (TOP VIEW)

The baseline stance is defined by four feet forming a rectangular support polygon. The projection of the center of mass (CoM) must remain inside this polygon to maintain static stability on level ground.

FOOT LOCATIONS (IN BODY FRAME)

$P_1 = (L/2,\ b/2)$

$P_2 = (L/2,\ -b/2)$

$P_3 = (-L/2,\ -b/2)$

$P_4 = (-L/2,\ b/2)$

BASELINE VALUES

- $L = 1.25$ m, $b = 0.82$ m

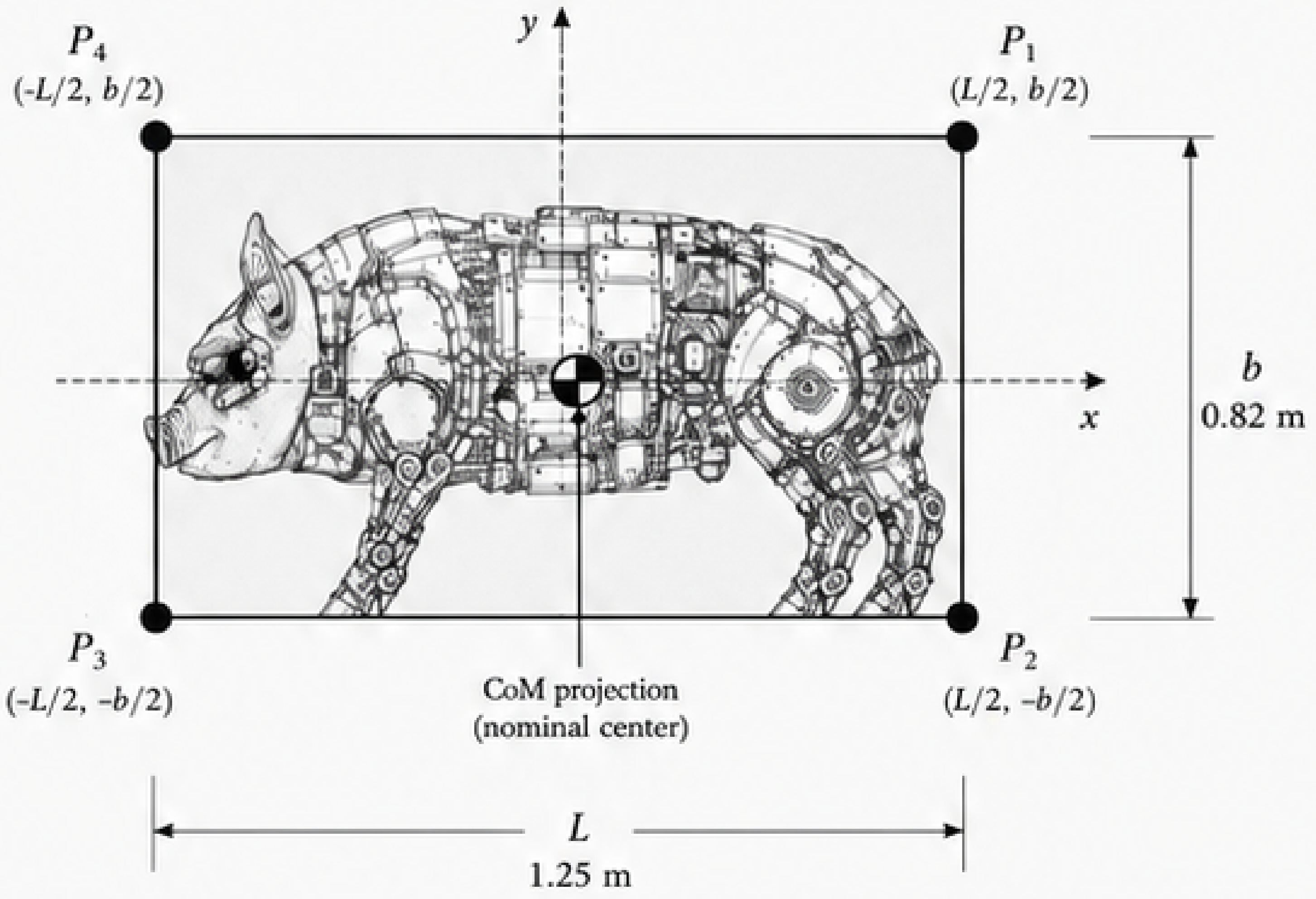
SUPPORT POLYGON AREA

$$\boxed{A = Lb = 1.025\ \text{m}^2}$$

STATIC STABILITY MARGIN (LEVEL GROUND)

$$\boxed{S = \min\left(\frac{L}{2}, \frac{b}{2}\right) = 0.41\ \text{m}}$$

TOP VIEW: SUPPORT POLYGON (LEVEL GROUND)



4.2 SLOPE STABILITY (SIDE SLOPE)

On a side slope of angle α, the CoM projection shifts laterally by Δx. The robot remains statically stable while this shifted projection stays within the support polygon. The available margin is compared to $b/2$.

SLOPE SHIFT (LATERAL)

$$\Delta x = h\tan(\alpha) \qquad [4]$$

For $h = 0.42$ m, $\alpha = 35°$:

