

MOXIE

610 mm Adaptive-Foot Humanoid Robot

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Concept Design, Procurement List, and Assembly Guide

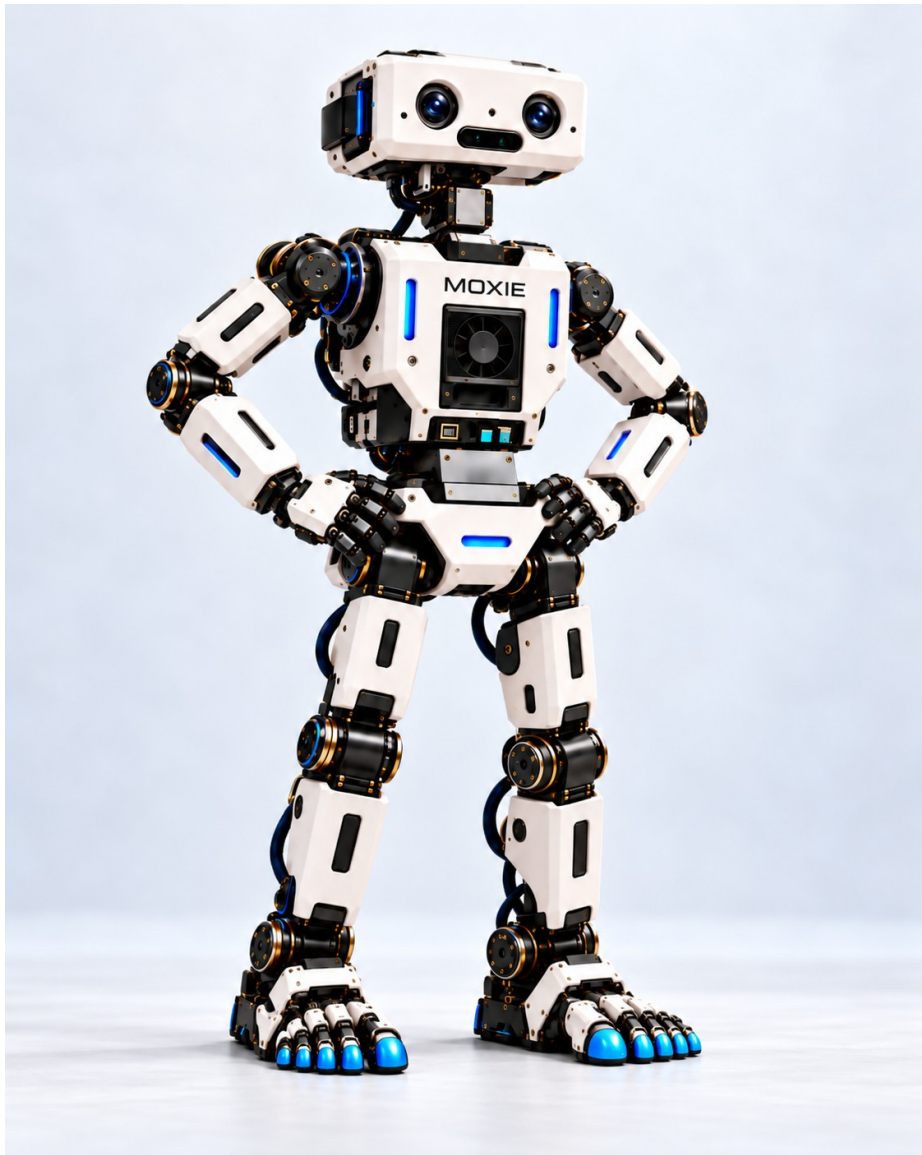


Figure 1. MOXIE fully assembled in the primary hero pose: standing proud with hands on hips, dual camera eyes, central mouth sensor, and more human-like five-toe feet.

Primary cover render update: the front page now shows MOXIE fully built in the proud hands-on-hips pose with refined human-like toes.

Version 3.9 • 27 September 2026

Project name: MOXIE — named for the super-robot Moxie in Rama Revealed, part of Arthur C. Clarke and Gentry Lee’s Rama series.

Designed around the existing Yahboom Jetson Orin NX Super 8GB camera kit and a hot-swappable Milwaukee M18 power system

Figure accuracy note: rendered concept images are illustrative. For actuator count, sensor selection, power architecture, foot anatomy, and purchase quantities, the written tables and BOM in this revision are authoritative. CAD drawings and prototype measurements should supersede visual renders whenever they differ.

Revision 3.3 update: this document now includes the MOXIE mechanical blueprint sheet and the MOXIE electrical architecture/circuit diagram as embedded figures in Sections 2D and 6A.

Engineering concept only: dimensions, actuator margins, thermal performance, and structural loads must be validated in prototype testing before unrestricted walking.

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1. Executive design summary

Objective. Build a roughly two-foot-tall research humanoid that can walk indoors, negotiate modestly rough surfaces, perceive and converse locally, and serve as a fully programmable embodied-AI platform. The design deliberately separates high-level AI from the fast balance loop: the Jetson reasons; a microcontroller keeps the robot upright. The hands use five visible fingers with three powered groups per hand so the robot can point, pinch and form a compliant power grip without a full five-motor-per-hand penalty.

Design item	Baseline
Height	600–620 mm

Design item	Baseline
Target mass	5.5–6.5 kg with one M18 XC8.0 pack + keep-alive battery (prototype target)
Powered DOF	32 (20 body + 6 toe groups + 6 hand groups)
Leg DOF	6 per leg
Arms	3 DOF each + 3 powered hand groups each
Neck	2 DOF
Foot design	5 visible/compliant toes per foot; anatomically mirrored left/right; independent medial big toe + toes 2–3 group + toes 4–5 group
Compute	Existing Yahboom Jetson Orin NX Super 8GB; stereo RGB cameras + depth/ToF sensor planned
Real-time controller	Teensy 4.1, 600 MHz Cortex-M7
Main battery	Milwaukee M18 REDLITHIUM FORGE XC8.0, 18 V nominal, 8 Ah (~144 Wh)
Control stack	Ubuntu + ROS2 on Jetson; 200–500 Hz gait/balance loop on MCU
Initial gait	Quasi-static / low-speed; dynamic gait after validation
Hand design	5 fingers per hand; independent thumb, independent index, middle/ring/pinky ganged; tendon-driven with passive compliance
Perception head	2 matched IMX219 CSI cameras + central multizone ToF sensor + microphone array
Build strategy	Prototype-first: one foot/hand -> one leg -> lower body -> upper body -> autonomy

Why this architecture works: ROBOTIS OP3 is a useful scale reference at about 510 mm, 3.5 kg and 20 DOF, with a Linux computer plus an OpenCR sub-controller and six-DOF legs. MOXIE follows the same separation of responsibilities but adds adaptive feet and a much more capable Jetson AI computer. [R1][R2]

Prototype-first accuracy note. This document is a concept-level engineering package intended to guide design, purchasing, fabrication, and early prototyping. It is not a final released production drawing set. Joint torques, structural margins, thermal behavior, and battery runtime should be validated experimentally before unrestricted walking or autonomous operation.

Design review improvements in this revision

- Clarifies that the build should proceed in prototype stages: foot and hand first, then one leg, then the lower body, and only later the full upper body and AI stack.
- Separates concept intent from validated performance so the document better distinguishes between design goals and prototype verification tasks.

- Adds subsystem graphics and build-roadmap visuals so mechanical, electrical, and software relationships are easier to understand at a glance.
- Emphasizes safe commissioning with bench testing, harness-supported walking tests, and incremental validation rather than jumping directly to full autonomy.

The workflow table below is the authoritative development sequence for this design. It freezes the 32-actuator baseline, puts the one-leg torque test ahead of bulk purchasing, and makes power validation a required gate before mobile integration.

