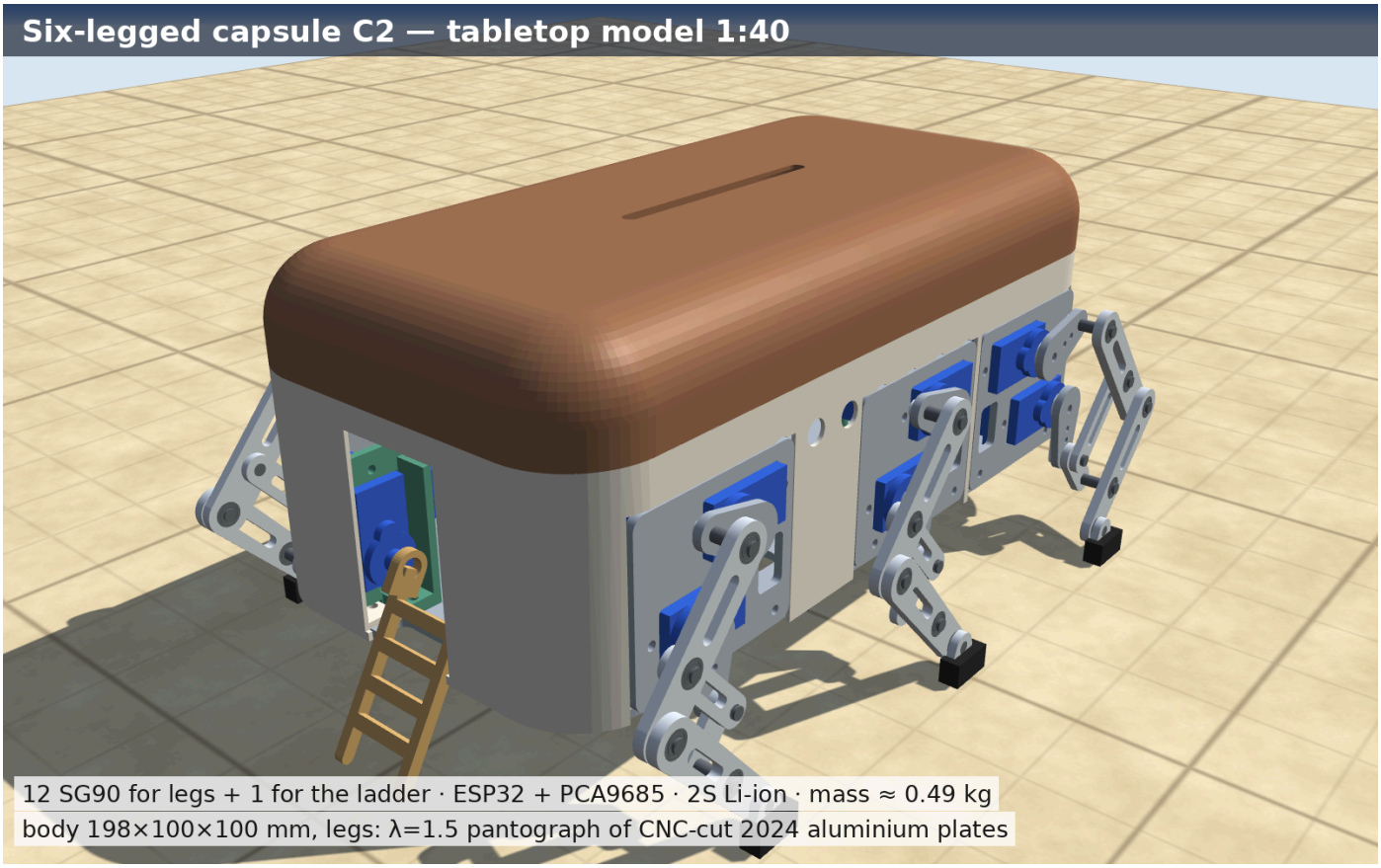
Six-legged capsule C2 v2 — working tabletop model, 1:40

12 SG90 for the legs + 1 SG90 for the ladder · ESP32 + PCA9685 · legs: decoupled λ = 1.5 pantograph made of CNC-cut 2024 aluminium plates · PETG body