$$\Delta x = 0.42\tan(35°) = 0.294\ \text{m} \qquad [5]$$

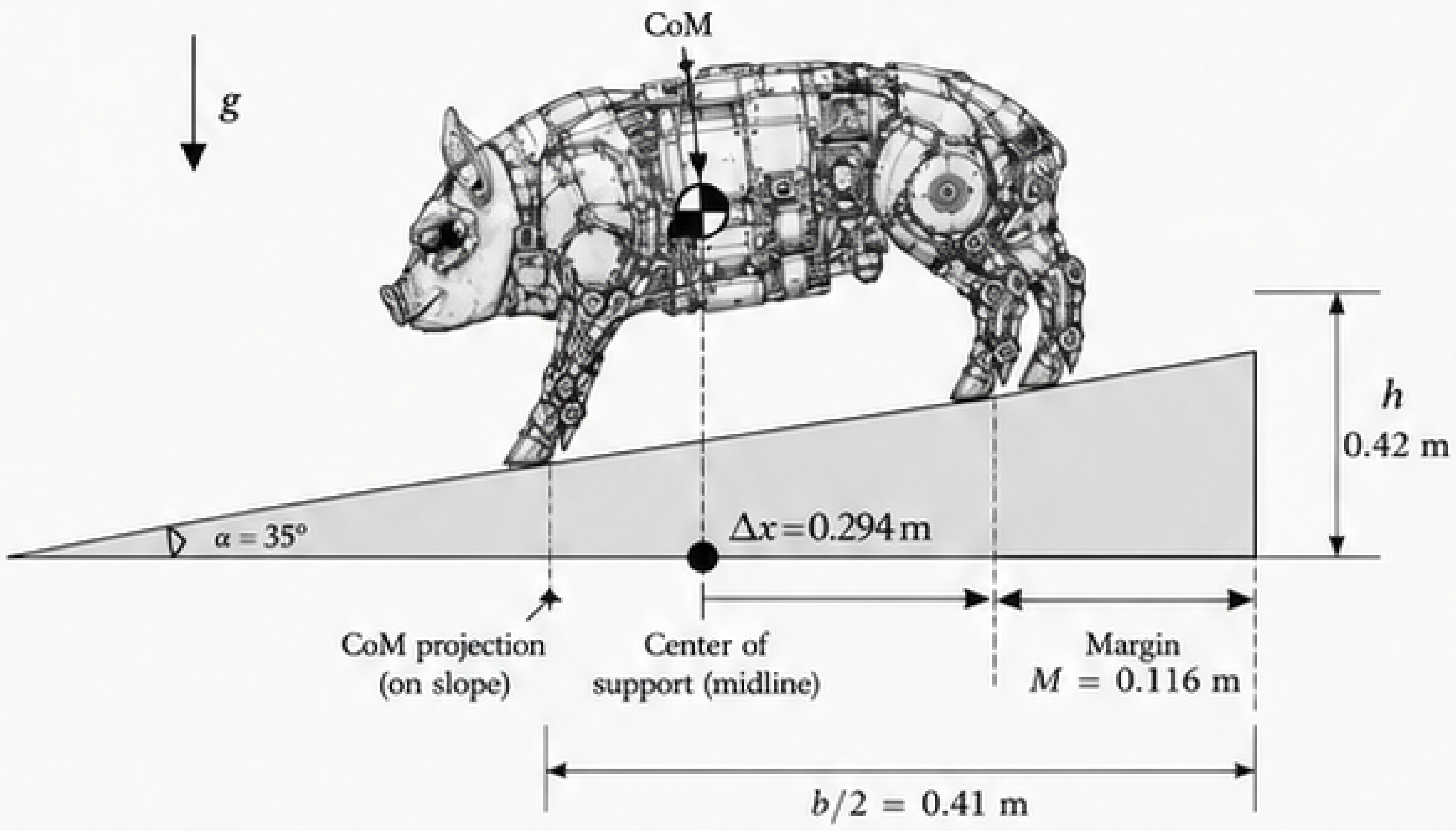
MARGIN COMPARISON

$$b/2 = 0.41\ \text{m} \qquad [6]$$

Remaining margin:

$$M = 0.41 - 0.294 = 0.116\ \text{m} \qquad [7]$$

SIDE VIEW: CO M SHIFT ON SIDE SLOPE ($\alpha = 35°$)



STATIC MARGIN SUMMARY

ITEM	SYMBOL	EXPRESSION / VALUE	NUMERICAL VALUE	UNITS	NOTES
Robot length	L	Baseline	1.25	m	Front–rear dimension
Robot width (stance)	b	Baseline	0.82	m	Left–right stance width
Support polygon area	A	$A = Lb$	1.025	m^2	Level ground
Static margin (level)	S	$S = \min(/2, b/2)$	0.41	m	To polygon edge
Slope height (CoM)	h	Assumed	0.42	m	Baseline configuration
Side slope angle	α	Assumed	35°	deg	Design condition
Lateral shift on slope	Δx	$\Delta x = h\tan(\alpha)$	0.294	m	CoM projection shift
Remaining margin	M	$M = b/2 - \Delta x$	0.116	m	Positive margin

STABILITY CONCLUSION

On a 35° side slope, the CoM projection shift is $\Delta x = 0.294$ m, which is less than $b/2 = 0.41$ m.

The robot is therefore statically stable with a remaining lateral margin of $M = 0.116$ m (11.6 cm).

6. DYNAMICS AND LOCOMOTION POWER

6.1 RIGID-BODY DYNAMICS AND GAIT MECHANICS

The Zog Hog is modeled as a planar-rigid quadruped with compliant actuated joints. Rigid-body dynamics govern the translational and rotational behavior of the body, while gait mechanics regulate contact sequencing, duty factor, and impulse exchange with the terrain. The centroidal dynamics capture the motion of the system's center of mass (CoM) under ground reaction forces (GRFs). Locomotion is analyzed in both quasi-static (low speed, negligible inertial effects) and dynamic (higher speed, inertial and centripetal effects significant) gait regimes.

GOVERNING EQUATIONS (RIGID-BODY)

$$\sum \boldsymbol{F} = m\boldsymbol{a} \quad [1]$$

$$\sum \boldsymbol{M} = \boldsymbol{I}\,\boldsymbol{\alpha} \quad [2]$$

Units: $\boldsymbol{F}$ [N], $\boldsymbol{M}$ [N·m], $\boldsymbol{m}$ [kg], $\boldsymbol{a}$ [m/s^2], $\boldsymbol{I}$ [kg·m^2], $\boldsymbol{\alpha}$ [rad/s^2]

FIGURE 4. CENTROIDAL DYNAMICS (FREE-BODY DIAGRAM)

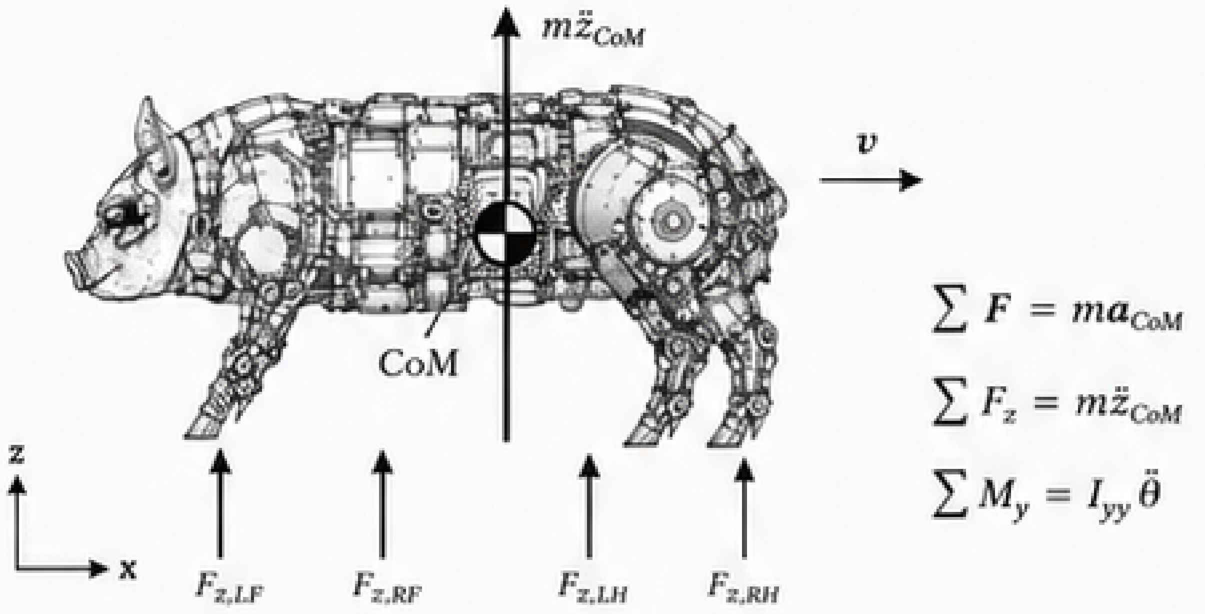


Figure 4. Centroidal free-body diagram. Vertical ground reaction forces (GRFs) support the body weight and generate pitching moment about the CoM.

FIGURE 5. LOCOMOTION AND AUXILIARY POWER CONTRIBUTIONS

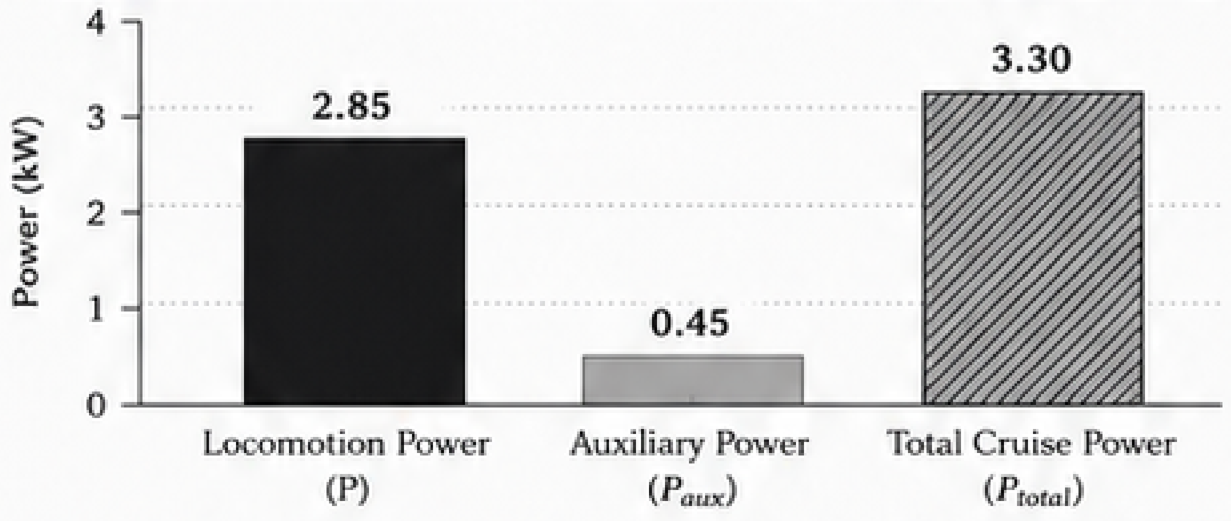


Figure 5. Breakdown of power contributions at a cruise speed of 1.2 m/s.