1A. Design workflow and development logic

Step	Design activity	Output / gate
1	Define mission, terrain, payload, runtime, safety limits	Requirements and acceptance criteria
2	Freeze kinematic baseline: 32 powered DOF	12 leg + 6 arm + 2 neck + 6 toe-group + 6 hand-group actuators
3	Build one leg and measure real torque/current/temperature	Go/no-go decision on HTD-45H for hips/knees/ankles
4	Finalize CAD around measured loads and exact components	Revision-controlled STEP/3MF/DXF files
5	Validate power on bench before mobile integration	Measured current budget, regulator sizing, fuse values
6	Build lower body and prove static balance in a harness	Stable stance and controlled weight shift
7	Add perception head, arms, hands, and Jetson	Calibrated stereo + ToF + upper-body manipulation
8	Iterate walking, manipulation, and AI behaviors	Validated prototype with logged limits and test results

2. Mechanical architecture

Recommended proportions. Keep the heavy items low. The Milwaukee M18 XC8.0 battery mounts in a guarded, quick-release dock across the rear of the pelvis/lower torso, as low and close to the sagittal centerline as practical. The Jetson remains in the lower torso, while the small keep-alive battery is mounted inside the pelvis/torso cage. The M18 pack is substantially heavier than the original 3S pack, so the expected prototype mass rises to roughly 5.5–6.5 kg and all hip/knee torque margins must be revalidated. The feet should remain deliberately oversized during V1 to preserve static margin while gait control matures.

Joint/function	Qty	Actuator	Purpose
Hip yaw	2	HTD-45H	Leg orientation / turning
Hip roll	2	HTD-45H	Lateral balance
Hip pitch	2	HTD-45H	Forward/backward leg motion

Joint/function	Qty	Actuator	Purpose
Knee pitch	2	HTD-45H	Primary stance/load joint
Ankle pitch	2	HTD-45H	Forward/back balance and toe-off
Ankle roll	2	HTD-45H	Lateral balance / terrain conformity
Shoulder pitch	2	HTS-20H	Arm swing / reach
Shoulder roll	2	HTS-20H	Lateral arm motion
Elbow pitch	2	HTS-20H	Reach / gestures
Neck yaw	1	HTS-20H	Look left/right
Neck pitch	1	HTS-20H	Look up/down
Big-toe flexion	2	HTS-20H, tendon drive	Independent medial balance / toe-off
Toes 2–3 flexion	2	HTS-20H, tendon drive	Central forefoot conformity
Toes 4–5 flexion	2	HTS-20H, tendon drive	Lateral edge conformity
Thumb flexion/opposition	2	HTS-20H, tendon drive	Opposition / pinch / power grip
Index flexion	2	HTS-20H, tendon drive	Independent pointing / precision pinch
Middle-ring-pinky flexion	2	HTS-20H, tendon manifold	Shared power grip with passive finger compliance

Leg actuator choice. The baseline uses the Hiwonder HTD-45H for all twelve leg axes. It is specified for 9–12.6 V, weighs 64 g, provides serial feedback, and is rated at 45 kg·cm maximum torque at 11.1 V. This is much closer to the torque class used by research humanoids than the lighter 20–35 kg·cm hobby servos. [R3]

Important margin note. A 610 mm, ~5 kg robot puts more demand on its knees/hips than a smaller hobby humanoid. The first leg test must measure real current, temperature, and static hold margin. If knee or hip-pitch temperatures rise too quickly, those axes are the first candidates for a higher-torque actuator or linkage ratio change.

Figure 3. Internal mechanical concept view with the outer shells removed, showing the Jetson computer, power modules, major servos, cable routing, and the tendon-driven hand mechanism.

This internal view complements the external concept render by showing the main mechatronic layout inside MOXIE. It highlights the torso compute stack, motor control and power electronics, rear-mounted M18 hot-swap battery, keep-alive battery, major joint actuators, and the internal tendon routing for the hand.

2A. Internal mechanical concept view

2B. Exploded subsystem overview

Subsystem	Validated baseline for this document
Head	2 matched IMX219 CSI cameras (stereo eyes), 1 central VL53L5CX-class ToF sensor (mouth/nose position), microphone array
Neck	2 powered DOF: yaw + pitch; HTS-20H class smart bus servos
Arms	3 powered DOF per arm: shoulder pitch, shoulder roll, elbow pitch
Hands	5 visible fingers per hand; 3 powered tendon groups per hand
Legs	6 powered DOF per leg: hip yaw/roll/pitch, knee pitch, ankle pitch/roll
Feet	5 toes per foot; anatomically mirrored; independent medial big toe plus two ganged toe groups
Compute	User-owned Yahboom Jetson Orin NX Super 8GB + 256GB SSD
Real-time control	Teensy 4.1; joint limits, gait interpolation, watchdog, sensor acquisition
Power	Milwaukee M18 main pack; regulated servo rail(s); separately validated Jetson rail; keep-alive compute battery

- The table below is the authoritative subsystem baseline for Revision 2.9 and should override older illustrative renders when a visual detail conflicts with the written specification.
- Use the subsystem table above as the authoritative checklist when creating CAD, routing wires, and packaging electronics.
 - The subsystem baseline separates structural parts, cosmetic shells, replaceable modules, compute, sensing, and power so those interfaces can be frozen independently.
 - Recommended service strategy: make feet, hands, head, and battery hardware removable without fully disassembling the torso.

2C. Moxie size options and scaling strategy

Moxie is a modular robot family rather than a single fixed height. The 610 mm Standard design remains the engineering baseline, but the same head, software architecture, five-finger hand concept, and left/right five-toe philosophy can be adapted to smaller or larger bodies. Scaling is not purely geometric: joint torque, frame stiffness, battery capacity, fall energy, and safety requirements rise quickly as the robot gets taller and heavier.

Figure 2C-1. Moxie family size study.

Variant	Target height	Target mass	Powered DOF	Compute / actuator approach	Estimated robot cost*	Best fit
Moxie Mini	~420 mm (16.5 in)	2.0-2.8 kg	20-24	Raspberry Pi 5	\$850-\$1,200	Education,

