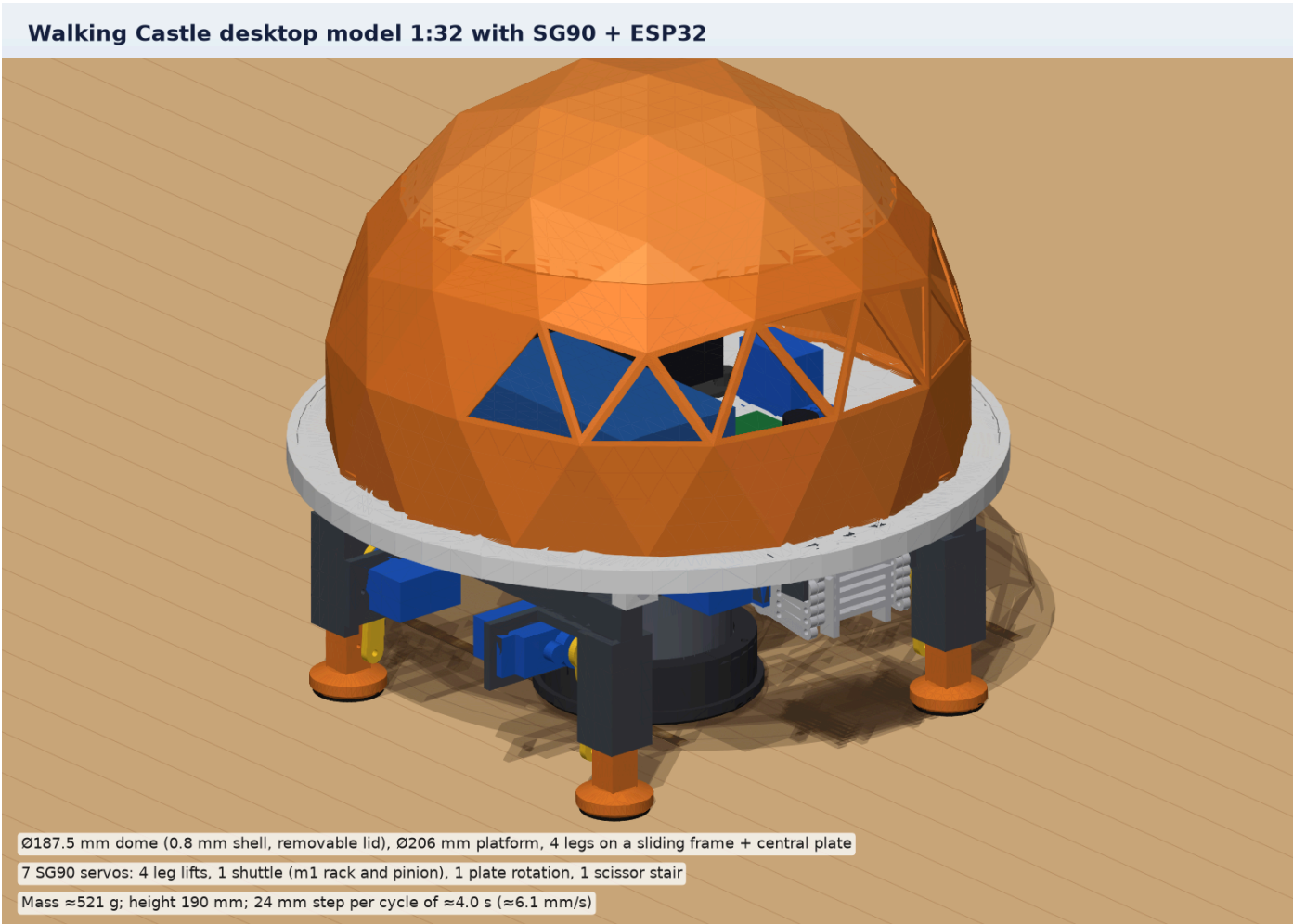


Working desktop model of the "Walking Castle" with SG90 + ESP32

All calculations are conceptual, without FEM strength analysis.

Basis: concept 1, scheme B: a dome on 4 legs, the legs on a common sliding frame, a central plate with rotation. Of all the options, this layout needs the fewest actuators. **Scale:** 1:32. **Actuators:** 7 × SG90 (4 leg lifts, 1 shuttle, 1 rotation, 1 scissor stair). **Mass:** ≈521 g. **Overall size:** Ø206 × 190 mm. **Speed:** a 24 mm step in ≈4 s (≈6 mm/s).

All figures are taken from `cad/mass.json` (masses and CoG calculated from the volumes of the FreeCAD parts) and `calc/results.json`. The model has not been physically assembled yet: clearances, friction and the real torque of the particular SG90s must be checked on the first build (section 12).



1. Summary

Parameter	Value
Prototype	Concept 1, scheme B: dome Ø6.0 m, platform Ø6.6 m, legs ±1.9 × ±2.0 m, step 600, lift 300
Scale	1:32: dome Ø187.5 mm, platform Ø206 mm (fits a 220×220 print bed), legs ±59 × ±62 mm
Height	190 mm on the legs. Underside of the deck 77 mm on the legs and 72 mm on the plate

Parameter	Value
Mass	≈ 521 g . Body with plate 407 g, leg frame with legs 115 g. Bought-in parts: battery 106 g, servos 63 g, rods 28 g, ESP32 10 g
Actuators	7 × SG90 : 4 lifts (crank r 7.5 + link 22 → slider), 1 shuttle (m1 z20 pinion + rack, stroke ±12 mm), 1 plate rotation (±25° per cycle), 1 stair
Torque margins (vs. continuous 0.7 kg·cm)	lift 2.5× (worst case on 2 diagonal legs, with dynamics ×1.3), holding while standing 16×, shuttle 3.4×, rotation 2.8×, stair 5×
Stability	on the legs ≥46 mm / ≥33°, on the plate ≥25 mm / ≥20.6°
Power	2S Li-ion 18650 → DC-DC 5 V 5 A → servo bus + ESP32 VIN. Peak ≈3 A, about 3 h of operation
Control	ESP32: Wi-Fi access point with a web remote + commands over USB serial. Smooth motion profiles, calibration in NVS, interlocks
Printing	19 part types, all ≤206 mm. About 310 g of filament (PETG + PLA), no supports except for the dome lid

2. Why scheme B and 7 servos

- **Scheme B** (4 legs on one frame + a central plate) walks using four synchronous lifts and one shuttle. At any moment the model stands **either on 4 feet or on the plate**, and it is stable in both poses. There is no three-support problem to solve, as in scheme A.
- **Scheme A** (each leg has its own pair of actuators) would need 8 SG90s and would have a small margin on three legs: 113 mm full-size, i.e. ≈3.5 mm in the model. On a table, play in the joints would use up such a margin.
- **Rotation** is one servo in the column: on the plate it rotates the body relative to the plate.
- **The stair** is the seventh servo: this is Pablo's requirement.