1. Summary

Parameter	Value
Prototype	concept C2 "capsule v2", `asv/cad/asv_castle_v2.py` (6 legs, λ = 1.5 pantograph)
Scale	**1:40** (body 7.9 × 4.0 × 4.0 m → 198 × 100 × 100 mm)
Chosen variant	**C — 12 SG90 (2 per leg: lift + step) + 1 ladder SG90, 13 total**, PCA9685 driver
Worst torque (tripod, ×1.3)	lift 0.253 kg·cm, step 0.304 kg·cm
Margin vs 0.7 kg·cm (continuous)	**lift 2.76, step 2.31 — minimum 2.31 ≥ 2**
Margin vs 1.8 kg·cm (stall)	≥ 5.93
Mass	492.3 g from FreeCAD B-rep volumes (+5 % → design 516.9 g)
Stride / foot lift / speed	12 mm / 6 mm / ≈ 10.0 mm/s (half-cycle 1.2 s)
Chassis clearance	22.5 mm; "sit" lowers the body by 6 mm
Power	2S Li-ion 2 × 18350 IMR (7.92 Wh), 5 V / 5.5 A BEC; current avg 2.35 A, peak 4.81 A; ≈ 29 min
Control	ESP32, Wi-Fi AP "Hexapod-C2", web remote, calibration stored in NVS

2. Variant selection (margin ≥ 2 vs 0.7 kg·cm)

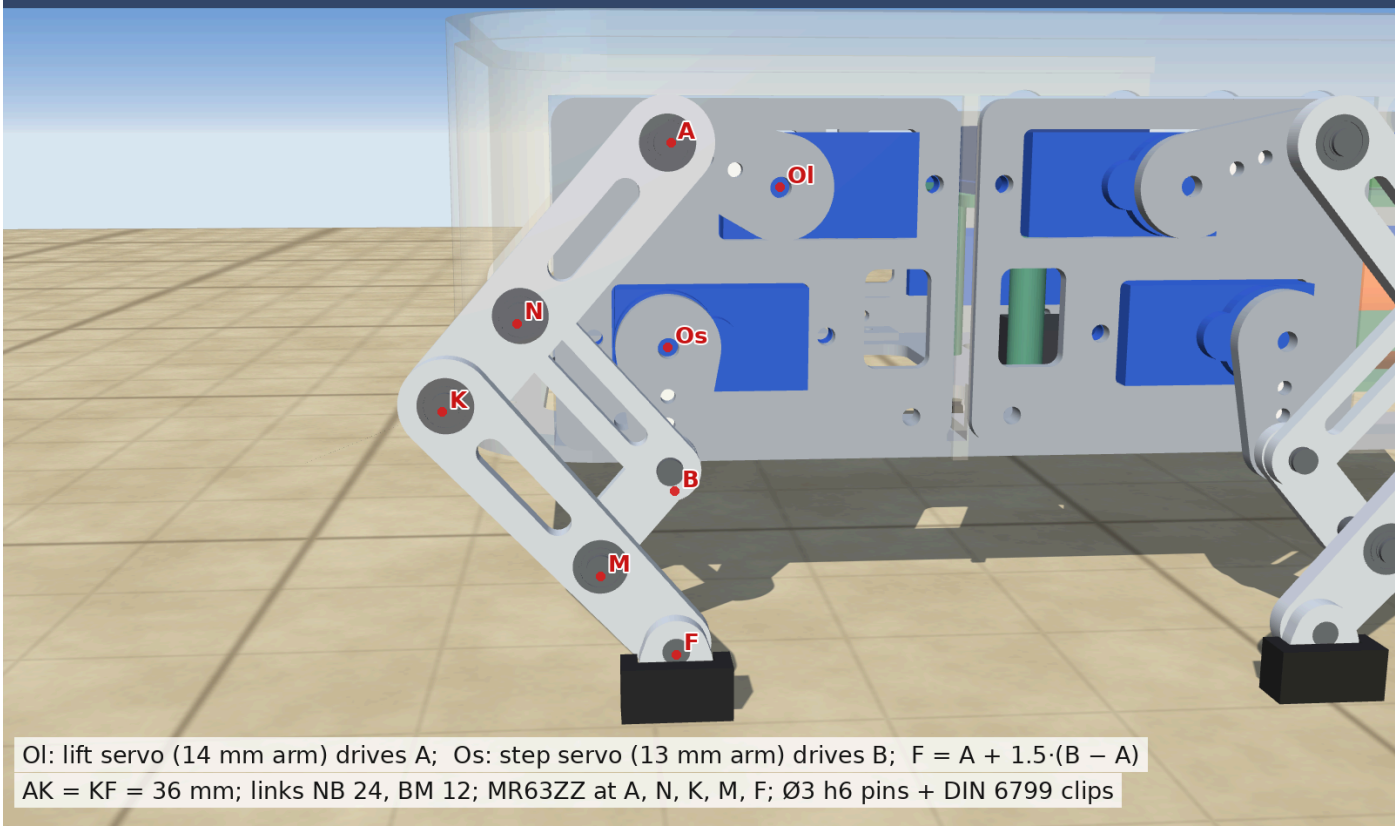
The previous 12-SG90 direct-drive design needed 1.66 kg·cm (margin 0.42). Comparison for this model (mass 516.9 g, the lone middle leg of the tripod carries W/2, dynamics ×1.3, horizontal force ±0.1·Fz, joint efficiency 0.9):