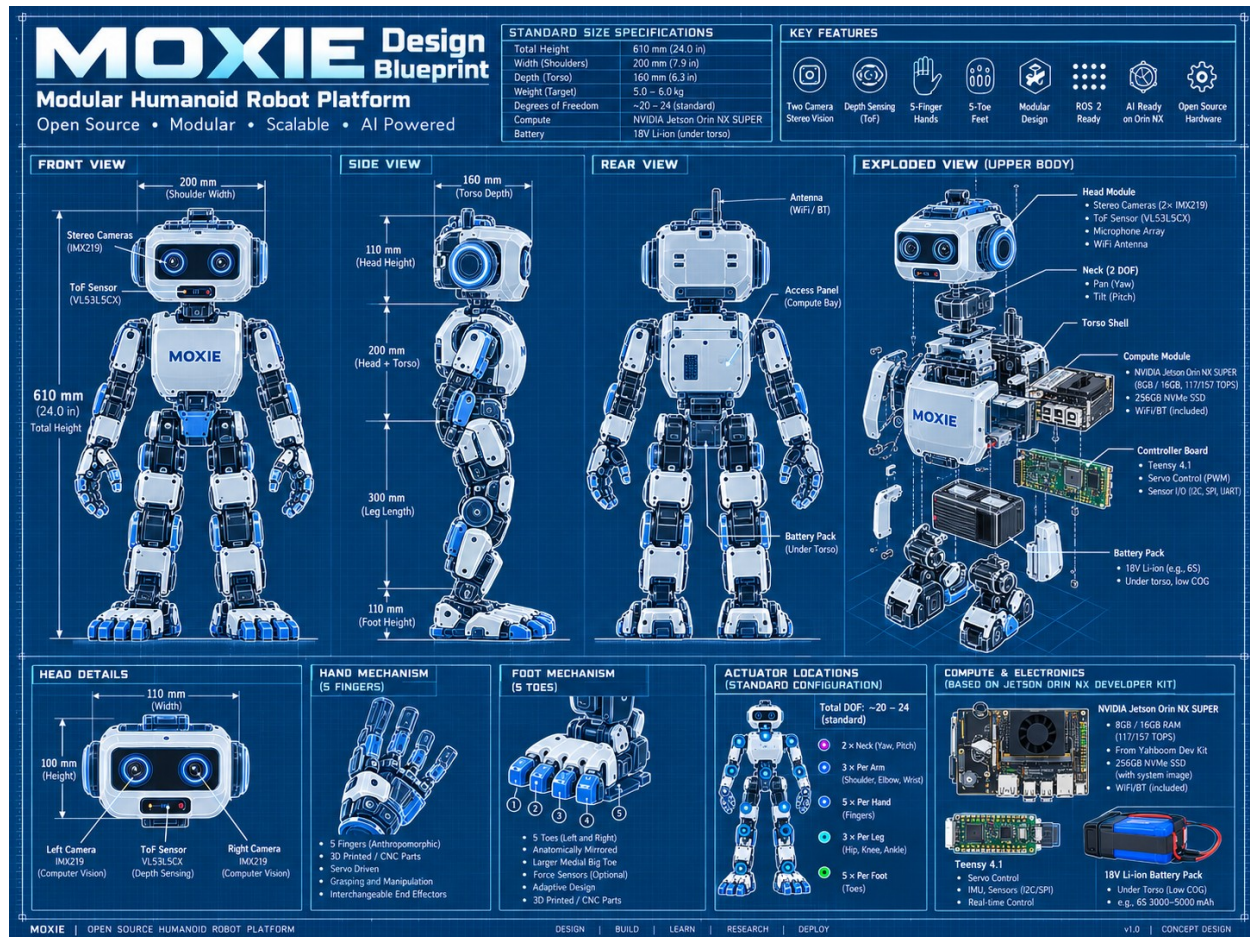
				standard; compact 15-25 kg-cm smart servos; Jetson optional/offboard		desktop experiments, low-cost embodied AI
Moxie Compact	~500 mm (19.7 in)	3.0-4.0 kg	24-28	Pi 5 or Orin NX; ~35 kg-cm lower-body and ~20 kg-cm upper-body servos	\$1,300-\$1,700	Advanced hobby, research prototyping, smaller lab robot
Moxie Standard	~610 mm (24 in)	5.0-6.0 kg	32	Existing Jetson Orin NX; HTD-45H lower body + HTS-20H upper body	\$2,400-\$3,200	Current baseline; full perception, hands, adaptive feet
Moxie XL	~850 mm (33.5 in)	9-12 kg	32-36	Orin NX / Orin AGX; integrated BLDC actuators recommended for lower body	\$6,500-\$9,000+	Advanced research; higher payload and reach

**Cost ranges are concept-level estimates before tax/shipping and assume the selected configuration rather than identical hardware at every size. The existing Jetson Orin NX lowers out-of-pocket cost for Compact and Standard builds.*

Scaling recommendations

- Mini: simplify aggressively. Use fixed or passively compliant toes, fewer tactile sensors, one or two cameras, and lighter actuators. Keep the high-level ROS 2 software compatible with Standard so behaviors transfer upward.
- Compact: preserve stereo vision and five-finger hands but reduce structure, battery size, and actuator torque. This is the best path if the goal is a lower-cost robot that still feels like the full Moxie architecture.
- Standard: retain the current 610 mm / 32-actuator design as the primary engineering reference because it balances onboard Orin NX compute, manipulators, adaptive feet, and manageable fall energy.
- XL: redesign the lower body around stronger integrated BLDC actuators, stiffer structural members, larger batteries, stronger emergency-stop hardware, and a fall-protection strategy. Do not simply scale the 610 mm servo brackets and assume equivalent margins.
- The hand and foot detail panels summarize the five-finger and five-toe mechanisms so they can be treated as repeatable modules across the Mini, Compact, Standard, and XL variants.
- The exploded upper-body callouts show the intended locations of the Yahboom Jetson Orin NX developer kit, the Teensy-based control electronics, and the under-torso battery pack.
- Use the blueprint as the dimensional starting point for CAD skeleton sketches, packaging studies, and service-access planning. All dimensions remain concept-level until verified in the first physical prototype.

Figure 2D-1. MOXIE mechanical blueprint showing orthographic front, side, and rear views, dimensional callouts, an exploded upper-body assembly view, and detail panels for the head, hands, feet, actuator locations, and compute stack.



The blueprint below converts the concept design into a more builder-friendly reference sheet. It combines orthographic views, key dimensions, module placement, and subsystem notes so the robot can be translated into CAD, fabrication drawings, and prototype assemblies with fewer ambiguities.

2D. Mechanical blueprint and dimensional reference

2C.1 Complete robot size-family visualization

The size-family image below shows complete MOXIE robots at four target sizes so the physical difference between the variants is easier to judge than from a specification table alone. Standard remains the primary 610 mm engineering reference; Mini and Compact prioritize cost and portability, while XL requires substantially stronger structure, actuators, and safety systems.

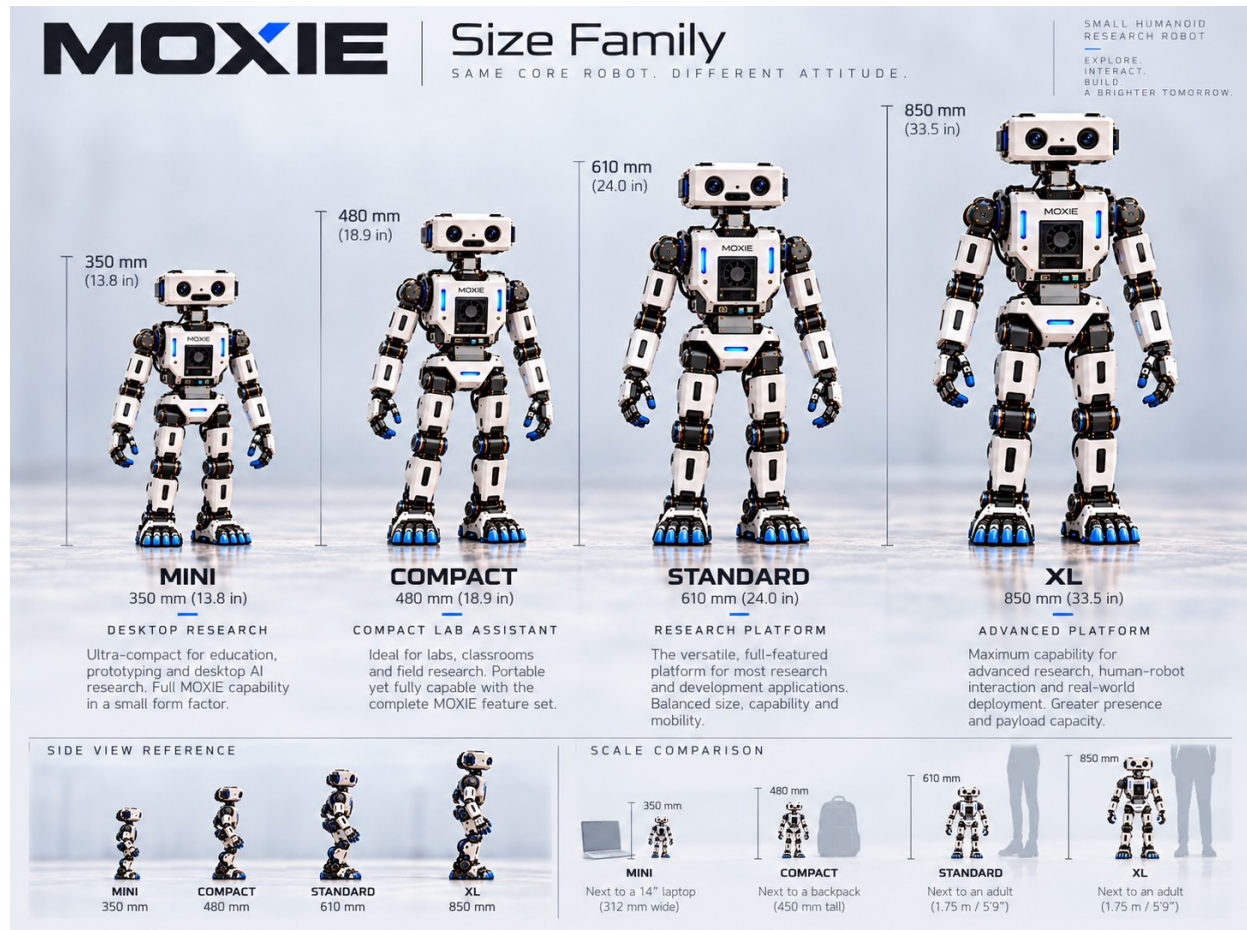


Figure 2C-2. Complete MOXIE size family: Mini, Compact, Standard, and XL shown at relative scale.