3. Choosing the scale for SG90

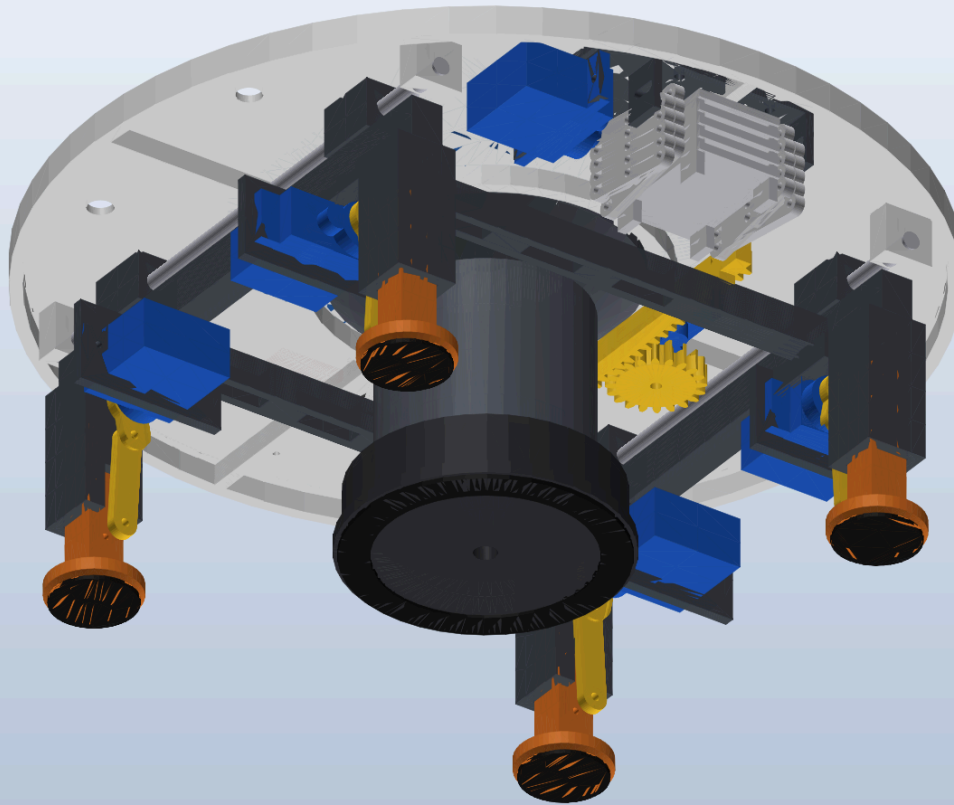
Scale	Dome / platform	Mass (estimate)	Lift torque	Printing
1:25	240 / 264 mm	≈750 g	margin ≈1.7×	the platform does not fit on 220×220
1:32	187.5 / 206 mm	521 g (CAD)	margin 2.5×	everything fits
1:40	150 / 165 mm	≈420 g (battery, servos and ESP32 do not shrink)	margin ≈3×	not enough room inside the dome for 2×18650 and wiring

The SG90 develops 1.8 kg·cm at stall at 4.8 V, but realistically 0.6–0.8 kg·cm continuously. 1:32 is the largest scale at which the platform prints as a single part and the lift keeps a margin of more than 2 even in the worst case.

What deliberately differs from strict scale: * A 24 mm step instead of 18.75, so that the motion is visible. * An 11 mm lift instead of 9.4. * A Ø48 column instead of 13: the rotation servo sits inside it. * A Ø66 plate instead of 62.5.

4. Design

View from below: leg frame, shuttle rack, column with plate, stair



Blue - SG90; yellow - cranks, links, rack and pinion; Ø4 rods - leg-frame guides (bushings in the frame)

Body (fixed part)

- **Ø206 platform.** 1.6 mm deck, rim, ring and 4 spokes underneath. Ø4×144 steel rods are pressed into 4 posts: these are the leg-frame guides. The column is fixed underneath (4 × M3). The shuttle servo passes through the deck: housing on top, shaft down.
- **Dome:** geodesic 3V 5/8, 0.8 mm shell, glazing openings $\pm 65^\circ$ as in concept 1. It consists of two parts:
 - the lower part with a flange is fixed with 4 M2 self-tapping screws;
 - the **removable lid** above 0.62R (Ø142 mm) sits on a centring lip with a 0.3 clearance. It gives access to the electronics.
- **Electronics on the deck:** a 2×18650 holder with BMS, a tray with the ESP32, the DC-DC, a capacitor and a switch.

Leg frame (moving, stroke ± 12 mm)

- A 133×134 mm frame: 2 longitudinal and 2 transverse beams, 4 Ø4.6 bushings sliding on the rods (alternatively LM4UU). A 104 mm m1 rack is fixed to the cross members.
- **4 leg modules.** Each is a 15×15 guide with a 9×9 square slider and a Ø22 foot with a TPU pad. The SG90 servo is mounted along the X axis. Drive: crank $r\ 7.5 \rightarrow$ link 22 $\rightarrow$ slider pin (slider-crank mechanism).
- **Crank positions** (angle from bottom dead centre):

Position	Angle
standing	10°

Position	Angle
feet touching, body on the plate	63°
feet raised by 6 mm	109°

Full servo travel is 99°.