Var.	Scheme	SG90	Required torque, kg·cm	Margin vs 0.7	≥ 2?
A	Direct hip/knee drive (12 SG90, 'spider', previous scheme)	12	1.493	0.47	no
B	Tripod coupling: 2 SG90 lift + 2 step (three legs per servo via rods)	5	0.634	1.10	no
C	CHOSEN: decoupled λ=1.5 pantograph (as C2 v2), 2 SG90 per leg via R14/R13 rocker arms + PCA9685	13	0.304	2.30	yes

Why C works. In the pantograph the foot is F = A + λ(B − A). The lift servo drives point A along the arc of a 14 mm arm; the step servo drives B along a 13 mm arm. Lift and step are decoupled: the vertical foot force loads the lift shaft only with Fz·(λ − 1)·RA·cos φ (≈ 0.5 × 14 mm), and the step shaft with Fz·λ·RB·sin ψ, i.e. proportional to the foot excursion. Hence the stride is limited (±6 mm, 12 mm = 480 mm full-scale vs 600 mm on the prototype), but both margins exceed 2. Short arms, working angles φ ≈ ±30°, ψ ≈ ±20°. Lightweight: 2–2.5 mm 2024 aluminium chassis and links with lightening slots, 1 mm PETG hull, 18350 cells.

3. Leg kinematics

Leg: decoupled λ=1.5 pantograph on two SG90



Ol: lift servo (14 mm arm) drives A; Os: step servo (13 mm arm) drives B; F = A + 1.5·(B − A)
AK = KF = 36 mm; links NB 24, BM 12; MR63ZZ at A, N, K, M, F; Ø3 h6 pins + DIN 6799 clips

Item	Value (module frame: x along the body, z up, mm)
λ, thigh AK, shank KF	1.5; 36; 36 (AN = 24, NK = 12; KM = 24, MF = 12)
Lift servo Ol / arm	(-12.65; 56.0) / RA = 14, A = Ol + 14 (cos φ, sin φ)

Item	Value (module frame: x along the body, z up, mm)
Step servo Os / arm	(0; 38) / RB = 13, B = Os + 13 (sin ψ, −cos ψ)
Links	N–B 24 mm, B–M 12 mm (pantograph parallelogram)
Foot	ankle axis F at z = 7 in stance, lift 6 mm; TPU shoe, bottom at z = 0
Inverse kinematics	Newton on (φ, ψ) for A + 1.5(B − A) = F; identical in `cad/hx_params.py` and `firmware/hx_kin.h` (agree to 1e-4 rad)
Working angles	φ ≈ −30…+30°, ψ ≈ −19…+19° (servo travel ≤ 60°)

Layer stack (y outward from the bracket, mm): bracket 48–50 · SG90 body 29.6–52.3 (tabs on the inner face) · horn 54.8–56.3 · arms 56.3–58.3 · B–M 58.8–60.8 · N–B 61.3–63.3 · thigh AK 63.8–66.3 · shank KF 66.8–69.3 · foot 69.8–71.8. 0.5 mm PTFE washers between layers.

4. Calculations

4.1 Mass (FreeCAD solid volumes × density; bought parts from datasheets)

Group	g
SG90 ×13	117.0
electronics (ESP32, PCA9685, BEC, 2×18350, switch)	70.5
PETG hull + roof	68.0
chassis 2024-T3 2 mm	67.3
leg links 2024/6061	46.5
brackets 2024-T3	40.9
PETG tray/battery holder	16.2
Ø3 steel pins	15.8
wires, connectors, M2 fasteners	14.0
MR63ZZ bearings	12.6
aluminium angles	7.2
SG90 horns	6.0
DIN 6799 clips	3.1
ladder + mount PETG	3.0
PTFE spacers/washers	2.2
TPU foot shoes	2.0
Total (CAD)	**492.3**

Centre of mass: x = -6.8 mm, z = 44.0 mm.