- Mini: optimized for desktop research, education, and low-risk manipulation experiments.
- Compact: a portable full-humanoid format suitable for classrooms, labs, and early field research.
- Standard: the 610 mm baseline used for the detailed BOM, electrical design, and CAD references in this document.
- XL: an advanced platform that must be re-engineered for higher loads rather than created by simple geometric scaling.

3. Adaptive five-toe foot

Design intent. Each foot has five physical toes and the left/right feet are mirror images of human anatomy. The big toe sits on the medial edge of each foot (toward the robot centerline): on the left foot it is on the right side when viewed from above, and on the right foot it is on the left side. Three powered groups are used per foot: (1) independent big-toe flexion, (2) toes 2–3, and (3) toes 4–5. Every toe also has a passive distal hinge with a torsion spring or elastomer return. This preserves terrain conformity while keeping actuator count manageable.

Feature	Baseline
Overall foot length	160–170 mm

Feature	Baseline
Overall width	95–105 mm
Toe zone	45–55 mm
Mid-foot/arch	60–70 mm
Heel zone	40–45 mm
Toe material	Nylon/PETG skeleton with TPU or silicone pads
Powered toe actuators	3 per foot, mounted in lower shin
Transmission	Dyneema/Spectra tendon through PTFE guides
Contact sensing	8 FSRs per foot: five toes + two forefoot + one heel
Passive compliance	Torsion spring / elastomer at each distal toe hinge

Why not five powered toes? Five independently powered toes per foot would add wiring, distal inertia, failure points, and control complexity. The three-group approach preserves the most useful degrees of freedom while allowing passive conformity. Recent humanoid-foot research reports improved adaptability on irregular surfaces using rigid-elastic/passive bionic structures, including lawn and cobblestone tests. [R4]

Sensing. The foot uses force-sensitive resistors as contact/relative-pressure sensors rather than precision scales. SparkFun’s 0.5-inch FSR is specified for roughly 0.1–10 kg of applied force and explicitly cautions that it is best for relative pressure/contact rather than accurate weighing. [R10] Two 16-channel multiplexers let the Teensy read sixteen foot sensors using only two ADC channels. [R11]

4. Five-finger adaptive hands

Design intent. Each hand keeps a human-like five-finger silhouette while using only three powered groups: an independent thumb, an independent index finger, and a ganged middle-ring-pinky group. This preserves useful pinch, pointing, and power-grip behaviors without the mass and complexity of one actuator per finger.

Figure 4-1. Proposed MOXIE five-finger / three-servo hand architecture.

Actuation. Use three HTS-20H-class smart bus servos per hand. Servo A drives thumb flexion/opposition, Servo B drives the index finger independently, and Servo C drives a tendon manifold for the middle, ring, and pinky. The three ganged fingers share the actuator but retain independent spring or elastomer compliance so each finger can wrap to a slightly different object radius.

Finger mechanics. Each finger uses two or three visible phalange links with a single closing tendon and passive spring return. Tendons run through low-friction PTFE guides. The thumb base is mechanically preset into an opposing orientation so one powered flexion axis can form a useful pinch against the index finger and a wrap grip against the remaining fingers.

Tactile sensing. Baseline sensing is four FSR channels per hand: thumb tip, index tip, a shared middle/ring/pinky contact zone, and the palm. The hand controller increases grip force only until stable contact is detected and monitors contact loss as a simple slip indicator.

Target capability. Design the palm around 55–65 mm wide with an 80–95 mm maximum opening. Initial manipulation targets are a 200–300 g continuous payload per hand and short-duration lifts up to about 500 g close to the torso, subject to shoulder/elbow torque validation.

Hand feature	Baseline
Visible fingers	5 per hand
Powered groups	3 per hand
Servo A	Independent thumb
Servo B	Independent index finger
Servo C	Middle + ring + pinky via compliant tendon manifold
Finger joints	2–3 passive/coupled joints per finger
Return	Torsion spring or elastomer return
Grip opening	80–95 mm
Tactile sensing	4 FSR channels per hand
Continuous payload target	200–300 g per hand
Short lift target	~500 g near torso
Stereo camera #2	Yahboom IMX219 8MP CSI camera, 22-pin for Orin NX Super, match existing FOV
Central ToF sensor	VL53L5CX 8x8 multizone ToF breakout/evaluation board

5. Electronics and control architecture

Authoritative control baseline: 32 smart servos total; 24 tactile/contact channels (16 foot + 8 hand); Jetson Orin NX for perception/planning; Teensy 4.1 for real-time safety, gait interpolation, contact sensing, and watchdog functions.

Jetson layer. The existing Yahboom kit combines the Jetson Orin NX Super module and Yahboom carrier board with a 256 GB SSD and Wi-Fi. Yahboom currently lists the 8 GB Super configuration at up to 117 TOPS and ships the kit with a 65 W GaN supply. The vendor does not publish a clear supported DC input range on the product page and has answered power questions by pointing users toward the supplied 19 V-class adapter rather than recommending direct battery power. Therefore the mobile Jetson rail must be treated as an engineering item to validate, not assumed from an undocumented voltage range. Bench-test the carrier board from its supplied adapter first, then qualify any mobile DC/DC solution under worst-case Jetson load before integrating it into the robot. [R5][R28]

Real-time layer. A Teensy 4.1 is recommended instead of asking Linux to maintain hard timing. It provides a 600 MHz Cortex-M7, eight serial ports, three CAN buses and eighteen analog inputs, which is ample for a 200–500 Hz gait/balance loop and servo telemetry. [R7] The MCU also enforces per-hand tendon travel, grip-force limits, and tactile stop thresholds.

5A. Perception head and stereo geometry

- Stereo eyes. Use two matched Yahboom IMX219 8 MP CSI cameras with the same lens/FOV and 22-pin Orin cable. The existing Camera Advanced Kit supplies one IMX219 camera; purchase one second matching camera. Yahboom lists the IMX219 as compatible with Orin NX Super and the carrier family supports multi-camera MIPI CSI-2 use. [R25][R27]

- Mechanical baseline. Mount the two camera optical centers on a rigid common head bracket at approximately 60–65 mm center-to-center. Make this baseline adjustable by a few millimeters in CAD. The two camera axes should be parallel for the first prototype; convergence can be evaluated later in software.
 - Calibration. Use a standard stereo calibration target to estimate intrinsics, distortion, rotation and translation after final assembly. Recalibrate after any camera mount change. Treat depth from stereo as a software function; the IMX219 pair is not assumed to provide hardware-synchronized global-shutter stereo.
 - Central range sensor. Mount an 8x8 multizone VL53L5CX-class ToF sensor between the eyes and slightly lower, matching the “mouth/nose” appearance. The sensor supports 4x4 or 8x8 ranging and up to about 4 m, making it useful for near-field obstacle distance and as a sanity check on stereo depth.
- [R26]

6. Power architecture

Power branch	Revision 2.2 baseline	Validation status
Main energy	Milwaukee M18 XC8.0, one pack onboard	Catalog item; dock/contact current rating still must be verified
Servo rail	12 V nominal; multiple fused branches; final converter count/capacity based on measured current	NOT frozen - current characterization required
Jetson main rail	Regulated 19 V-class mobile buck-boost, ≥ 65 W continuous, only after carrier-board input validation	NOT frozen - bench validation required
Keep-alive rail	11.1 V backup battery -> regulated compute voltage -> ideal-diode OR; ≤ 20 W swap mode	Prototype concept; validate converter and switchover
Safety	Main fuse, branch fuses, E-stop, current monitoring, strain relief	Required before powered stance

Runtime clarification. Four XC8.0 packs provide about 576 Wh of nameplate energy in total. That can support an all-day demonstration schedule only when walking and manipulation are intermittent and packs are rotated/charged; it is not an eight-hour continuous-walking guarantee. Measure average robot power during representative use before finalizing the required day-kit quantity.