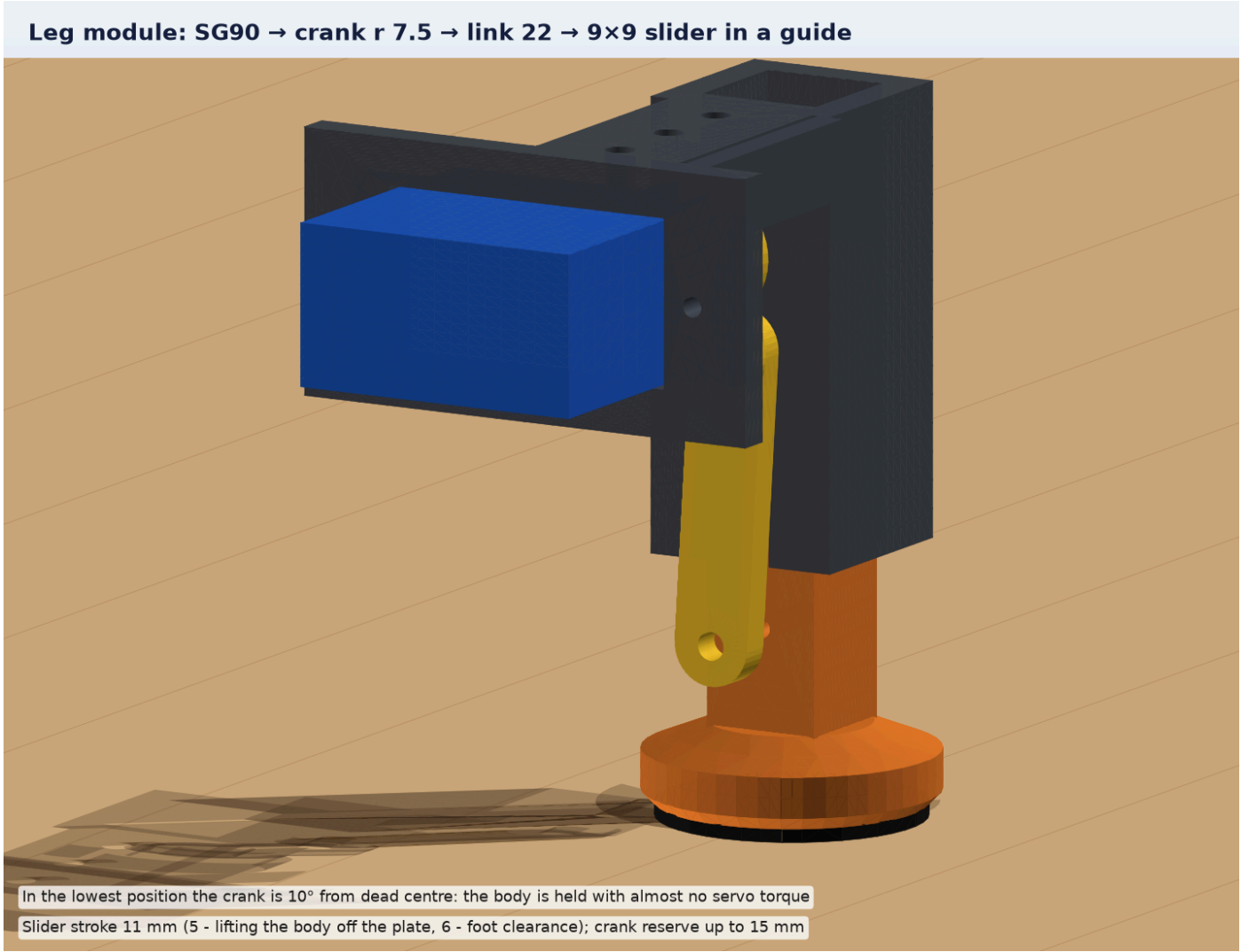


Plate and rotation

- **Column:** a Ø48.2/45 tube with a shelf for the SG90 flange (shaft down).
- **Ø66 plate** with a socket for the cross horn. Axial play is 1 mm, so the servo does not carry the weight. The load goes through a thrust face: the column flange rests on the plate hub, with lubricated friction.
- When the body is raised onto the legs, the plate hangs on a **split retainer** (2 half-rings, 3 × M2).
- Under the plate is a **rubber ring**: it stops the plate from turning while the body rotates.

Scissor stair (pantograph)

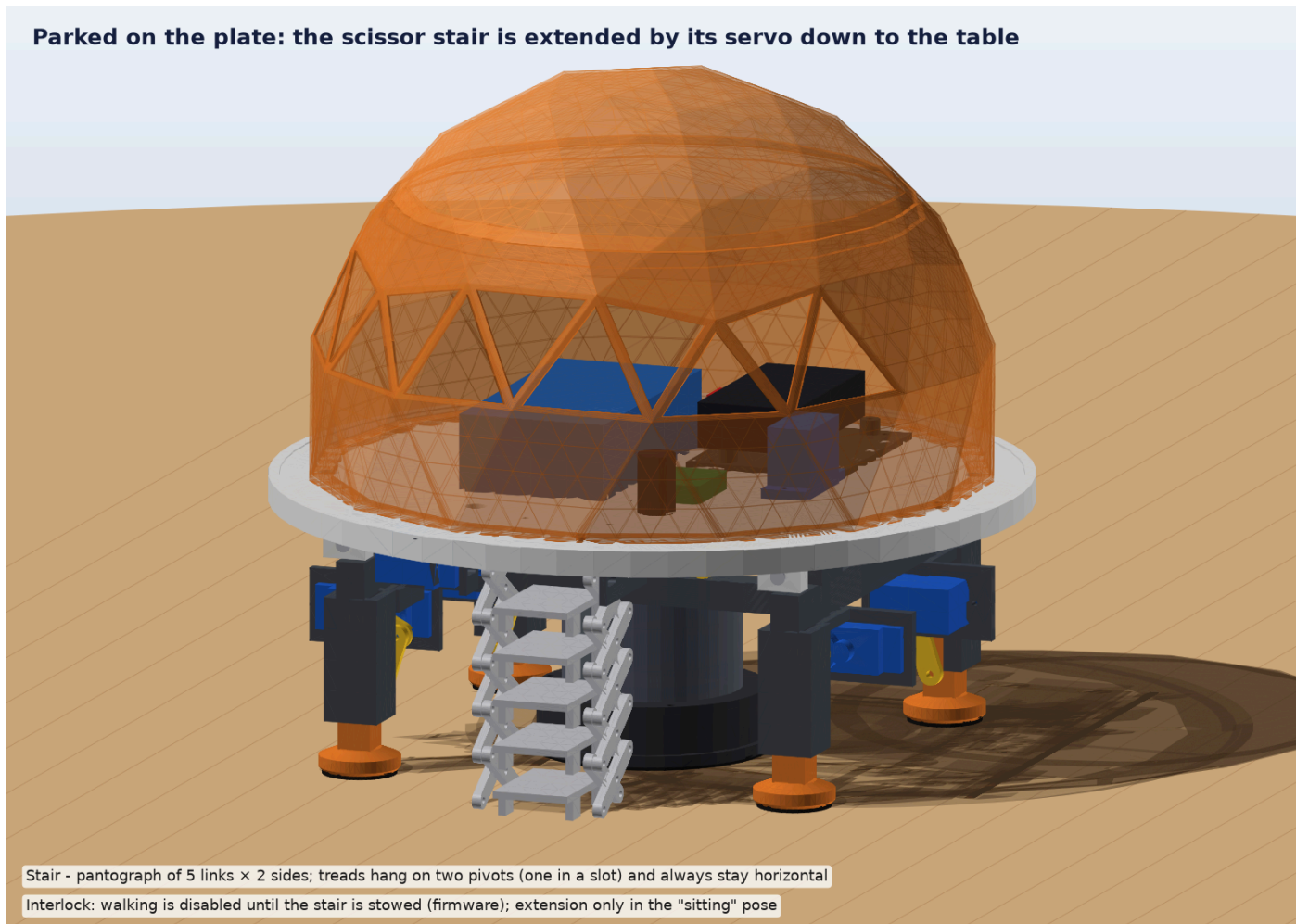
- 5 cells × 2 sides, 24 mm links. The treads hang on two pivots at the same level, one of them in a slot, so they are **always horizontal**.
- **Drive:** the top pivot A sits directly on the SG90 shaft (the driving link with a horn socket); pivot B slides in a slot in the bracket.
- **Positions:**