FIGURE 3. GAIT PHASE / CONTACT SEQUENCE

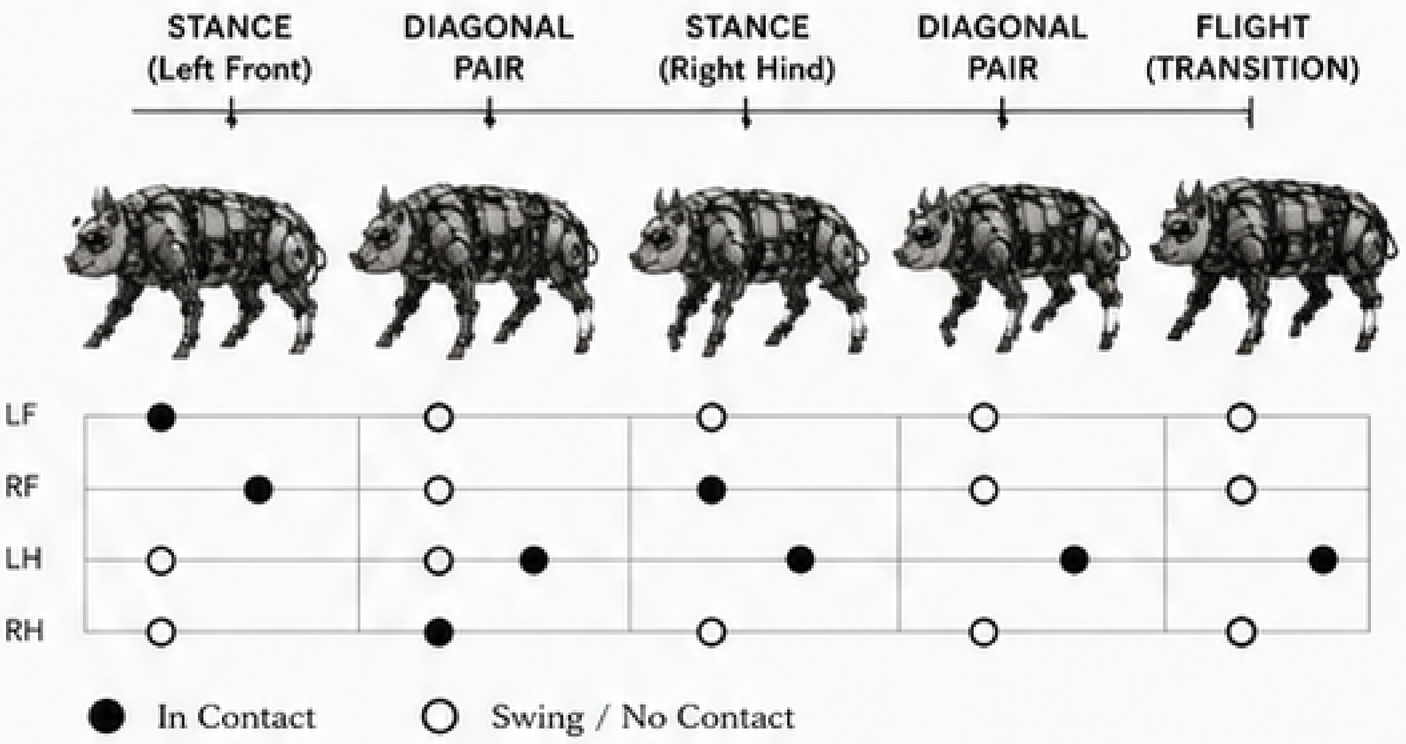


Figure 3. Nominal trot gait sequence and footfall pattern (LF: left front, RF: right front, LH: left hind, RH: right hind).

6.2 LOCOMOTION POWER

Walking mechanical power is estimated using the cost of transport (COT) relation. Auxiliary power accounts for onboard subsystems (electronics, thermal management, sensing, communications, etc.).

POWER ESTIMATION

$$P = COT \times mgv \quad [3]$$

Given:

$\mathrm{COT} = 1.1\,,\quad m = 220\ \mathrm{kg}\,,\quad v = 1.2\ \mathrm{m/s}\,,\quad g = 9.81\ \mathrm{m/s^2}$

$$\begin{aligned} P &= 1.1 \times 220 \times 9.81 \times 1.2 \\ &= 2848\ \mathrm{W} \approx 2.85\ \mathrm{kW} \end{aligned}$$

Auxiliary Power	$P_{aux} = 450\ \mathrm{W}$	[4]
Total Cruise Power	$P_{total} = P + P_{aux}$ $= 2.85\ \mathrm{kW} + 0.45\ \mathrm{kW}$ $= 3.30\ \mathrm{kW}$	[5]

The average total cruise power is **approximately 3.3 kW.**

6.3 SCIENTIFIC COMMENTARY

At 1.2 m/s, the Zog Hog operates in a dynamic trotting regime where inertial effects are non-negligible but remain within the platform's actuation and power capabilities. The estimated average total cruise power of ~3.3 kW informs battery sizing, thermal management, and mission endurance calculations.

5. ACTUATOR SIZING AND STEP-CLIMBING PHYSICS

5.1 SIMPLIFIED LEG MODEL AND JOINT MOMENT ARM

Each leg is approximated as a planar two-link mechanism operating in the sagittal plane. The hip and knee joints provide pitch motion only. External ground reaction force at the foot generates moments about each joint through the perpendicular (normal) moment arm r, measured from the joint center to the line of action of the ground reaction force.

- Two-link assumption: thigh (l_1) and shank (l_2)
- Ground reaction force F acts vertically at the foot
- Joint moment arm r is the perpendicular distance from joint center to the line of action of F

JOINT MOMENT ARM

The effective joint moment arm used for sizing is:

$$r = 0.28\ \text{m}$$

5.2 ACTUATOR TORQUE SIZING

The governing relationship between joint torque and ground reaction force is given by the moment equation:

$$\tau = Fr$$

Baseline case ($m = 220$ kg)

- Peak leg force: $F = 971$ N
- Joint torque: $\tau = 971 \times 0.28 = 271.9$ N· m
- Safety factor: SF = 2.0
- Design torque: $\tau_{\text{design}} = 271.9 \times 2.0 = 544$ N· m

Heavier case ($m = 280$ kg)

- Peak leg force: $F_{\text{peak leg}} = 1236$ N
- Joint torque: $\tau = 1236 \times 0.28 = 346.1$ N· m
- Design torque (SF = 2.0): $\tau_{\text{design}} \approx 692$ N· m

5.3 STEP-CLIMBING PHYSICS

To climb a vertical step of height H, the leg must raise the body's center of mass by H, requiring a minimum potential energy input:

$$H = 0.48\ \text{m} \quad \text{(step height)}$$
$$E_p = mgH = 1035.9\ \text{J} \quad (\text{for } m = 220\ \text{kg})$$

During the step-up transition, the front legs bear approximately half the body weight. The peak front-leg force and corresponding hip torque are estimated as:

- Front-leg force: $F_{\text{front}} = \dfrac{mg}{2} = 1079.1$ N
- Joint torque: $\tau = 1079.1 \times 0.28 = 302.1$ N· m
- Design torque (SF = 2.0): $\tau_{\text{design}} \approx 604$ N· m

DESIGN GUIDANCE (220 kg CASE)

Major hip and knee actuators should be designed for approximately **500–600 N·m peak torque** in the 220 kg case.