Primary battery. Replace the original 3S LiPo/LiHV pack with a Milwaukee M18 REDLITHIUM FORGE XC8.0 (48-11-1881). Milwaukee specifies 8 Ah capacity, $5.3 \times 3.4 \times 3.5$ in dimensions, and 2.38 lb mass. At 18 V nominal this is approximately 144 Wh. Mount one pack at a time in an external quick-release dock on the rear pelvis/lower torso; do not open, modify, or bypass the battery pack electronics. The dock must have a mechanical latch, contact guard, main fuse, reverse-polarity-safe wiring, and strain relief. A full workday is achieved by rotating packs rather than carrying multiple packs on the robot.

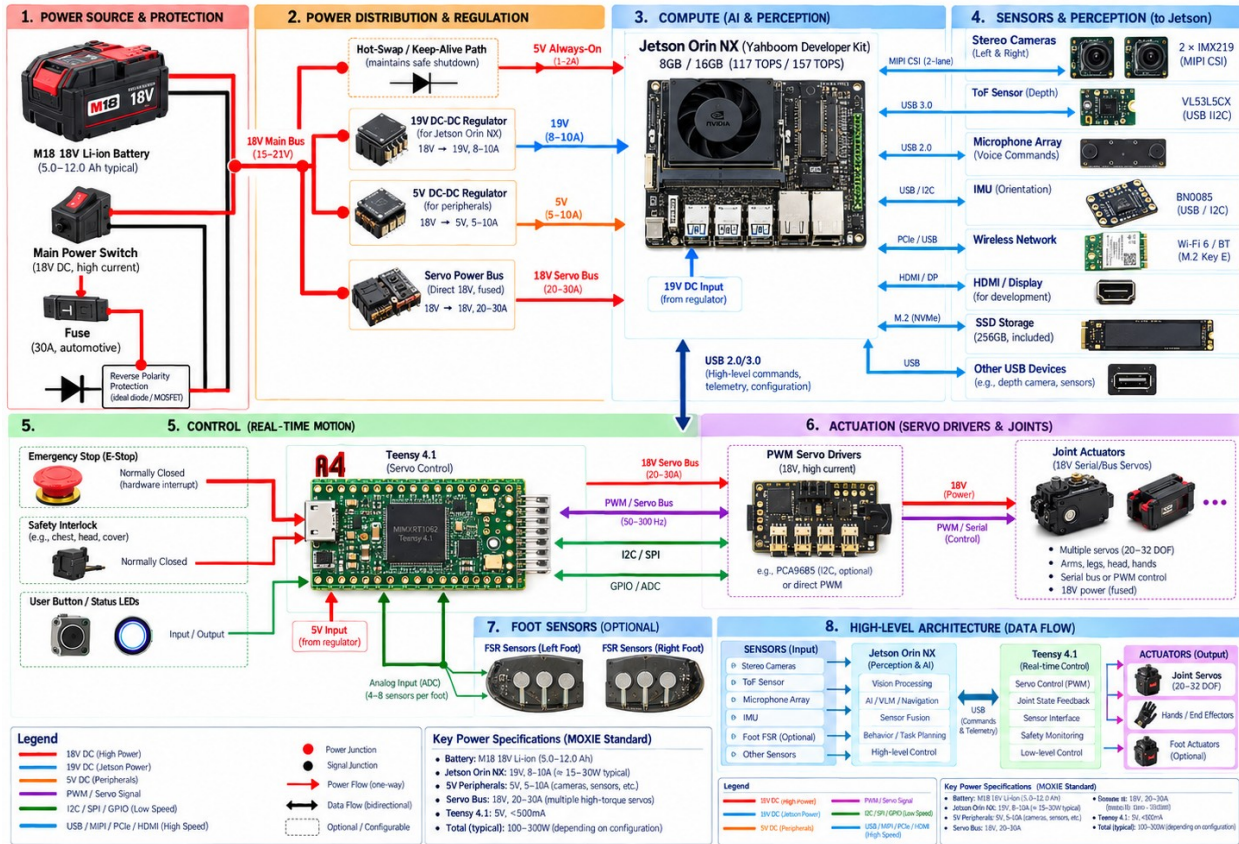
Compute + hot-swap branch. Do not use the earlier fixed 15 V assumption as the production baseline. First characterize the Yahboom carrier board using its supplied adapter. For untethered operation, select a

regulated DC/DC stage that reproduces the validated carrier-board input (nominally 19 V-class based on the supplied adapter) and can deliver at least 65 W continuously with margin across the full M18 discharge range. Because M18 pack voltage varies above and below an 18–19 V target, a true buck-boost topology is preferred. The keep-alive path should feed the same validated compute voltage through its own boost/buck-boost stage and ideal-diode ORing so the Jetson does not see a large voltage step during a battery swap. During swap mode, cap Jetson power to ≤ 20 W, disable actuator rails, and suspend nonessential peripherals. The 11.1 V / 3 Ah TalentCell pack is appropriate only for this reduced-power keep-alive role, not normal robot operation.

Servo branch. The selected HTD-45H and HTS-20H servos are specified for 9–12.6 V and each lists a 3 A stall current. The theoretical simultaneous stall current of 32 servos is therefore far beyond the capacity of the three 9 A prototype regulators previously shown. Treat the Pololu D42V110F12 modules as bench/prototype branch regulators only. Final servo-power sizing must be based on measured current during stance, stepping, recovery, and manipulation, with a design margin and branch fusing. A practical architecture is multiple isolated 12 V branches (left proximal leg, left distal leg, right proximal leg, right distal leg, left upper body, right upper body, toe/neck auxiliary), plus software current limiting and stall detection. Do not select final wire gauge, connector rating, fuse values, or regulator count until the one-leg and lower-body current tests are complete. [R3][R13][R21]

- Optional foot force-sensing resistor arrays, microphone hardware, additional USB sensors, and hot-swap keep-alive circuitry are all shown so the builder can decide what to implement in the first prototype versus later revisions.
- Jetson Orin NX handles perception, planning, speech, and AI behaviors, while the Teensy 4.1 handles real-time servo control, sensor polling, and safety inputs such as E-stop and interlocks.
- The diagram separates high-current servo power from Jetson power and low-voltage peripheral power, which is important for safety, noise isolation, and staged bring-up.

Figure 6A-1. MOXIE electrical architecture and circuit diagram showing battery protection, voltage regulation, Jetson compute interfaces, Teensy-based real-time control, servo actuation, optional foot sensors, and the high-level data flow between perception, control, and actuation.



The electrical architecture diagram below is intended as a practical integration map for wiring and bring-up. It shows how battery power flows through protection and regulation stages, how compute and control electronics are partitioned, and how sensors and actuators connect to the Jetson and Teensy subsystems.

6A. Electrical architecture and circuit diagram

7. Software stack and control loops

Layer / rate	Responsibility
Jetson / 5-30 Hz	Vision, speech recognition, local LLM/VLM, semantic mapping, behavior planning, ROS2 nodes
Jetson / 30-100 Hz	Whole-body target generation, footstep plan, state estimator fusion
Teensy / 200-500 Hz	IMU filter, contact sensing, balance corrections, gait interpolation, joint limits, watchdog
Servo internal loop	Position control and joint telemetry
Passive mechanics / immediate	Toe/sole compliance reacts before software

ROS2 interface. The high-level agent should call safe actions such as `walk_forward(distance)`, `turn(angle)`, `look_at(target)`, `wave()`, `stop()`, and `recover_stance()`. It should never emit raw joint PWM or unrestricted servo targets. ROBOTIS OP3's software is a useful reference for separating walking, head control, tuning and sensor modules. [R12]

7A. Open-source robotics platform research and recommended stack

Research conclusion. MOXIE should use a two-track software strategy. Keep the current JetPack 6.2.x / Ubuntu 22.04 / ROS 2 Humble branch as the stable development baseline until the Yahboom carrier board is validated with a JetPack 7.2 BSP. In parallel, create a next-generation branch targeting JetPack 7.2 / Ubuntu 24.04 / ROS 2 Lyrical / NVIDIA Isaac ROS 5.0, which is now NVIDIA's current accelerated ROS stack for Jetson Orin. This avoids destabilizing working camera, SSD, Wi-Fi and carrier-board support while still giving MOXIE a clear migration path to the newest physical-AI stack.