Position	Angle α	Height	Width
folded	8°	16.7 mm	23.8 mm (under the deck, at the front)

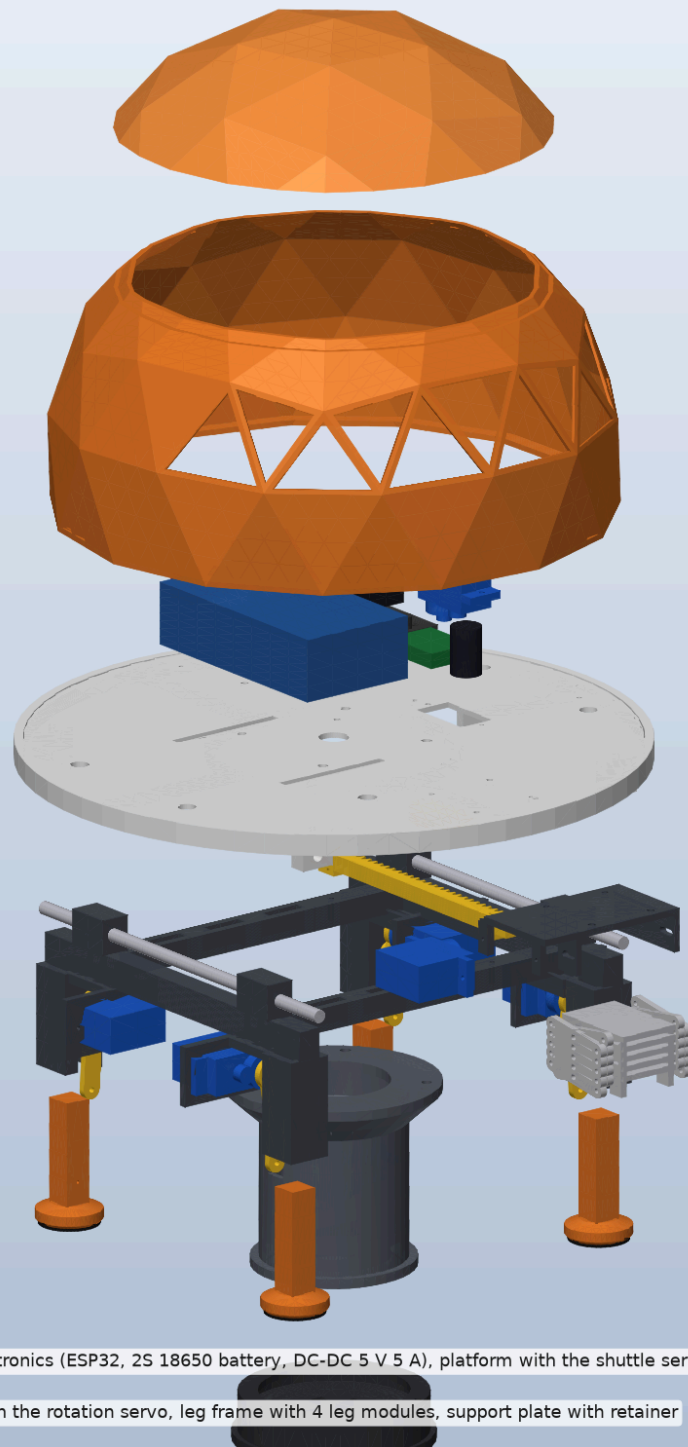
Position	Angle α	Height	Width
extended	31.7°	63 mm (down to the table, "sitting" pose)	—

The servo turns only 24°.

Parked on the plate: the scissor stair is extended by its servo down to the table