FIGURE 5.1 TWO-LINK LEG KINEMATIC MODEL

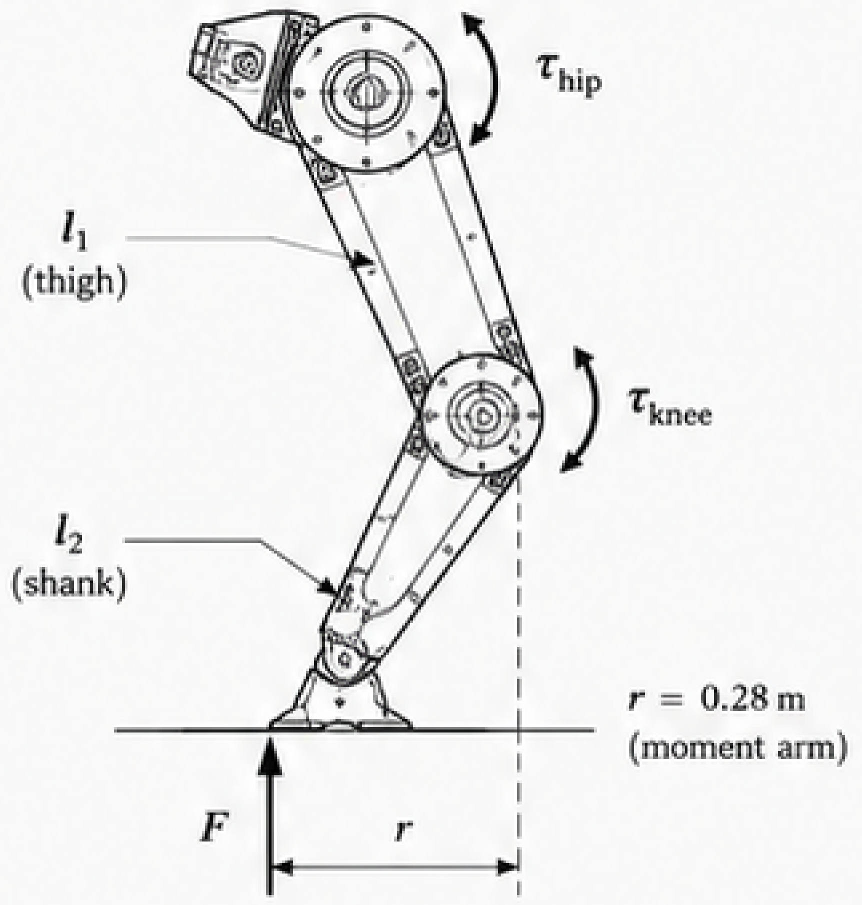


FIGURE 5.2 JOINT TORQUE VS. JOINT ANGLE (220 kg CASE)

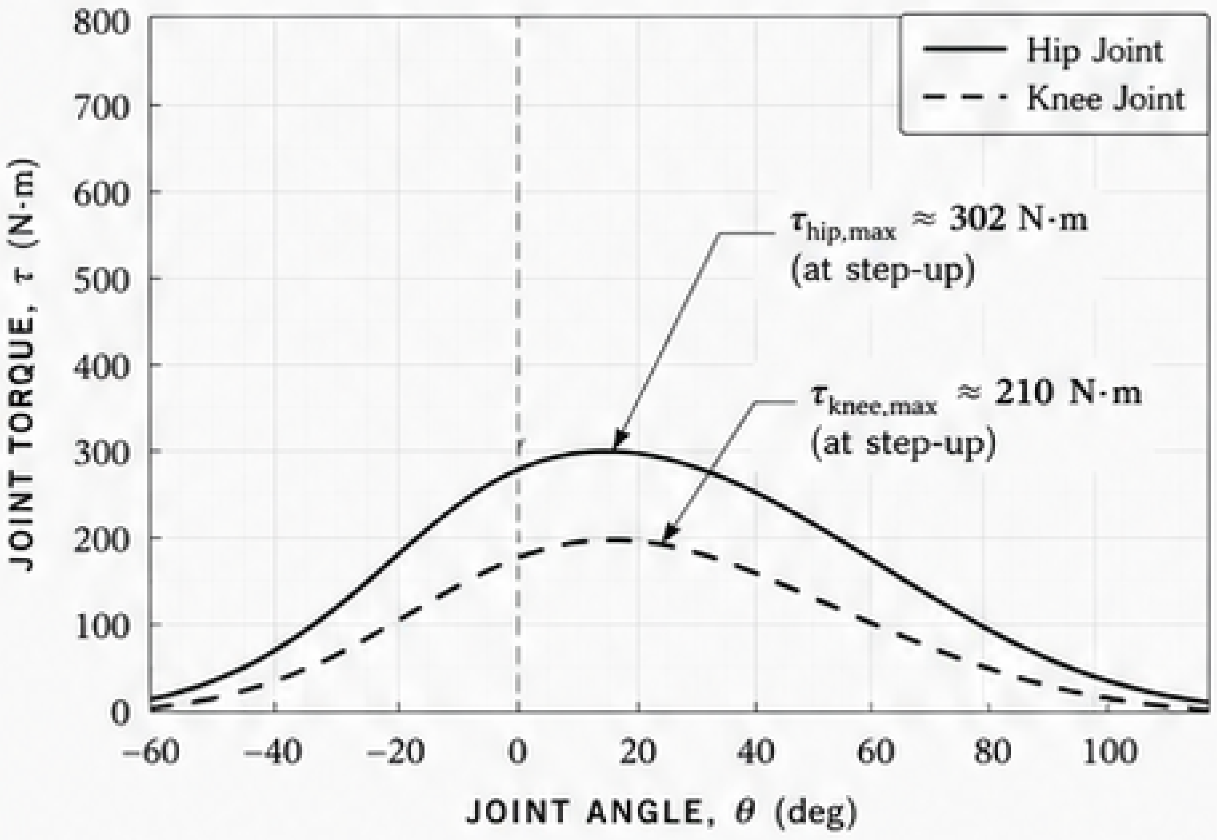


TABLE 5.1 JOINT TORQUE REQUIREMENTS

CONDITION	LOAD CASE	$F_{\text{peak leg}}$ (N)	$\tau = Fr$ (N·m)	SAFETY FACTOR (SF)	τ_{design} (N·m)
Level Ground (Static Stand)	220 kg	971	271.9	2.0	544
	280 kg	1236	346.1	2.0	692
Step-Up (Front-Leg Support)	220 kg	1079.1 ($mg/2$)	302.1	2.0	604

NOTES

- Moment arm used for all calculations: $r = 0.28$ m
- For dynamic events (impact, acceleration), design torque should be further increased as needed.
- Recommended continuous torque rating ≥ 60% of peak torque rating.

7. BATTERY AND HYBRID ENDURANCE

7.1 BATTERY ENDURANCE ANALYSIS

Battery energy capacity:

$$E = 5.8 \text{ kWh}$$

Usable energy fraction:

$$\eta_b = 0.90$$

Usable battery energy:

$$E_{\text{usable}} = \eta_b \times E = 0.90 \times 5.8 = 5.22 \text{ kWh}$$

From the baseline parameter table (Page 2), the total average power requirement is:

$$P_{\text{total}} = 3.30 \text{ kW}$$

Battery-only endurance:

$$t = \frac{E_{\text{usable}}}{P_{\text{total}}} = \frac{5.22}{3.30} = 1.58 \text{ h} \approx 95 \text{ min}$$

This result matches the proposed 94-minute battery endurance target.