4.2 Torque per servo (worst tripod case)

The supporting tripod {FL, MR, RL} is statically determinate: the middle leg is alone on its side → W/2; the front and rear legs share W/2 according to the CoM. Shaft torque by virtual work $\tau = J^{T} \cdot F / \eta$ (pantograph Jacobian), swept over the whole stance u = −6…+6 mm and both signs of the horizontal force.

Channel	Servo	Fz max, g	T max, kg·cm	Margin vs 0.7	Margin vs 1.8
0	FL lift	164.1	0.117	**5.98**	15.38
6	FL step	164.1	0.148	**4.73**	12.16
1	ML lift	336.0	0.253	**2.77**	7.11

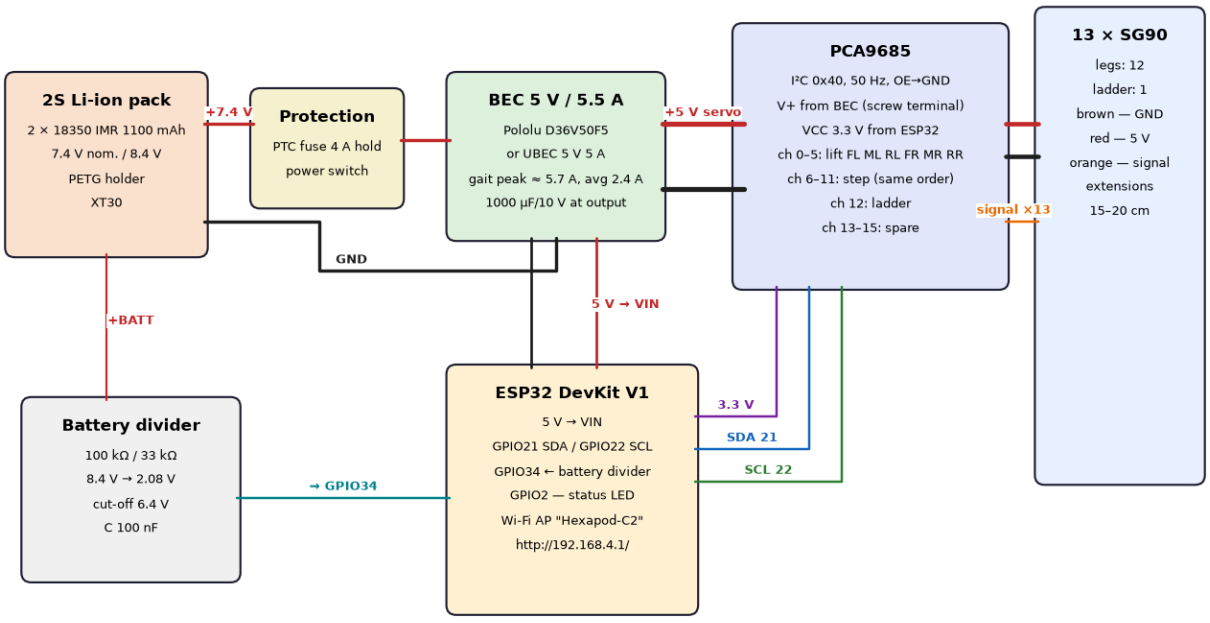
Channel	Servo	Fz max, g	T max, kg·cm	Margin vs 0.7	Margin vs 1.8
7	ML step	336.0	0.304	**2.30**	5.92
2	RL lift	227.5	0.163	**4.29**	11.04
8	RL step	227.5	0.194	**3.61**	9.28
3	FR lift	164.1	0.117	**5.98**	15.38
9	FR step	164.1	0.148	**4.73**	12.16
4	MR lift	336.0	0.253	**2.77**	7.11
10	MR step	336.0	0.304	**2.30**	5.92
5	RR lift	227.5	0.163	**4.29**	11.04
11	RR step	227.5	0.194	**3.61**	9.28
12	ladder	—	0.007 (20 g finger press at the tip: 0.082)	> 10	> 10

Sit/stand on 6 legs: lift ≤ 0.135, step ≤ 0.161 kg·cm.

4.3 Power

2S Li-ion 18350 IMR 1100 mAh (2×21 g), 7.4 V nominal; 5 V / 5.5 A step-down BEC (Pololu D36V50F5 or a 5 A UBEC) with a 1000 µF/10 V capacitor on the servo rail. Average gait current 2.35 A, peak 4.81 A (6 swinging + 6 loaded servos). Switching all 12 SG90 on at once would draw ≈ 7.8 A, so the firmware enables channels one by one every 80 ms. Average power ≈ 13.1 W → ≈ 29 min per charge. PTC fuse 4 A (hold) + switch; 6.4 V cut-off in firmware (100k/33k divider on GPIO34).