Platform	Primary role in MOXIE	Jetson / ROS fit	Recommendation
ROS 2 Humble	Messaging, actions, services, TF, lifecycle, tooling	Native fit for Ubuntu 22.04; matches Isaac ROS 3.2	Core platform - install on host
ros2_control	Hardware abstraction, controller manager, joint state and trajectory controllers	Humble packages available; custom SystemInterface supported	Core control layer
NVIDIA Isaac ROS 3.2	GPU-accelerated stereo vision, image processing, VSLAM and AI perception	Officially supports Jetson Orin + JetPack 6.1/6.2 + ROS 2 Humble	Use selectively in Docker
MoveIt 2 Humble	Arm/hand kinematics, collision checking, planning and grasp motion	Supported on ROS 2 Humble / Ubuntu 22.04	Use for upper-body manipulation
Pinocchio	Fast rigid-body kinematics, Jacobians, dynamics, CoM calculations	ROS package available for Humble	Use for whole-body math and gait development
MuJoCo + mujoco_ros2_control	Physics simulation and controller-in-the-loop testing	Linux AArch64 supported; Humble integration package available	Primary digital-twin simulator
Nav2	Mapping, localization, goal navigation and behavior-tree navigation	Humble binaries available	Optional: feed goals/velocity to gait manager, never joints directly

7B. Recommended MOXIE software architecture

Figure 7B-1. Recommended MOXIE open-source software stack on the Jetson Orin NX, including perception, planning, simulation, ROS 2 control, the Teensy real-time layer, and suggested MOXIE-specific packages.

Version pinning matters. The existing MOXIE baseline remains JetPack 6.2.x + ROS 2 Humble because that is the currently proven Yahboom/Orin development environment. NVIDIA Isaac ROS 5.0, released in September 2026, moves to ROS 2 Lyrical on Ubuntu 24.04 and officially supports Jetson Orin with JetPack 7.2 and a 128+ GB NVMe SSD. Do not upgrade the physical robot until the carrier-board BSP, CSI cameras, Wi-Fi and storage path have been validated on a cloned drive.

7C. Jetson installation guide

- 1. Step 0 - Preserve the working Yahboom image. Before changing the software stack, clone or image the existing SSD/NVMe. Do not flash a generic NVIDIA image over a carrier-board-specific Yahboom installation until Yahboom confirms the BSP and device-tree compatibility for that carrier. First record the installed Jetson release:

```
cat /etc/nv_tegra_release
dpkg-query --show nvidia-jetpack 2>/dev/null || true
```

```
uname -a
lsb_release -a
```

2. Step 1 - Use JetPack 6.2.x / Ubuntu 22.04 as the initial MOXIE baseline. If the existing Yahboom installation already boots correctly with camera, Wi-Fi, SSD and CUDA working, prefer an in-place package update or vendor-supported upgrade rather than reflashing the carrier board.
3. Step 2 - Configure the ROS 2 apt repository. The current ROS documentation recommends the ros2-apt-source package, which manages the ROS repository key and source configuration:

```
sudo apt update
sudo apt install -y software-properties-common curl
sudo add-apt-repository universe
export ROS_APT_SOURCE_VERSION=$(curl -s https://api.github.com/repos/ros-infrastructure/ros-apt-source/releases/latest |
grep -F 'tag_name' | awk -F'"' '{print $4}')
curl -L -o /tmp/ros2-apt-source.deb \
  "https://github.com/ros-infrastructure/ros-apt-source/releases/download/${ROS_APT_SOURCE_VERSION}/ros2-apt-source_${ROS_APT_SOURCE_VERSION}.${_etc_os_release} && echo ${UBUNTU_CODENAME:-${VERSION_CODENAME}}_all.deb"
sudo dpkg -i /tmp/ros2-apt-source.deb
sudo apt update
```

4. Step 3 - Install ROS 2 Humble and core MOXIE development packages:

```
sudo apt install -y \
  ros-humble-ros-base ros-dev-tools \
  python3-colcon-common-extensions python3-vcstool python3-rosdep \
  ros-humble-rviz2 ros-humble-xacro ros-humble-robot-state-publisher \
  ros-humble-tf2-tools

source /opt/ros/humble/setup.bash
sudo rosdep init 2>/dev/null || true
rosdep update
echo 'source /opt/ros/humble/setup.bash' >> ~/.bashrc
```

5. Step 4 - Install the open-source robot control, manipulation, dynamics, simulation, and optional navigation layers:

```
sudo apt update
sudo apt install -y \
  ros-humble-ros2-control ros-humble-ros2-controllers \
  ros-humble-moveit \
  ros-humble-pinocchio \
  ros-humble-mujoco-ros2-control ros-humble-mujoco-ros2-control-demos \
  ros-humble-navigation2 ros-humble-nav2-bringup
```

6. Step 5 - Create the MOXIE ROS 2 workspace. Keep all robot-specific code separate from vendor packages so upgrades remain manageable:

```
mkdir -p ~/moxie_ws/src
cd ~/moxie_ws/src
ros2 pkg create moxie_description --build-type ament_cmake
ros2 pkg create moxie_hardware --build-type ament_cmake
ros2 pkg create moxie_control --build-type ament_cmake
ros2 pkg create moxie_perception --build-type ament_cmake
ros2 pkg create moxie_behaviors --build-type ament_python
ros2 pkg create moxie_bringup --build-type ament_python
cd ~/moxie_ws
```

```
rosdep install --from-paths src --ignore-src -r -y
colcon build --symlink-install
source install/setup.bash
```

- Step 6 - Stable branch: keep Isaac ROS 3.2 isolated from the core MOXIE workspace while the robot remains on JetPack 6.2.x / ROS 2 Humble. Use it only for GPU-accelerated perception packages that are already validated on the current carrier image. The migration procedure for Isaac ROS 5.0 is documented in Section 7M and should be performed on a cloned NVMe or separate development SSD first.

```
mkdir -p ~/workspaces/isaac_ros-dev/src
export ISAAC_ROS_WS=~/.workspaces/isaac_ros-dev
cd ${ISAAC_ROS_WS}/src
git clone -b release-3.2 \
  https://github.com/NVIDIA-ISAAC-ROS/isaac_ros_common.git isaac_ros_common
cd ${ISAAC_ROS_WS}
./src/isaac_ros_common/scripts/run_dev.sh
```

- Step 7 - Verify the ROS host installation before connecting real servos. Run the ROS 2 demo nodes, load the URDF in RViz2, and run a MuJoCo simulation before enabling the physical actuator rail.

```
source /opt/ros/humble/setup.bash
ros2 run demo_nodes_cpp talker
# In a second terminal:
ros2 run demo_nodes_py listener

# After moxie_description exists:
ros2 launch moxie_bringup display.launch.py
```

7D. MOXIE ROS 2 package organization

Package	Contents	Design rule
moxie_description	URDF/Xacro, meshes, inertias, joint limits, sensor frames	Single source of truth for geometry and frames
moxie_hardware	Teensy protocol, ros2_control SystemInterface, sensor drivers	No AI logic; deterministic state/command bridge
moxie_control	Controller YAML, gait manager, balance, safety supervisor	Owens joint limits, rate limits and actuator authorization
moxie_perception	Stereo/ToF/IMU/FSR nodes; optional Isaac ROS launch files	Publishes calibrated perception; does not command motors
moxie_moveit_config	SRDF, planning groups, IK, collision matrix	Arms/hands/head only at first; add whole-body planning later
moxie_navigation	Nav2 config, maps, goal interface, gait bridge	Converts navigation intent into safe biped goals
moxie_behaviors	Wave, point, inspect, pick, carry, sit, stand, recovery behaviors	Only high-level actions; never raw servo commands
moxie_bringup	Launch files, lifecycle orchestration, parameter sets	One command to start simulation or hardware mode

7E. ros2_control and Teensy integration

- Implement moxie_hardware as a ros2_control SystemInterface. The read() path receives measured joint positions, velocities, servo temperatures/current flags, IMU state and safety status from the Teensy. The write() path sends bounded desired joint targets or trajectory setpoints back to the Teensy.
- Keep the Teensy as the final actuator authority. It should reject stale commands, enforce hard joint limits, implement the watchdog and E-stop behavior, and disable the actuator bus if the Jetson disappears.