7.2 HYBRID ENDURANCE ANALYSIS

Hybrid (fuel + battery) endurance target:

$$t_h = 6.4 \text{ h}$$

Total mission energy required:

$$E_h = P_{\text{total}} \times t_h = 3.30 \times 6.4 = 21.12 \text{ kWh}$$

Energy contributions:

$$E_b = E_{\text{usable}} = 5.22 \text{ kWh}$$

$$E_{\text{hybrid}} = E_h - E_b = 21.12 - 5.22 = 15.90 \text{ kWh}$$

Hybrid (generator) efficiency:

$$\eta_h = 0.28$$

Fuel energy requirement:

$$E_{\text{fuel}} = \frac{E_{\text{hybrid}}}{\eta_h} = \frac{15.90}{0.28} = 56.8 \text{ kWh}$$

CONCLUSION

Battery-only endurance is limited by power draw, while hybrid endurance is limited by heat and noise management constraints.

FIGURE 7.1 MISSION ENERGY BUDGET OVER TIME

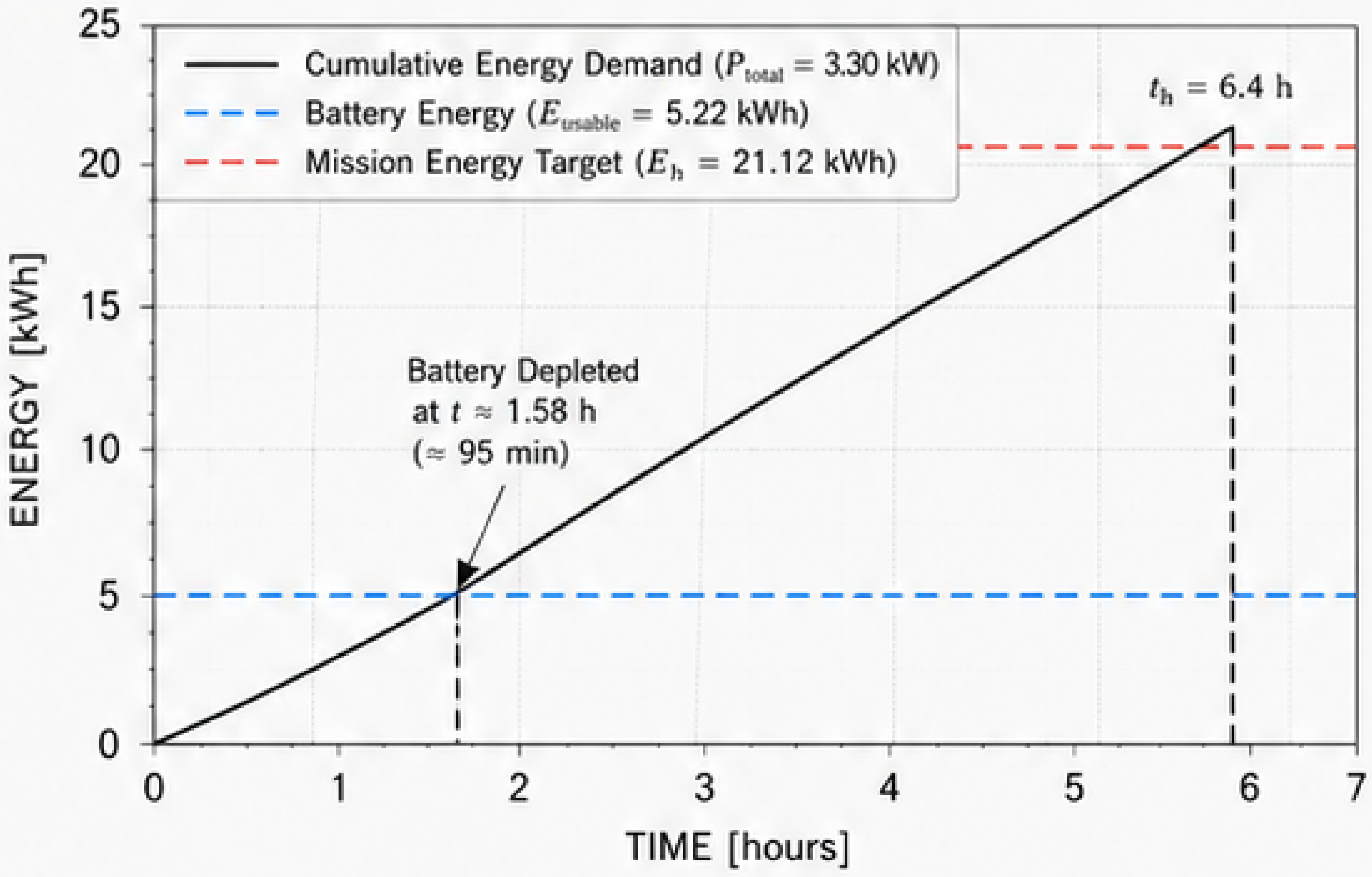


FIGURE 7.2 ENERGY FLOW DIAGRAM (HYBRID MODE)