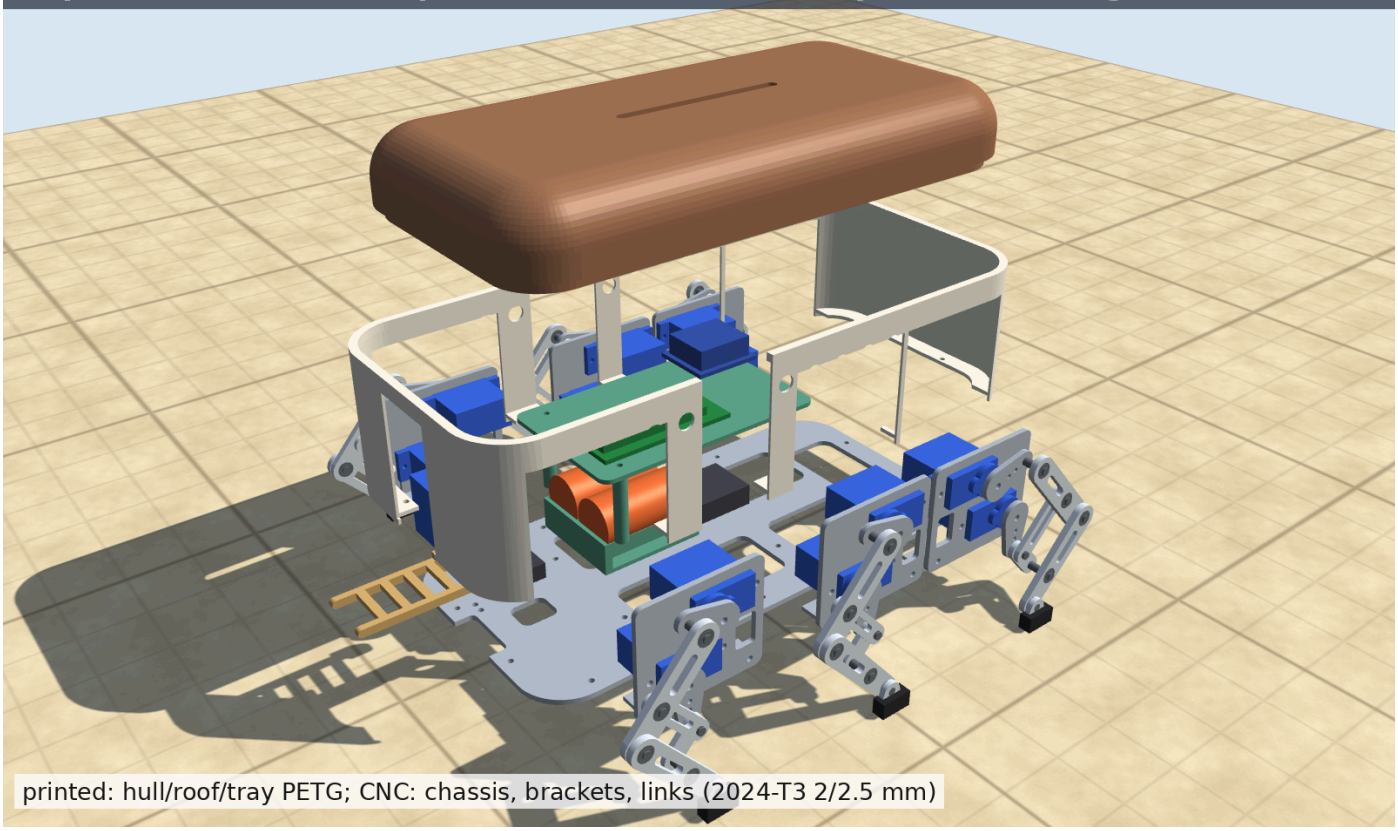
Wiring diagram — six-legged capsule C2, 1:40 model



Wire gauges: battery→BEC 0.5 mm² (AWG20), BEC→PCA9685 V+ 0.75 mm² (AWG18), stock servo leads. Common ground ESP32/PCA/BEC is mandatory. Never power the servos from the ESP32 board 5 V!