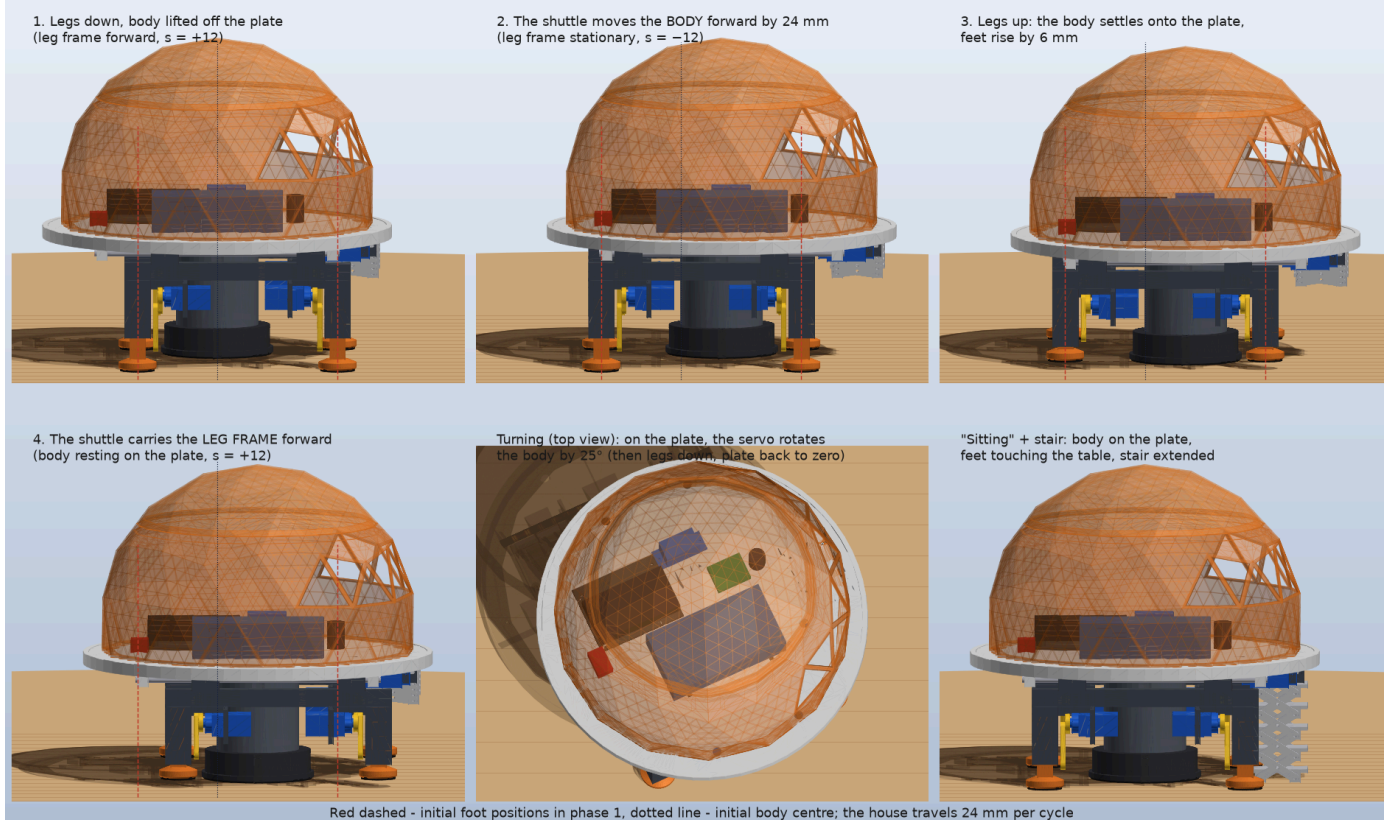
Exploded assembly view



Top to bottom: dome lid, dome, electronics (ESP32, 2S 18650 battery, DC-DC 5 V 5 A), platform with the shuttle servo, bracket and scissor stair, column with the rotation servo, leg frame with 4 leg modules, support plate with retainer

5. Gait, turning, stair

Scheme B step cycle (side view, dome semi-transparent)



"Forward" cycle (s is the position of the leg frame relative to the body). Total ≈ 4.0 s per 24 mm ≈ 6 mm/s (0.36 m/min).

Phase	Action	Support	Time, s
1	Legs down ($\phi 109^\circ \rightarrow 10^\circ$): the feet land on the table, the body rises by 5 mm, the plate hangs	4 feet	0.95
2	Shuttle $s +12 \rightarrow -12$: the body moves forward by 24 mm	4 feet	1.0
3	Legs up: the body settles onto the plate, the feet rise by 6 mm	plate	0.6
4	Shuttle $s -12 \rightarrow +12$: the leg frame is carried forward	plate	0.8
	Pauses between phases		4×0.15

Backward: the same cycle in reverse order.

Turning (25° per cycle, up to $\pm 60^\circ$ possible): 1. The body is on the plate, legs raised. The servo in the column rotates the body relative to the stationary plate. 2. Legs down: the body rises together with the plate. 3. The servo returns the plate to zero (the plate is in the air). 4. Legs up.

Stair: * The `stair_down` command is executed only from the "sitting" pose (body on the plate, feet on the table) and only when not moving. * Until the stair is stowed, the forward/back/left/right/stand commands are blocked.

6. Torque and friction calculation (calc/calc.py)

SG90: 0.7 kg·cm continuous (0.069 N·m), 1.8 kg·cm at stall.

Actuator	Load	Torque	Margin (continuous / stall)
Leg lift, worst case	505 g of lifted mass on 4 legs; $\times 2$ (2 diagonal legs carry it) $\times 1.3$ (dynamics) = 3.2 N per slider; lever arm up to 7.8 mm; efficiency 0.9	0.28 kg·cm	2.5× / 6.3×
Lift, nominal (shared equally by 4)	1.24 N	0.11 kg·cm	6.4×
Holding while standing ($\phi = 10^\circ$, lever arm 1.7 mm)	2.5 N	0.044 kg·cm	16×
Shuttle, phase 2 (body along the rods)	378 g, $\mu = 0.35$ (PETG on steel, dry), misalignment $\times 1.3$, acceleration	0.21 kg·cm	3.4×
Shuttle, phase 4 (frame hanging)	115 g	0.06 kg·cm	11×
Rotation on the plate	thrust face r 7...27 (r_mean 19 mm), $\mu = 0.25$, weight 492 g + inertia	0.25 kg·cm	2.8×
Stair	16 g, worst angle 8° , $\times 1.5$ for friction in 30 pivots	0.14 kg·cm	5×

Slip checks: * Phase 2: the shuttle pushes with 1.7 N, the feet hold up to 2.6 N at μ 0.5 (TPU on the table). * Phase 4: force 0.5 N, the plate holds up to 2.2 N. * Rotation: the rubber ring holds the plate with a 3.6× margin. Without rubber (PETG on the table) the margin is only ≈ 1.2 .

Resolution: the SG90 dead band is $\approx 1^\circ$. That is 0.03 mm of lift near bottom dead centre and 0.17 mm of shuttle travel.