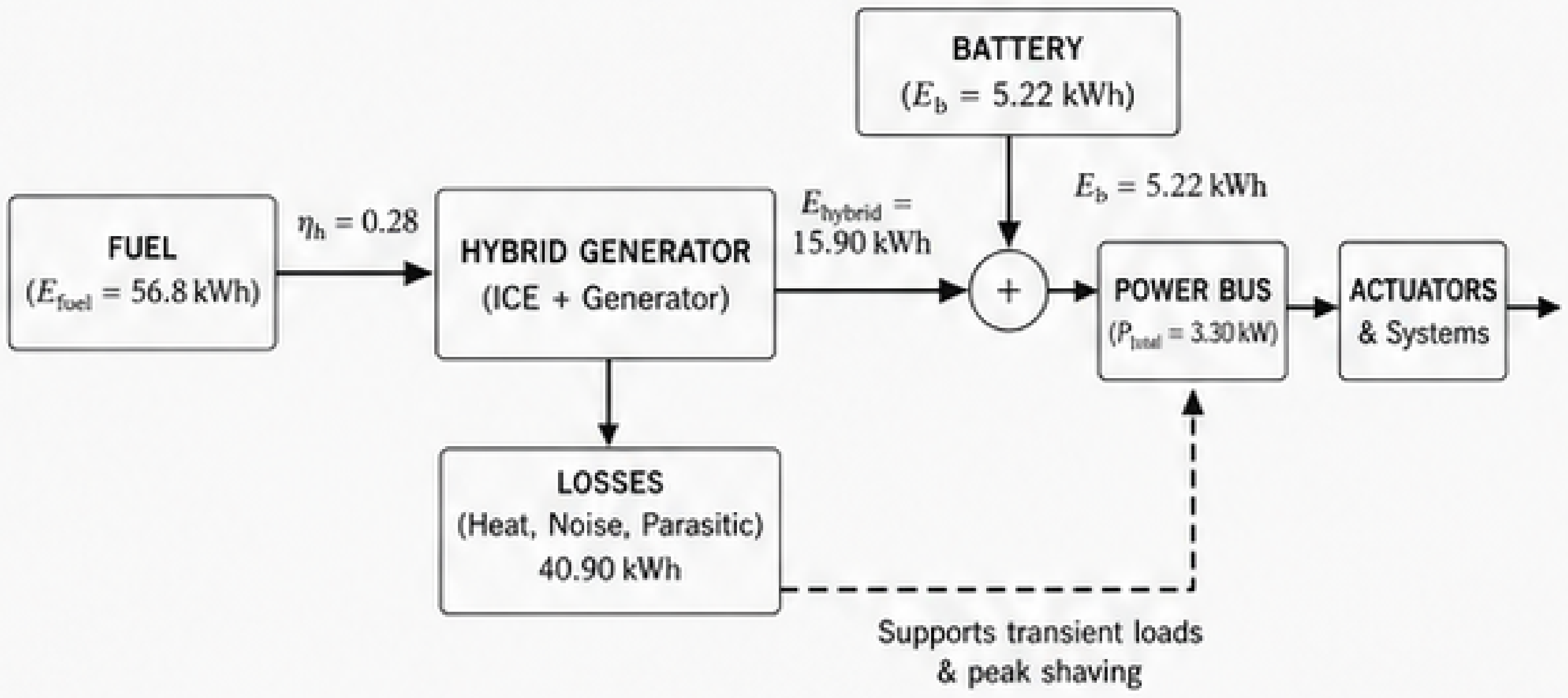


TABLE 7.1 MISSION ENDURANCE CASES

CASE	DESCRIPTION	ENDURANCE TIME	TOTAL ENERGY REQUIRED (KWH)	PRIMARY LIMITER
1	Battery-Only	1.58 h (≈ 95 min)	5.22	Power Draw (P_{total})
2	Hybrid (Target)	6.4 h	21.12	Heat & Noise Constraints
3	Hybrid (Energy Contributions)	–	Battery: 5.22 Hybrid: 15.90 Total: 21.12	–
4	Fuel Energy Requirement	–	56.8 (chemical energy)	Generator Efficiency (η_h = 0.28)

8. SNOUT PROBING AND BURIED-OBJECT SENSING

The Zog Hog's snout is a forward probing subsystem that combines mechanical palpation and ground-penetrating radar (GPR) to detect and characterize buried hazards and objects. The probe applies a controllable contact force while maintaining static stability, and the embedded GPR provides subsurface imaging for target localization.

8.1 SNOUT PROBING: STABILITY AND FORCE LIMITS

When the snout applies a downward probing force F_s at a vertical height h_s above the ground, a forward-overturning moment M_s is generated about the front stance edge. Stability is maintained when M_s is less than the resisting moment M_g from the robot weight acting at horizontal offset d.

Tipping moments about the front stance edge:

- Snout moment: $M_s = F_s h_s$
- Gravitational resisting moment: $M_g = mgd$

Stability condition:

$$F_s < \frac{mgd}{h_s} \qquad [1]$$

Using baseline parameters:

- $m = 220$ kg, $g = 9.81\ \mathrm{m/s^2} \Rightarrow mg = 2158.2$ N
- $d = 0.55$ m (buried-sensing depth target)
- $h_s = 0.38$ m (snout probe height)

Substitute into Eq. [1]:

$$F_s < \frac{(2158.2)(0.55)}{0.38} = 3124\ \mathrm{N}$$

Maximum allowable probing force:

$$F_s < 3124\ \mathrm{N}$$

With a safety factor of 3 for terrain uncertainty and dynamic effects:

$$F_{s,\mathrm{safe}} \approx \frac{3124}{3} \approx 1041\ \mathrm{N}$$

Safe operational probing force:

$$F_{s,\mathrm{safe}} \approx 1041\ \mathrm{N}$$

8.2 GROUND-PENETRATING RADAR (GPR) SENSING

The snout integrates a shielded ultra-wideband (UWB) GPR antenna to image subsurface structures. The theoretical range resolution ΔR is governed by the signal bandwidth B and propagation velocity v.

Range resolution:

$$\Delta R = \frac{v}{2B} \qquad [2]$$

Propagation velocity in soil:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \qquad [3]$$

Using $\varepsilon_r = 9$ (typical low-conductivity soil):

$$v = \frac{3 \times 10^8}{\sqrt{9}} = 1 \times 10^8\ \mathrm{m/s}$$

With $B = 1.5$ GHz:

$$\Delta R = \frac{1 \times 10^8}{2(1.5 \times 10^9)} = 0.0333\ \mathrm{m} \approx 3.3\ \mathrm{cm}$$

For buried depth target $D = 0.55$ m, the two-way travel time is:

$$t = \frac{2D}{v} = \frac{2(0.55)}{1 \times 10^8} = 11\ \mathrm{ns}$$

With low-conductivity soil and moderate moisture, the sensing target at $D = 0.55$ m is plausible using UWB GPR.