5. Design

Exploded view: roof, 2-piece hull, electronics tray, chassis, 6 leg modules



printed: hull/roof/tray PETG; CNC: chassis, brackets, links (2024-T3 2/2.5 mm)

- **Chassis** — 2 mm 2024-T3, 195 × 96 mm, R18, lightening windows, stern notch for the ladder. Carries the 6 leg modules, electronics tray, battery holder, ladder-servo bracket and the hull (4 M2 screws through the flange).
- **Leg module** (×6, identical, mirrored in x/y): 2 mm bracket + two 10×10×1.5 aluminium angles (M2 to the chassis), two SG90 on their tabs (2×6 self-tappers) through the bracket windows, aluminium arms screwed to the stock horn (M2 on the axis + 2 × 1.6 self-tappers).
- **Joints** — Ø3 h6 pins (lengths A 11.0, B 8.0, N 6.0, K 7.1, M 11.5, F 5.8 mm) with grooves for DIN 6799-2.3 clips. MR63ZZ bearings (3×6×2.5) in Ø6 H7 bores of the thigh (A, N, K) and shank (K, M, F); links rotate on pins in Ø3.05 holes; pins are pressed into Ø3 N7 holes of the arms, links and foot. Brass Ø5/3.1 spacers: A 5.5 mm, M 6.0 mm.
- **Hull** — 1 mm PETG tub, R20 in plan, split at x = −24: front 123 × 100 × 54, rear 75 × 100 × 54 (fits 220 × 220 × 250). Each half is screwed to the chassis — no glue. Windows for the leg brackets, stern ladder door, vent "portholes".
- **Roof** — removable, 1 mm PETG, R16 edges, locating lip and 4 magnets 4×2.
- **Electronics bay** — PETG tray on 4 posts (z = 52): ESP32 DevKit and PCA9685; below: 2 × 18350 holder, BEC and switch on the chassis.
- **Ladder** — folding, on SG90 #13 (150°: stowed vertically inside, deployed at 60° down to the table). The prototype's scissor stair gives only 1–2 mm actuator travel at 1:40 and is not feasible with an SG90 — replaced (see caveats).

Collision checks (FreeCAD boolean intersections): assembly in "stand" — 0 intersections; one leg in 6 extreme poses (u = ±6/0, z = 7/13) incl. pins and spacers — 0; ladder stowed/mid/deployed — 0 (`calc/collision_check.json`).

6. CNC parts and settings

Part	Purpose	t, mm	Qty	Size, mm	Holes
`link_AK`	thigh A-N-K	2.5	6	46×10	H7 ×3
`link_KF`	shank K-M-F	2.5	6	45×10	H7 ×3
`link_NB`	link N-B	2.0	6	31×7	N7 ×1, Ø3,05 ×1
`link_BM`	link B-M	2.0	6	19×7	Ø3,05 ×1, N7 ×1
`arm_lift`	lift arm R14	2.0	6	24×12	Ø2,4 ×1, Ø1,7 ×2, N7 ×1
`arm_step`	step arm R13	2.0	6	23×12	Ø2,4 ×1, Ø1,7 ×2, N7 ×1
`foot_plate`	foot plate	2.0	6	8×9	N7 ×1
`bracket`	leg-module bracket	2.0	6	48×42	Ø2,2 ×6
`chassis`	chassis	2.0	1	195×96	Ø2,2 ×22

- Material: 2024-T3 (D16T) or 6061-T6, sheet 2.0 and 2.5 mm; nesting `dxf/nest_sheet_t2.0.dxf` (≈ 200 × 275 mm) and `dxf/nest_sheet_t2.5.dxf` (≈ 200 × 50 mm).
- **Ø2 mm end mill** (2-flute carbide for aluminium); all inner radii ≥ 1.0 mm (built into the geometry). 0.1 mm finishing pass; feed 300–500 mm/min, 18–24k rpm, DOC 0.3–0.5 mm, coolant/alcohol mist.
- **Ø6 H7 (+0.012/0)** for MR63ZZ — circular interpolation with a finishing pass or 5.8 drill + 6H7 reamer; Ra 1.6. **Ø3 N7** — 2.9 drill + 3.0 reamer (press fit for h6 pins). **Ø3.05** — 3.0 reamer + polish (running fit). M2 — Ø2.2.
- DXF layers: CUT_OUTER, CUT_INNER, H7_BEARING, PIN_PRESS, PIN_RUN, M2, HORN, TEXT. Work holding: 0.3 mm tabs or vacuum/tape; deburr 0.2×45°. Optional anodising (before reaming the fits!).
- Per-part STEP in `step/`, flat profiles in `dxf/` (origin at the first joint).