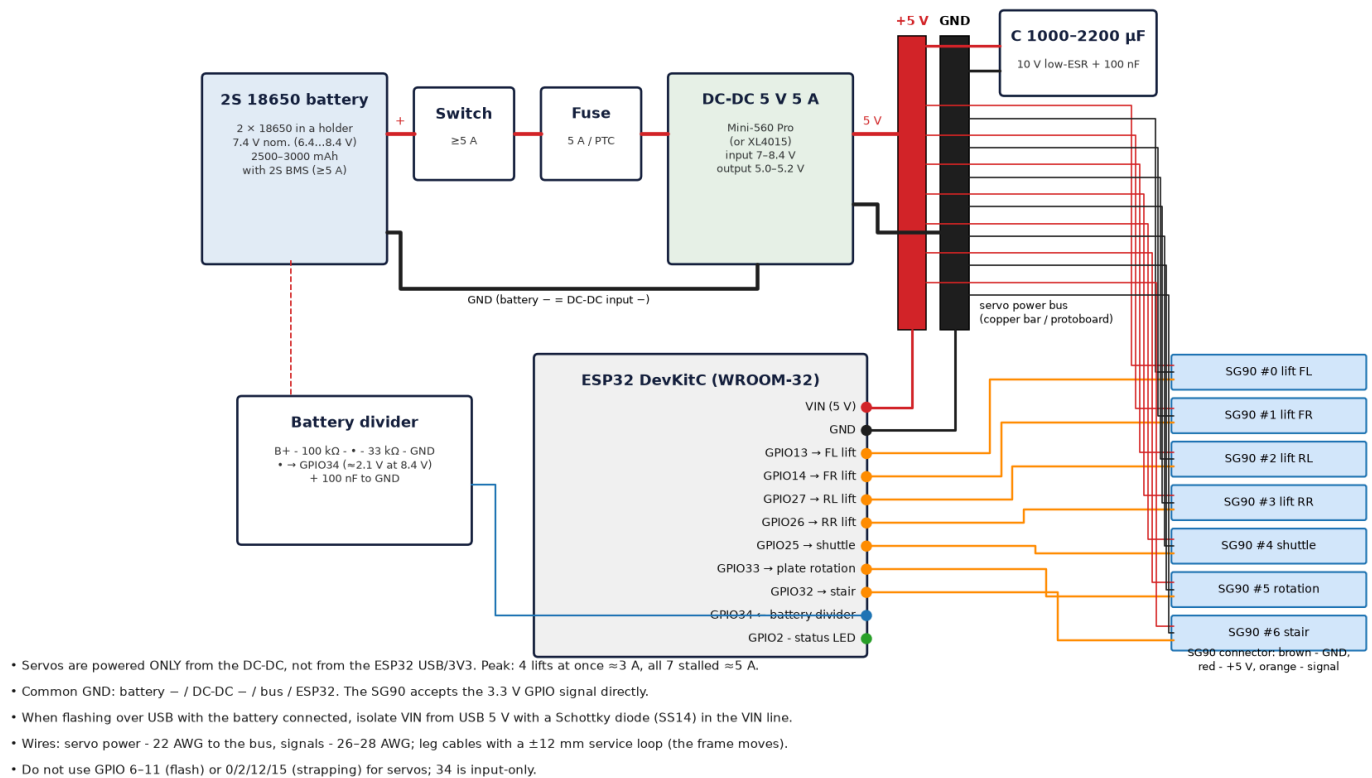
7. Stability

Pose	Support	CoG margin to the edge	Tip-over angle
Phase 1 (frame forward)	4 feet	53 mm	36.6°
Phase 2 (body forward)	4 feet	46 mm	32.8°
Phases 3–4	Ø64 plate	25–29 mm	$20.6\text{--}23.5^\circ$
Turning / "sitting"	plate (+ feet)	27.5 mm	22°

- The CoG on the legs is at a height of 72 mm. The battery is offset to $Y \approx -20$ so that the CoG is near the axis.
- Shuttle accelerations are $\approx 0.1 \text{ m/s}^2$; their effect on the CoG is negligible.
- On an inclined table (up to 10°) and on fabric the model is stable, but grip is worse on fabric.

8. Electrics

Wiring diagram: ESP32 + 7 × SG90, 2S Li-ion supply → DC-DC 5 V 5 A



- **Source: 2S 18650 (7.4 V) → DC-DC 5 V 5 A.**
- Peak with 4 lifts at once ≈ 3 A. If all 7 servos stall: ≈ 5 A.
- A "1S + boost converter" option is not suitable: 4.5-5 A would have to be drawn from a single cell, and cheap boost converters handle 1-2 A. There would be voltage dips and ESP32 resets.
- A ~50 g lighter option: 2S LiPo 800-1000 mAh.
- **Protection and filtering:** a 1000-2200 µF capacitor on the bus, a 5 A fuse, a switch. A 2S BMS is mandatory for 18650 cells.
- **ESP32 pins:**

Actuator	GPIO
lift FL / FR / RL / RR	13 / 14 / 27 / 26
shuttle	25
rotation	33
stair	32
battery (100k/33k divider)	34
status LED	2

Leg designations: FL – front left, FR – front right, RL – rear left, RR – rear right. * **Leg cables:** the frame moves by ±12 mm, so a service loop is needed.

9. Firmware (firmware/walking_castle_sg90/)

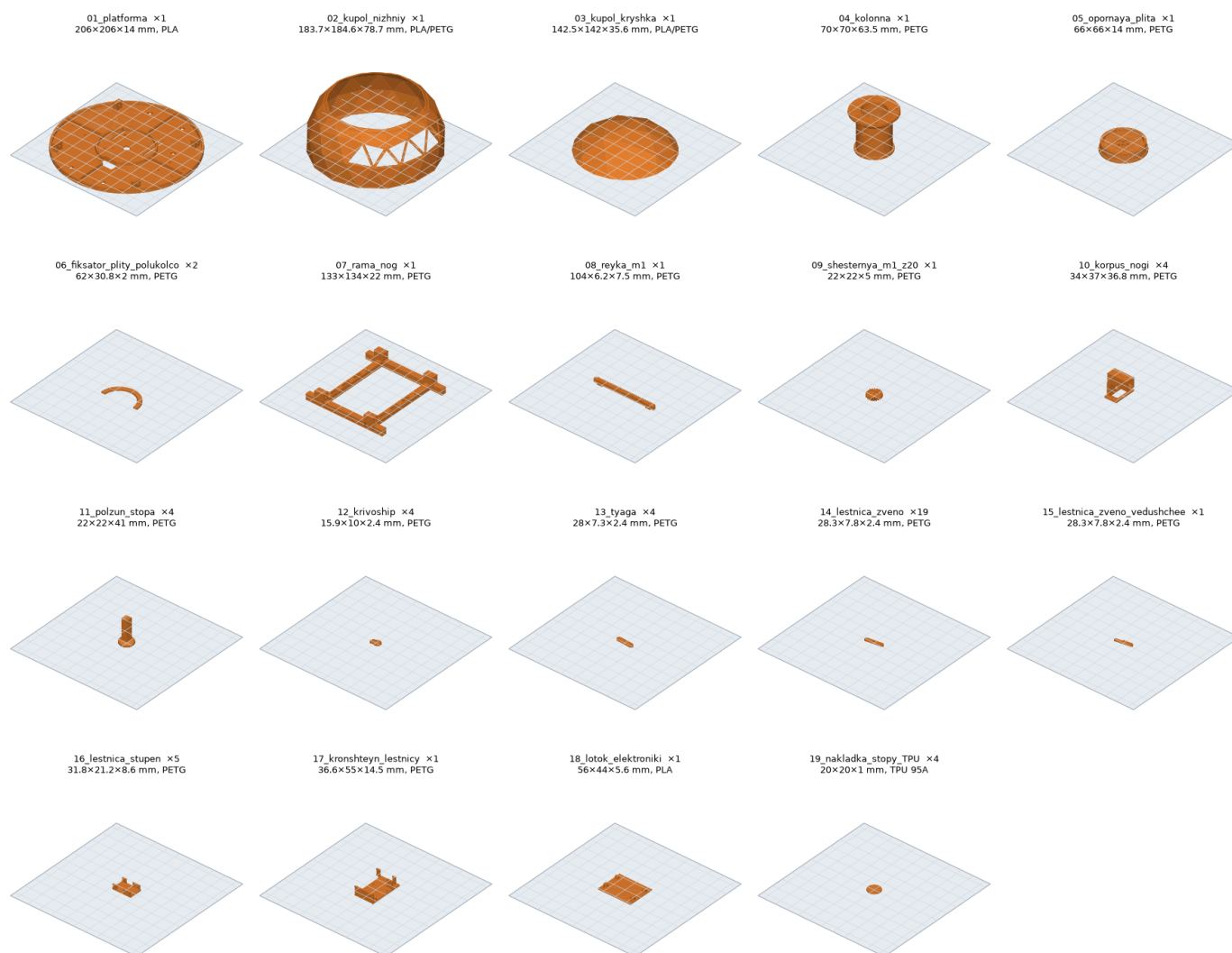
- **Build:** Arduino IDE 2.x or arduino-cli, **esp32 3.x** core, **ESP32Servo** library, "ESP32 Dev Module" board. The sketch **was compiled** with arduino-cli (esp32:esp32 3.3.12, ESP32Servo 3.2.1): 967 KB (73% of flash), 49 KB RAM.
- **Control:**