FIGURE 1. SNOUT CROSS-SECTION AND SENSING PATH

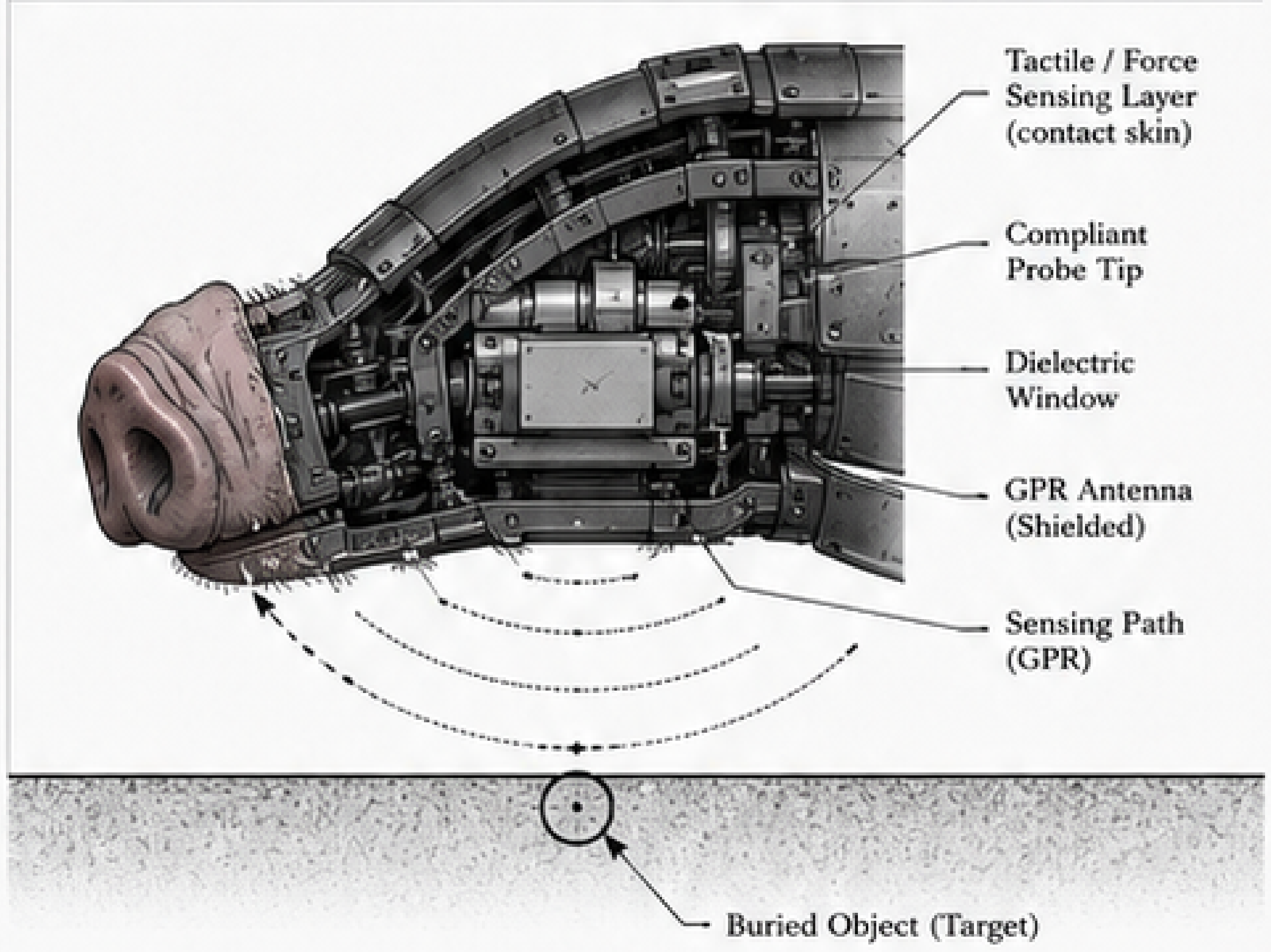


FIGURE 2. PROBING FORCE AND STABILITY DIAGRAM

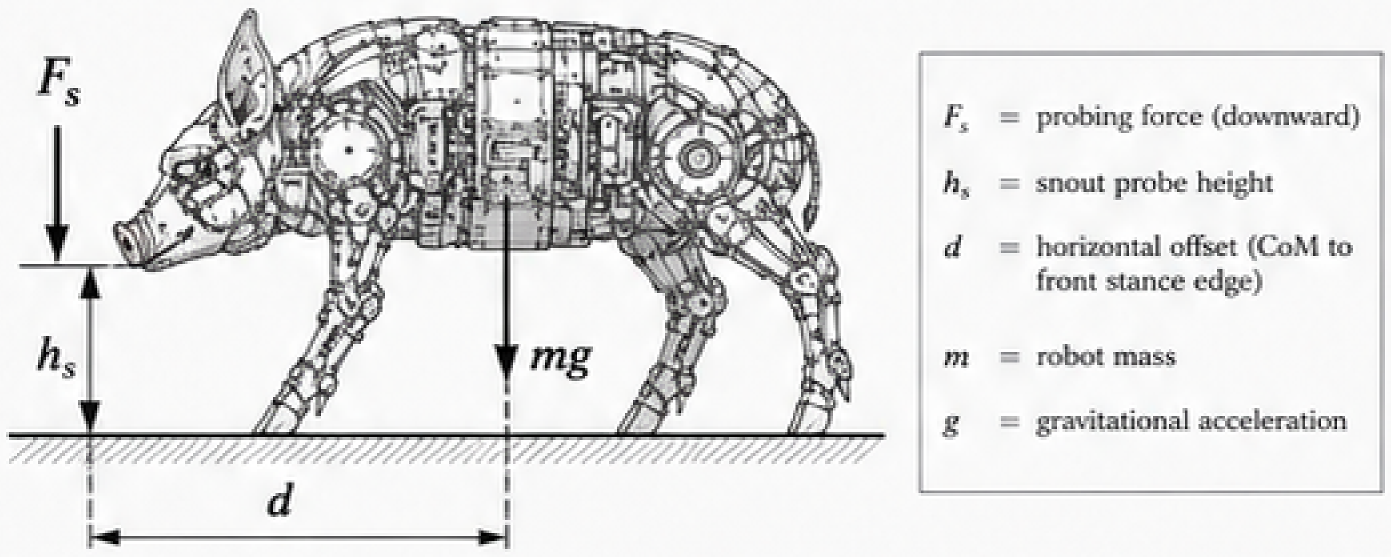


TABLE 1. GPR SENSING SUMMARY (BASELINE CONFIGURATION)

PARAMETER	SYMBOL	VALUE (BASELINE)	UNITS	NOTES
Relative permittivity	ε_r	9	—	Low-conductivity soil
Propagation velocity	v	1×10^8	m/s	From Eq. [3]
Antenna bandwidth	B	1.5	GHz	UWB
Range resolution	ΔR	0.0333	m	≈ 3.3 cm
Buried depth (target)	D	0.55	m	Design target
Two-way travel time	t	11	ns	From $t = 2D/v$
Operational probing force (safe)	$F_{s,\mathrm{safe}}$	≈ 1041	N	SF = 3
Peak probing force (limit)	F_s	3124	N	From Eq. [1]

9. THERMAL AND ACOUSTIC PERFORMANCE

9.1 THERMAL ANALYSIS

Internal power dissipation arises from drivetrain losses, onboard computing, power electronics, and auxiliaries. The resulting thermal load must be rejected through the chassis skin to maintain component temperatures within safe limits.

Total power (electrical input) $P_{total} = 3.30\ \text{kW}$

Drivetrain efficiency $\eta = 0.82$

Lost power (heat from drivetrain)

$$P_{heat} = P_{total}(1-\eta) = 3.30(1-0.82) = 0.594\ \text{kW} = 594\ \text{W}$$

Compute & electronics heat $P_{compute} = 300\ \text{W}$

Total thermal load

$$P_{thermal} = P_{heat} + P_{compute} = 594 + 300 = 894\ \text{W}$$

Thermal resistance requirement

$$\Delta T = P_{thermal}\, R_\theta$$

Design target: $\Delta T < 25°\text{C}$

$$R_\theta < \frac{25}{894} \approx 0.028\ \ °\text{C/W}$$

Thermal control is a major bottleneck. Achieving $R_\theta < 0.028\ °\text{C/W}$ requires aggressive conduction paths, high-performance TIMs, and extensive external surface area.

9.2 ACOUSTIC ANALYSIS

The platform's acoustic signature must remain below mission thresholds to avoid detection and ensure stealth capability.

Acoustic target (mission requirement)

$$L_p = 49\ \text{dB(A) at 7 m}$$

Distance conversion (inverse-square law for sound)

$$L_{p,1\text{m}} = L_{p,7\text{m}} + 20\log_{10}(7) = 49 + 20\log_{10}(7) = 65.9\ \text{dB(A)}$$

Sound power summation (independent sources)

$$L_{total} = 10\log_{10}\left(\sum 10^{L_i/10}\right)$$

Example source combination at 1 m

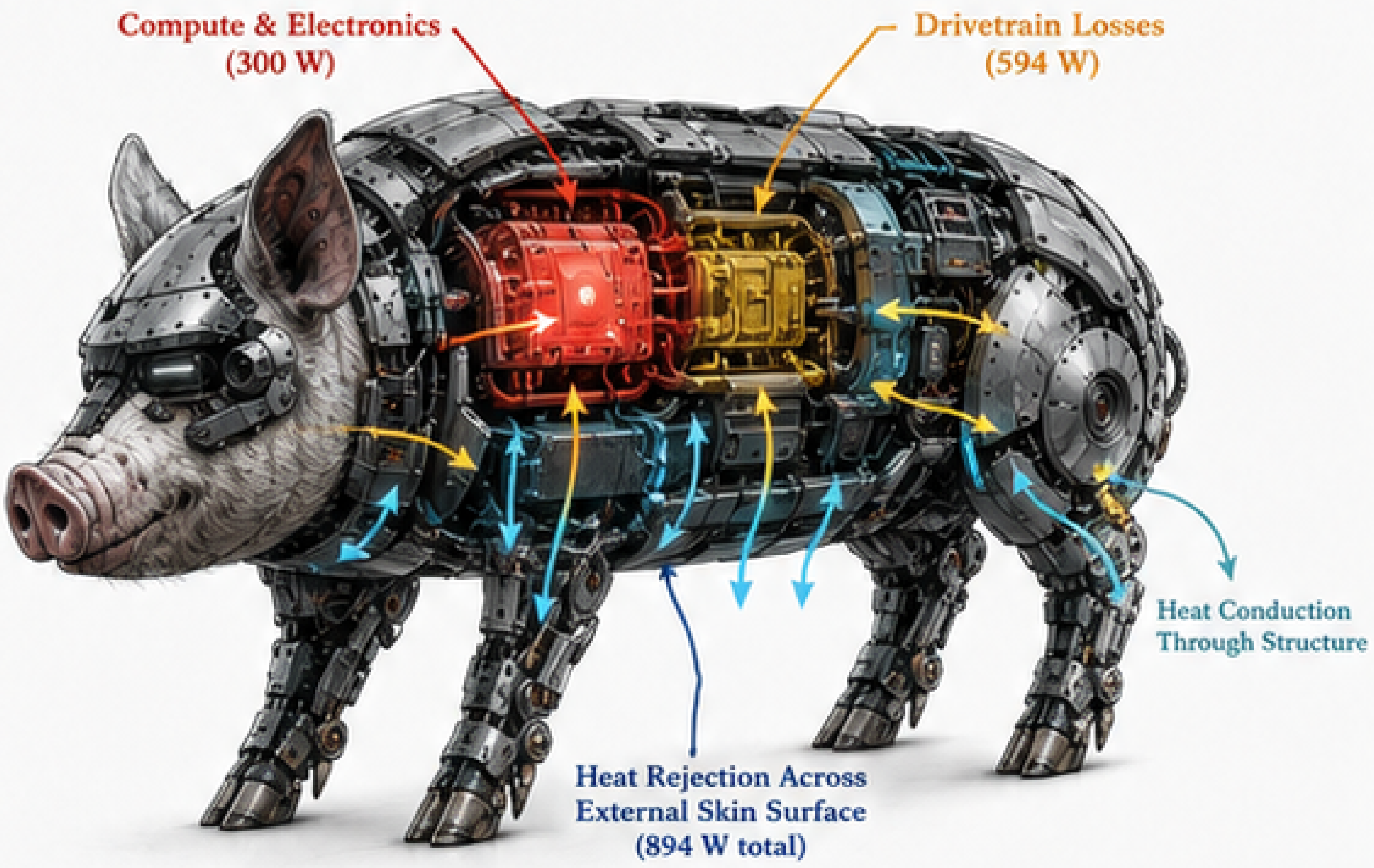
Sources (example): Drivetrain 58 dB(A), Fans 60 dB(A), Actuators 57 dB(A), Vent Exhaust 55 dB(A)