7. 3D printing (FDM, bed 220 × 220 × 250)

Part	Material	Orientation	Settings
hull_tub_front / rear	PETG	open side up	0.4 nozzle, 0.2 layer, 2 perimeters (1.0 wall), 240/80 °C, no supports
roof	PETG	top down on the bed	0.2 layer, 2 perimeters, 5 bottom layers, no supports
tray, battery_holder, stair_mount	PETG	flat face down	3 perimeters, 30 % infill
ladder	PETG	flat	3 perimeters, 50 %
foot_shoe ×6	TPU 95A	flat	100 %, 25 mm/s

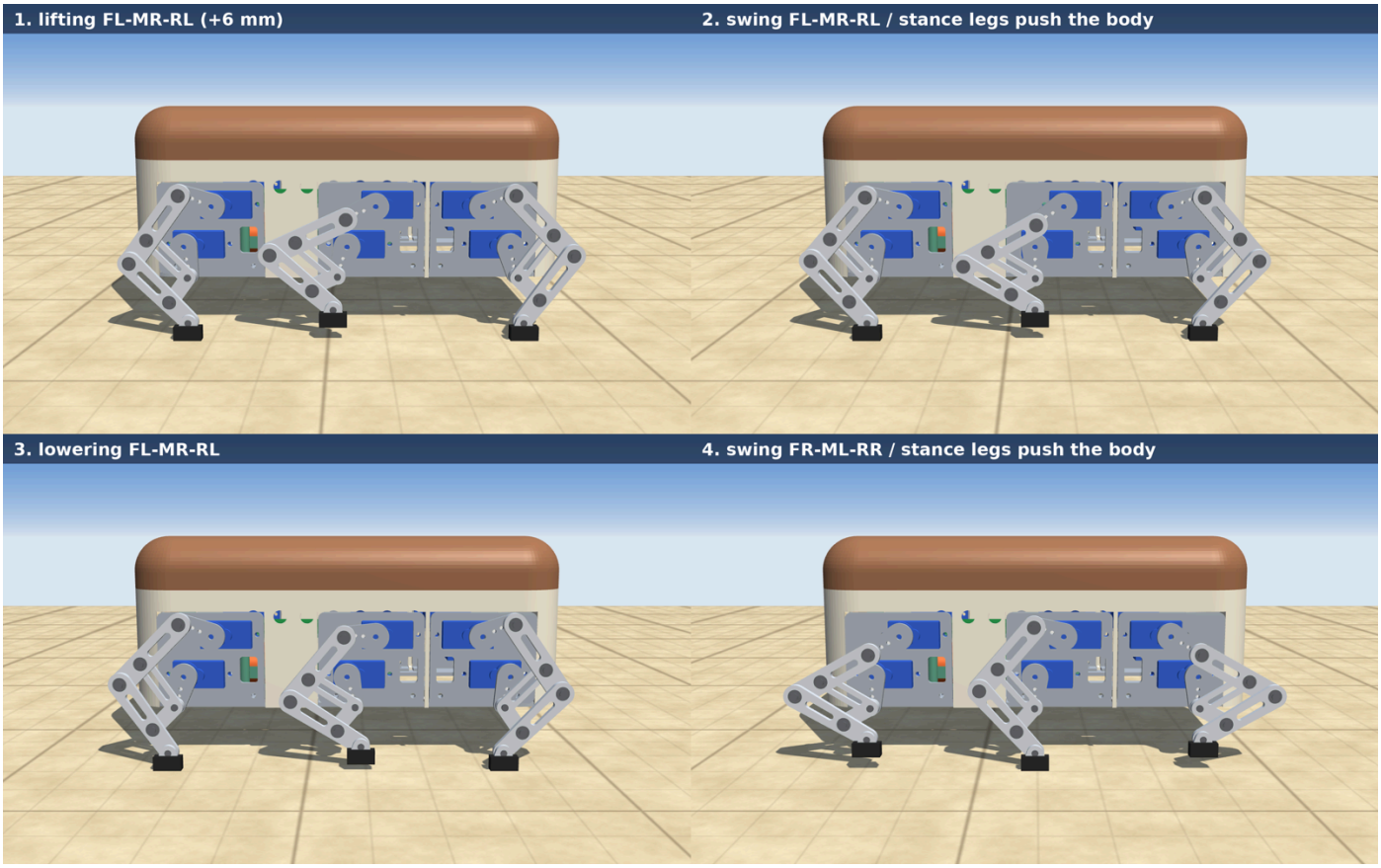
8. Assembly guide

1. Press the MR63ZZ bearings into the thighs and shanks (Ø5.9 arbour on the outer ring). Cut Ø3 h6 pins to the lengths in §5 and turn the 2.3 grooves (or use ISO 2338 dowels).
2. Press the pins: A and B into the arms; N into link NB; M into link BM; F into the foot. Check free swing.
3. Leg module: SG90s through the bracket windows, tabs to the inner face (2×6 self-tappers). Angles to the bracket (M2×6).
4. **Calibrate before fitting the arms**: flash the ESP32, open http://192.168.4.1/cal → "assembly mode" (all channels 1500 µs). Fit the horns so that the lift arm points horizontally towards the knee and the step arm points straight down; screw the aluminium arms on.

5. Build the pantograph: lift arm → 5.5 spacer → thigh (A); links BM and NB on pin B; N into the thigh; shank on K; M (6.0 spacer) into the shank; foot on F; 0.5 PTFE washers between layers; DIN 6799 clips on the ends.
6. Modules onto the chassis (M2 via the angles). Tray, battery holder, BEC, switch, ladder bracket and servo, ladder.
7. Wiring per §4.3; common ground; 1000 µF capacitor on V+.
8. Hull halves (M2 through the flange), magnets into the rim and roof (mind polarity!), roof on.
9. Fine calibration in /cal: offset ±400 µs and direction per channel, ladder end points; "save".

9. Firmware (`firmware/hexapod_c2`)

- ESP32 Arduino (esp32 core 3.3.x), no external libraries: own PCA9685 driver (I²C 400 kHz, 50 Hz), WiFi/WebServer/Preferences from the core. Build: `arduino-cli compile --fqbn esp32:esp32:esp32 hexapod_c2` — **compiles** (≈ 976 KB, 74 % flash).
- Channels: 0–5 lift FL, ML, RL, FR, MR, RR; 6–11 step in the same order; 12 ladder. Default direction −m·sy (mirrored modules), inversion in calibration.