- Start with position interfaces only. Add velocity/current-like interfaces only after the selected Hiwonder bus protocol and measured servo behavior prove that those commands are reliable and safe.
- Use joint_state_broadcaster plus joint_trajectory_controller for arms/head and a custom gait controller for legs. Do not use generic trajectory playback as the only balance controller.

7F. Humanoid locomotion and navigation customization

- Phase 1 gait: quasi-static stepping. Use IMU tilt, FSR center-of-pressure estimates, and conservative precomputed swing-foot trajectories. This is the correct first locomotion target for the servo-class hardware.
- Phase 2 gait: use Pinocchio for forward kinematics, Jacobians, center-of-mass and support-polygon calculations. Add online ankle/hip corrections and foot-placement adjustment while retaining Teensy watchdog protection.
- Nav2 should not command leg joints. Create an moxie_navigation gait bridge that accepts geometry_msgs/Twist or NavigateToPose goals and converts them into step length, lateral offset, turn angle, and stop requests for moxie_control.
- For early versions, limit Nav2 speeds aggressively and treat stopping as a full stable-stance transition, not merely a zero velocity command.
- If dynamic walking or reinforcement-learning locomotion is pursued later, train and validate policies in simulation first and retain a deterministic fallback stand/stop controller.

7G. Perception customization for MOXIE

- Stereo eyes: calibrate each IMX219 intrinsics and the left-right extrinsic transform, publish camera_info, rectify both streams, and keep the physical camera baseline fixed in the head CAD. Use Isaac ROS acceleration only after basic V4L2/CSI capture and ROS image topics are reliable.
- Central ToF “mouth” sensor: publish a dedicated range/depth topic and use it for close-range obstacle confirmation, docking, and manipulation safety rather than treating it as a replacement for stereo depth.
- IMU: publish sensor_msgs/Imu with a fixed base_link transform. Balance code should consume filtered orientation/angular velocity while preserving access to raw data for debugging.
- FSR feet and hands: publish both raw channels and normalized contact estimates. Record calibration values per physical sensor because inexpensive FSRs vary significantly from part to part.
- Use rosbag2 during every walking and manipulation test so failures can be replayed offline with the same sensor and command timeline.

7H. MoveIt 2 and manipulation

- Create MoveIt configuration from MOXIE’s URDF/SRDF. Initial planning groups should be left_arm, right_arm, left_hand, right_hand and head. Keep the balancing legs locked during the first manipulation milestones.
- Use the Setup Assistant to define self-collision exclusions and joint groups. Model the three-actuator hand accurately: thumb, index, and grouped middle/ring/pinky mimic/tendon relationships.
- Expose task-level ROS 2 actions such as point_at(), reach_pose(), pinch(), power_grip(), hand_open() and hand_release(). The behavior layer should call these actions instead of commanding hand servos directly.

- When whole-body reaching is added, coordinate MoveIt goals with the gait/balance controller rather than allowing MoveIt to overwrite leg commands.

7I. Simulation and digital twin workflow

- Maintain one authoritative URDF/Xacro description and generate/convert simulation assets from it. Use realistic link masses, centers of mass and inertia tensors measured from the actual printed/metal parts as the prototype matures.
- Use MuJoCo + mujoco_ros2_control for rapid controller-in-the-loop testing. Simulate IMU, contact/force sensors and joint limits before running new control code on the real robot.
- Create automated regression tests: neutral stand for 60 s, left/right weight shift, single step, five-step walk, sit/stand, arm reach, grasp/release, E-stop, communications loss, and battery-swap state.
- Simulation success is necessary but not sufficient. Servo backlash, compliance, cable forces and FSR behavior must be re-measured on hardware and fed back into the model.

7J. Local AI / agent customization

- Keep the local language/vision model above the ROS 2 behavior layer. Its output should be structured intents such as {action: "inspect", target: "box"}, not joint angles.
- Create an moxie_behaviors skill registry whose actions advertise preconditions, maximum duration, whether walking is permitted, and which safety state is required.
- Use a behavior tree or explicit state machine for multi-step tasks. The LLM can choose a skill sequence, but the deterministic behavior executor decides whether each transition is legal.
- On an 8 GB Orin NX, prioritize one primary local model at a time and offload vision preprocessing to accelerated ROS nodes. Do not reserve most GPU memory for an oversized LLM if stereo perception and control are simultaneously active.
- Speech recognition, text-to-speech and conversational models should be optional processes that can be stopped without affecting balance, watchdogs, or locomotion.

7K. Recommended bringup sequence

1. safety + hardware monitor (no actuator enable)
2. Teensy communications + joint state broadcaster
3. IMU / foot contact sensors
4. cameras + ToF perception
5. balance controller in disabled/output-zero state
6. actuator enable after explicit safety checks
7. gait controller
8. MoveIt / navigation
9. AI behavior manager and speech services last

7L. Software customization priorities

Priority	Customization	Why it matters
P0	Accurate URDF/Xacro + joint limits + link inertias	Everything else depends on correct geometry and frames
P0	Teensy protocol + ros2_control hardware interface + watchdog	Creates a safe deterministic actuator boundary
P0	IMU + FSR calibration and rosbag2	Essential for balance debugging and

	logging	repeatable tests
P1	MuJoCo digital twin + controller regression tests	Reduces risk before physical walking experiments
P1	Stereo camera calibration + ToF fusion	Enables reliable near-field perception and inspection
P1	MoveIt arm/hand configuration	Unlocks useful manipulation without destabilizing legs
P2	Nav2 gait bridge	Adds autonomous room-scale goal navigation after walking is stable
P2	Local VLM/LLM skill planner	Adds natural-language autonomy after safe behaviors exist
P3	Dynamic/RL whole-body locomotion	High complexity; only after mechanical and control baseline is mature