$$L_{total,1\text{m}} = 10\log_{10}\left(10^{5.8} + 10^{6.0} + 10^{5.7} + 10^{5.5}\right) = 62.6\ \text{dB(A)}$$

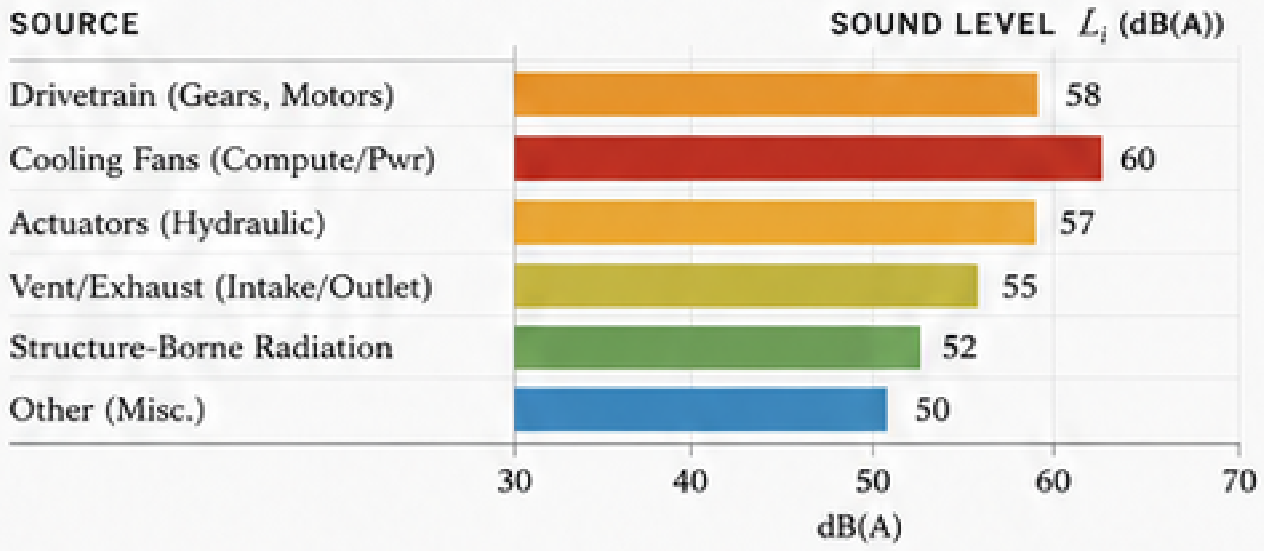
At 7 m: $L_{total,7\text{m}} = 62.6 - 20\log_{10}(7) = 45.7\ \text{dB(A)}$

The 49 dB(A) at 7 m target is realistic for electric-only mode and potentially achievable in hybrid mode only with extremely muffled exhaust and optimized isolation.

HEAT-FLOW DIAGRAM THROUGH BARREL CHASSIS



ACOUSTIC SOURCE BREAKDOWN (AT 1 m)



EXAMPLE COMBINATION

$$\left.\begin{aligned} L_{total,1\text{m}} &= 62.6\ \text{dB(A)} \\ L_{total,7\text{m}} &= 45.7\ \text{dB(A)} \end{aligned}\right\}$$ Below target (49 dB at 7 m)

TABLE 2. THERMAL AND ACOUSTIC THRESHOLDS

CATEGORY	PARAMETER		VALUE / REQUIREMENT	STATUS
THERMAL	Total Input Power	P_{total}	3.30 kW	—
	Drivetrain Efficiency	η	0.82	—
	Total Thermal Load	$P_{thermal}$	894 W	—
	Design Target	ΔT	< 25 °C	Req.
	Required R_θ	R_θ	< 0.028 °C/W	Req.
ACOUSTIC	Mission Acoustic Target	L_p	49 dB(A) at 7 m	Req.
	Equivalent at 1 m	$L_{p,1\text{m}}$	65.9 dB(A)	—
	Example Combined (1 m)	$L_{total,1\text{m}}$	62.6 dB(A)	OK
	Example Combined (7 m)	$L_{total,7\text{m}}$	45.7 dB(A)	OK

10. CONFIGURATION SUMMARY, FAILURE MODES, AND FEASIBILITY CONCLUSION

CONFIGURATION SUMMARY COMPARISON

METRIC	180 kg	220 kg	280 kg
Weight mg	1766 N	2158 N	2747 N
Peak Leg Force $F_{peak\ leg}$	795 N	971 N	1236 N
Design Torque (with safety factor) τ_{design}	446 N·m	544 N·m	692 N·m
Estimated Cruise Power P_{cruise}	2.34 kW	2.85 kW	3.62 kW
Total Power (with auxiliaries) P_{total}	2.79 kW	3.30 kW	4.07 kW
5.8 kWh Battery Endurance	112 min	95 min	77 min
35° Slope Stability	Stable	Stable	Marginal–Unstable
0.48 m Step Capability	Capable	Capable	Marginal
Main Bottleneck	Power margin	Thermal margin (edge)	Torque & thermal

FAILURE MODES

- Tip-over during lateral shove
- Foot placement error on stairs
- Insufficient actuator torque during ascent
- Thermal saturation
- Battery depletion on return leg
- Acoustic overshoot from hybrid auxiliaries
- GPR degradation in saturated soils

FEASIBILITY CONCLUSION

The Zog Hog meets the mission requirements if the following conditions are satisfied:

$$h < 0.586\ \text{m}$$

$$\tau_{peak} \geq 600\ \text{N·m}$$

$$P_{avg} \leq 3.3\ \text{kW}$$

Safe snout force $\approx$ 1.0 kN

Under these constraints, the **220 kg configuration** is the most balanced case.

RECOMMENDED EXPERIMENTAL PROGRAM

1. Static tilt-rig test
2. Joint dynamometer test
3. 94-minute endurance mission
4. Thermal-chamber evaluation
5. Acoustic range measurement
6. Buried-object soil test

CONCLUSION

The Zog Hog is feasible if it stays low, wide, torque-heavy, and thermally controlled.