- Gait: tripod, half-cycle lift 20 % / swing 60 % / lower 20 %; each leg has a half-cycle target u0 → u1, so command changes and "stop" are smooth (feet return to neutral within one half-cycle). Turning by different side stride factors (kL, kR); in-place turns with foot slip.
- Web remote: forward / back / left / right / stop / stand / sit / ladder, speed slider 30–100 % (half-cycle 2.4…0.9 s). /cal page — offsets, directions, ladder end points, assembly mode, save to NVS.
- Safety: ladder only when stationary; battery cut-off 6.4 V → sit; staggered servo start.



10. Files

- `cad/hx_params.py` — parameters, kinematics, placement; `cad/hx_profiles.py` — 2D CNC profiles; `cad/hx_model.py` — FreeCAD model (`freecadcmd hx_model.py`); `cad/hx_dxf.py` — DXF; `cad/hx_check_poses.py` — collisions; `cad/hx_verify.py` — checks.
- `cad/hx_assembly.FCStd`, `cad/hx_assembly.step` — assembly (267 bodies, all Part::Feature B-rep); `step/` — 33 parts; `dxf/` — 9 parts + 2 nesting sheets; `stl/` — 8 printed parts.

- `calc/calc.py` → `calc/results.json`; `calc/mass.json`, `calc/cnc_profiles.json`, `calc/collision_check.json`, `calc/verify.json`.
- `bom/bom_en.csv`, `bom/bom_en.md` — approx. **19,115 RUB**.
- `renders_en/`, `anim/hx_walk*.mp4/gif`, `hx_walk_poster.jpg`; `src/` — rendering and animation.

11. Caveats

- Designed and verified in CAD and by calculation; **not physically built yet** — build the first legs and bench-test them (current, SG90 heating, play).
- Stride reduced to 12 mm (480 mm full-scale vs 600 mm on C2) to keep the step-servo margin ≥ 2; with mass < 450 g ±7 mm can be restored (`hx_params.U_MAX` and `hx_kin.h`).
- The scissor stair is replaced by a folding ladder (scissor travel ≈ 1–2 mm at 1:40). In-place turning slips the feet (like the prototype without swivel feet).
- SG90 torque varies between batches; SG90 play ≈ 1° → ≈ 0.3 mm at the foot. Metal-gear MG90S are a drop-in replacement (+4.5 g each, not included).
- Prices are indicative (Oct 2026); machining cost depends on the shop.
- H7/N7 fits need reamers; otherwise use retaining compound for pins and bearings.