- Wi-Fi access point WalkingCastle / castle123 → <http://192.168.4.1>: buttons, speed slider, calibration, status in JSON.
- The same commands via the serial monitor at 115200.
- **Commands:**
 - motion: forward [N], back [N] (0 = until stop), left, right, stop;
 - poses: stand, sit, rest;
 - stair: stair_down, stair_up;
 - settings: speed 0.3...2, cal <0..6> <±deg>, save, center, status.
- **State machine:** a queue of phases (legs / shuttle / rotation / stair / pause), cosine velocity profile. stop takes effect at the end of the current cycle, so the model always stops in a stable pose.
- **Interlocks:**
 - walking with the stair extended;
 - the stair outside the "sitting" pose or during motion;
 - battery below 6.4 V → stop + sit.
- **Conversion to servo angles:**
 - lift: $90^\circ \leftrightarrow \phi 60^\circ$; the sign is reversed on the right legs;
 - shuttle: $5.73^\circ/\text{mm}$;
 - stair: $90^\circ \leftrightarrow \alpha 20^\circ$.
- Calibration offsets are stored in NVS (Preferences).

10. Printing

Part	Qty	Material	Orientation / settings
01 platform Ø206	1	PLA	deck down; 3 walls, 20% gyroid; no skirt or brim (220 bed)
02 dome, lower part Ø184	1	PLA / PETG	base down; 0.8 mm wall (2 perimeters of 0.4), no infill and no supports
03 dome lid Ø142	1	PLA / PETG	cut face down; tree supports from the bed only
04 column	1	PETG	flange down; 4 walls; 45° chamfers instead of supports
05 plate / 06 retainer (2 half-rings)	1 / 2	PETG	flat
07 leg frame 133×134	1	PETG	beams down; 4 walls, 30%
08 m1 rack / 09 m1 z20 pinion	1 / 1	PETG	flat, 0.12 layer
10 leg housing	4	PETG	servo plate down; 4 walls, 40%
11 slider with foot	4	PETG	foot down; 100%
12 crank / 13 link	4 / 4	PETG	flat; 100%
14 stair link / 15 driving link	19 / 1	PETG	flat
16 tread	5	PETG	flat
17 stair bracket	1	PETG	plate down
18 electronics tray	1	PLA	flat
19 foot pad	4	TPU 95A	or 1 mm rubber

Printed parts in print orientation on a 220×220 bed (all of them fit)



The part labels in this figure are the STL file names (01_platforma, 02_kupol_nizhniy, ...); their English names are given in the table above under the same numbers.

General settings: * 0.4 nozzle, 0.2 mm layer. * Solid volume of the parts 314 cm³; with infill ≈310 g of filament. * Print time ≈22–28 h. The platform and the dome take 5–7 h each.

Tolerances (parameter CLR = 0.3 in kinematics.py):

Feature	Size
Clearance fits	0.3 per side
SG90 pockets	22.5+0.6 × 12.2+0.6
Horn sockets	+0.3
For M2 self-tapping screws	Ø1.6
M2 clearance holes	Ø2.2
M3	Ø3.3
Frame bushings	Ø4.6; ream with a 4.5 drill to a light sliding fit
Rods in the posts	Ø3.9, interference fit
Stair pivots	Ø2.0–2.2 for 1.75 filament rod or an M2 screw

If your printer prints oversize, decrease or increase CLR and rebuild.

11. Bill of materials (BOM, approximate 2026 prices, RUB)

Item	Qty	Price
SG90 servo (buy 1-2 spares)	7 (+1)	8 × 120 = 960
ESP32 DevKitC / DevKit V1 30-pin	1	450
DC-DC Mini-560 Pro 5 V 5 A (or XL4015)	1	200
18650 cell, 2500-3000 mAh, 20 A (Samsung 25R / LG HG2 / equivalent)	2	800
2×18650 holder + 2S BMS 5-8 A	1	150
2S balance charger (if you do not have one)	1	400
6 A switch, fuse holder + 5 A fuse	1	90
1000-2200 µF 10 V capacitor, 100 nF, 100k/33k resistors, SS14 diode	—	50
Ø4 mm × 144 steel rod (hardened / silver steel)	2	150
(option) LM4UU linear bearings	4	200
M2×6/8/10/12 screws with nuts (set), M3×8 + 4 nuts	—	280
22/26 AWG wire, 15 cm servo extensions ×4, protoboard for the bus	—	200
1 mm rubber (self-adhesive) for the plate and feet	—	100
Filament: PETG ≈200 g + PLA ≈120 g + TPU ≈2 g	—	600
Total		≈4,500-5,000 RUB (≈50-60 USD)

12. Assembly and setup

- Preparing the parts.** Print and deburr. * Ream the frame bushings (4.5 mm), the pivot holes (2.0 mm) and the slider slot. * The sliders must move in the guides without play and without binding. Lubricate them with silicone grease or dry PTFE lubricant.
- Electronics.** * Set the DC-DC to **5.1 V before connecting the servos**. * Assemble the power bus with the capacitor and connect per the diagram (section 8). * Flash the ESP32 and check the web page.
- Centring the servos.** Connect all 7 servos without horns and send the `center` command: all servos will move to 90°.
- Leg modules.** * Insert the slider into the guide. * Connect the link to the slider (M2×12) and to the crank (M2×8 + nut, washer). * Screw the crank to a single-arm horn shortened to 11 mm (2 self-tapping screws from the SG90 kit). * Insert the servo into the housing plate (2 self-tapping screws from the kit). * Fit the horn on the spline so that the crank points **60° from vertical, downward and towards the centre of the model**. Tighten the horn screw.
- Leg frame.** Screw the leg housings to the beams from below (3 × M2×8 per leg), and the rack to the cross members (2 × M2×8).
- Guides.** Pass the Ø4 rods through the frame bushings, press them into the platform posts and secure them with M2 self-tapping screws from above.
- Shuttle.** * Insert the servo into the deck opening from above, shaft down, and fix it with 2 self-tapping screws. * Set the frame to the centre (s = 0) and fit the pinion with the cross horn so that it meshes with the rack.
- Rotation.** * Insert the servo into the column from above, shaft down, and fix it with 2 self-tapping screws on the shelf. * Screw the column to the deck with 4 × M3. * Fit the cross horn on the spline at 90°. Put on the plate: the horn goes into the socket. * Close the plate with the retainer half-rings (3 × M2). Lubricate the thrust face.

9. **Stair.** * Join the links with pins: 1.75 filament rod with melted ends or M2×8 + nyloc nut; the treads go on the lower pivots of each cell. * Screw on the bracket with 4 × M2. * Fit the driving link onto the servo horn at $\alpha = 20^\circ$: mid-travel, center command.
10. **Electronics and dome.**
 - Tray with the ESP32 and DC-DC, battery holder (cable ties through the slots), switch.
 - Route the leg cables through the Ø6 holes with a ± 12 mm loop.
 - Screw on the lower part of the dome with 4 × M2 and put the lid on the lip.
11. **Calibration.**
 - cal i $\pm$ deg for each servo;
 - sit: all 4 feet touch the table;
 - stand: the body is raised by 5 mm, the plate hangs 3–4 mm up;
 - rest: the feet are 6 mm above the table;
 - the stair in stair_down touches the table.
 - Check that left turns left. If not, change the sign of DIR[S_TURN] in the sketch.
 - Save: save.
12. **First run.** speed 0.6, then forward 3. Watch that the feet do not slip in phase 2 and the plate does not slip in phase 4.
 - If a lift servo "hums" while standing, shift its calibration by 1–2°.
 - When idle, keep the model in sit: the leg servos are unloaded.

13. ASV variant (6 legs × 2 SG90 = 12 servos): estimate

- **Mass:** ≈ 570 g (12 servos 108 g, legs 6 × 12 g, body and battery as here). On three legs (tripod gait) each leg carries 1.8 N; $\times 1.5$ unevenness, $\times 1.3$ dynamics = 3.6 N.
- **Torque:** with the foot ≈ 45 mm out from the "hip", **1.7 kg·cm** is needed. This is 2.4 times the SG90's continuous torque and almost its stall torque. **It does not work.**
- **Peak current** $12 \times 0.7 \approx 8.4$ A: an 8–10 A BEC and a PCA9685 (16 PWM channels over I²C) are needed.
- **What it would take to make this variant work** (one of):
- MG90S (2.2 kg·cm, metal gears): margin ≈ 1.3 , on the edge;
- MG996R / DS3218 at a scale of $\approx 1:20$, but with a mass of about 1.5 kg;
- a 1:50 scale (Ø120 dome) with the ASV pantograph leg, where the vertical servo works through a lever with a mechanical advantage of ≈ 2 –3.
- **Conclusion:** for SG90, scheme B with 7 servos is the right choice. The ASV variant makes sense as a separate project on MG90S.

14. Caveats and risks

- **Not assembled and not tested.**
- Friction (μ of the bushings 0.35, of the plate thrust face 0.25, of the feet 0.5) and the $\times 2$ load unevenness are estimates.
- Real SG90s vary a lot (counterfeits give 0.5 kg·cm and 2–3° of play).
- The lift margin is 2.5× in the worst case. If a servo cannot cope: lubricate, fit an MG90S (same mounting, 13.4 g) or lighten the model; 2S LiPo instead of 18650 saves 50 g.
- **A crank at 10° from dead centre** holds the body with almost no torque. But if the crank passes over dead centre (calibration error), the leg will "fold". So calibrate the lift carefully using stand.
- **The 0.8 mm dome** is a decorative shell: do not lift the model by the dome. Print the lid with supports.
- **A 206 mm platform on a 220 bed:** no skirt or brim, use glue or PEI.
- **The plate on the table:** without rubber the plate turns during rotation. On slippery glass or varnish the model may slip in phase 2; TPU on the feet is needed.
- **The model is faster than a "similar" full-size house.** By Froude scaling, the full-size 0.92 m/min corresponds to 0.16 m/min in the model, while the model walks at 0.36 m/min. This is fine

for a demonstration; the speed is changed with the `speed` command.

- **At power-up** the servos jerk into the starting `sit` pose, so switch the model on while it is standing on the plate.

15. Files

- `cad/sg90_model.py`: parametric FreeCAD 1.0 model (`freecadcmd sg90_model.py`): all parts, assembly, poses, masses, collision check in 5 poses (no collisions). Parameters are in `cad/kinematics.py`.
- `cad/sg90_assembly.FCStd`, `cad/sg90_assembly.step`: assembly in the "standing" pose. 72 bodies, all STEP bodies are valid.
- `stl/01...19_*.stl`: parts in print orientation, all closed (solid, no non-manifold geometry).
- `cad/mesh_*/`: pose meshes for rendering; `cad/render_mpl.py`, `cad/render_parts.py`: renderers.
- `calc/calc.py` → `calc/results.json`: calculation.
- `firmware/walking_castle_sg90/walking_castle_sg90.ino` (+ `castle_types.h`): firmware.
- `renders/01...08`: isometric view, view from below, exploded view, stair, step phases, leg assembly, parts on the print bed, wiring diagram.
- `doc/wiring.py`: wiring diagram; `doc/build_pdf.py`: builds HTML/PDF from this MD.