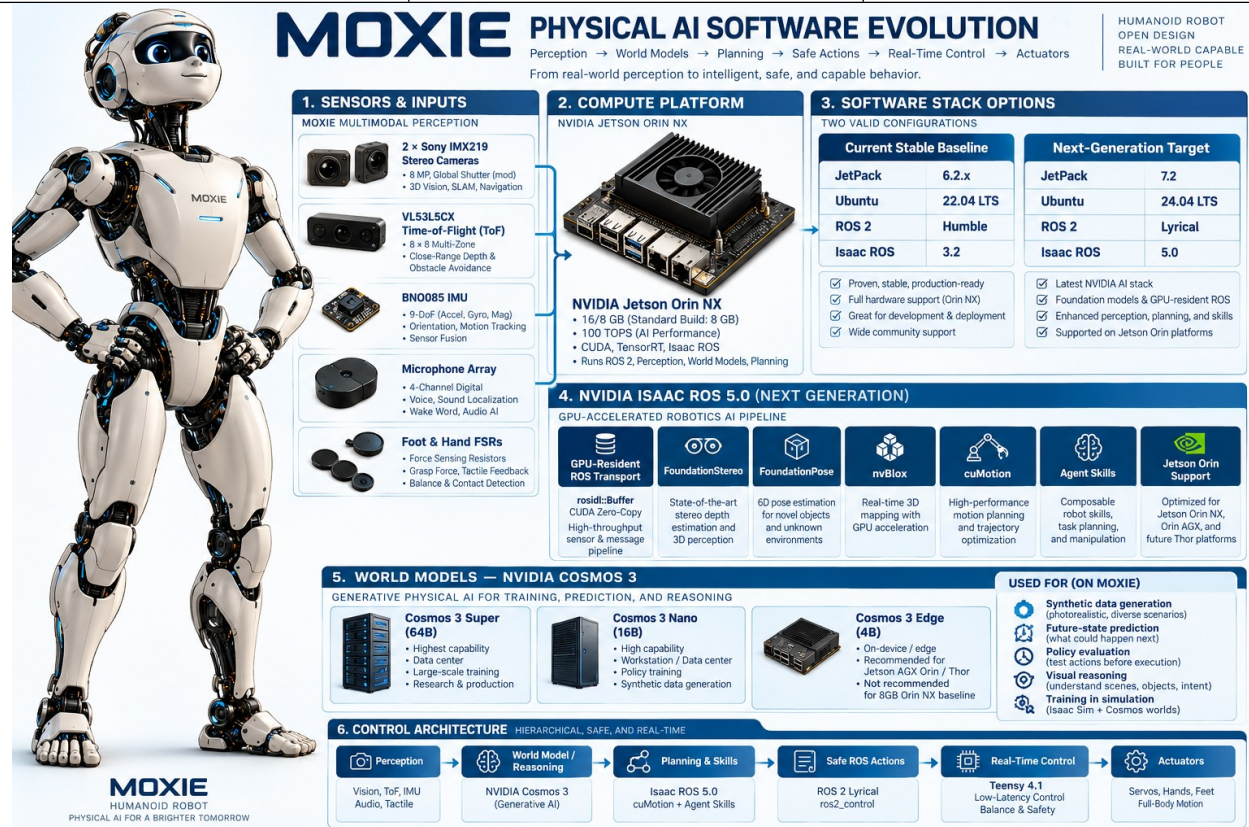


Figure 7M-1. MOXIE physical-AI software evolution: stable JetPack 6.2.x / ROS 2 Humble development branch, next-generation Isaac ROS 5.0 / ROS 2 Lyrical branch, and the recommended world-model integration pattern for perception, prediction, planning, safe ROS actions, and Teensy-controlled actuation.

7M. Isaac ROS 5.0 migration strategy

NVIDIA Isaac ROS 5.0 was released in September 2026. It moves the accelerated ROS stack to ROS 2 Lyrical Luth on Ubuntu 24.04 and uses JetPack 7.2 on supported Jetson Orin systems. NVIDIA also replaced the older custom NITROS message packages with standard ROS 2 messages that can use rosidl::Buffer and a CUDA buffer backend, allowing GPU-resident data paths without forcing custom message types.

Why this matters to MOXIE. Stereo perception, depth, 3D mapping, pose estimation and motion planning are exactly the workloads where GPU-resident ROS data can reduce unnecessary memory copies. Isaac ROS 5.0 also adds agent-ready workflows and reusable skills, including FoundationStereo adaptation and pick-and-place workflows, which fit MOXIE's stereo-eye and dexterous-hand design.

- Recommended migration policy. Do not replace the working robot image in place. Keep the stable Humble branch bootable, clone the current NVMe, and qualify Isaac ROS 5.0 on a second drive. The migration is accepted only after both IMX219 cameras, ToF sensor, Wi-Fi, SSD, Teensy link, ROS control bridge and actuator-safety services pass the same regression suite used on the Humble branch.
- Hardware/storage target. NVIDIA lists Jetson Orin + JetPack 7.2 and at least 128 GB NVMe storage as an officially supported Isaac ROS 5.0 platform combination. Because MOXIE uses a Yahboom carrier board rather than a stock NVIDIA carrier, treat Yahboom BSP compatibility as a hard gate before flashing.
- GPU data path. Prefer standard sensor_msgs and geometry_msgs interfaces that can take advantage of rosidl::Buffer/CUDA-backed storage where supported. Keep MOXIE-specific behavior messages conventional ROS 2 interfaces so the robot remains interoperable with non-NVIDIA nodes.
- Perception priority. Evaluate FoundationStereo first for the dual camera eyes, then nvBlox for local 3D mapping, FoundationPose for object tracking, and cuMotion for collision-aware upper-body manipulation. Add one accelerated package at a time and benchmark end-to-end latency and memory pressure on the 8 GB Orin NX.

7M.1 Isaac ROS 5.0 installation / qualification path

The sequence below is a migration recipe, not an instruction to overwrite the existing working Yahboom image. Perform it on a cloned or spare NVMe and only after confirming JetPack 7.2 support for the specific Yahboom carrier board.

9. 1. Flash or install the carrier-supported JetPack 7.2 image. After boot, verify the Jetson Linux release and storage. NVIDIA's Isaac ROS 5.0 documentation expects the Jetson R39.2 release family and 128+ GB NVMe.

```
cat /etc/nv_tegra_release
lsblk
df -h /
```

10. 2. Create a dedicated Isaac ROS workspace and install the Isaac ROS CLI.

```
mkdir -p ~/workspaces/isaac_ros-dev/src
echo 'export ISAAC_ROS_WS="${ISAAC_ROS_WS:-${HOME}/workspaces/isaac_ros-dev/}'" >> ~/.bashrc
source ~/.bashrc
sudo apt update
sudo apt-get install -y isaac-ros-cli
```

11. 3. Install ROS 2 Lyrical using NVIDIA's Isaac ROS Buildfarm instructions, then source it from the shell.

```
echo "source /opt/ros/lyrical/setup.bash" >> ~/.bashrc
source ~/.bashrc
```

12. 4. Configure rosdep with NVIDIA's Isaac ROS 5.0 dependency definitions.

```
sudo rosdep init 2>/dev/null || true
sudo curl -o /etc/ros/rosdep/sources.list.d/nvidia-isaac.yaml \
  https://raw.githubusercontent.com/NVIDIA-ISAAC-ROS/isaac-ros-cli/release-5.0/docker/rosdep/extra_rosdeps.yaml
echo "yaml file:///etc/ros/rosdep/sources.list.d/nvidia-isaac.yaml" | \
  sudo tee /etc/ros/rosdep/sources.list.d/00-nvidia-isaac.list
rosdep update
```

13. 5. Start with the Isaac ROS CLI-managed environment rather than a bare-metal deployment. Bring up one camera and one accelerated node first, then expand to stereo and 3D perception. Record GPU memory, CPU load, latency, frame drops and thermal behavior before enabling locomotion.
14. 6. Port MOXIE packages without changing safety boundaries. The high-level Jetson branch may change from Humble to Lyrical, but the Teensy watchdog, joint-limit enforcement, E-stop handling and actuator cutoff policy remain unchanged.

7N. World models and physical-AI prediction

World models add a new capability above conventional perception: instead of only estimating what is present now, they learn or generate how the physical scene may evolve after an action. For MOXIE, the useful goal is not photorealistic video generation by itself; it is better prediction, safer action selection, synthetic training data, and policy evaluation before the robot commits to a motion in the real world.

NVIDIA Cosmos 3 is the most directly relevant open world-model family for the NVIDIA-based MOXIE architecture. Cosmos 3 combines physical reasoning, world generation and action prediction. NVIDIA positions Cosmos 3 Super (64B) for data-center teacher/synthetic-data workloads, Cosmos 3 Nano (16B) for workstation/data-center post-training, and Cosmos 3 Edge (4B) for real-time edge policy and visual reasoning on Jetson AGX Orin or Jetson Thor.

Important 8 GB constraint. The baseline MOXIE uses an 8 GB Jetson Orin NX. That is not an official Cosmos 3 Edge target in NVIDIA's current model matrix, and the larger Cosmos 3 models require far more memory. Therefore the Standard MOXIE should initially consume world-model capabilities offboard during development rather than trying to run the full Cosmos 3 model family continuously on the robot.

7N.1 Recommended world-model architecture for MOXIE

- Development / training loop: record synchronized stereo, ToF, IMU, FSR, joint-state and action data with rosbag2; replay it in MuJoCo / Isaac Sim; use Cosmos 3 offboard to generate or vary physically plausible scenes and future outcomes; train or evaluate compact task policies; then test those policies in simulation and hardware-in-the-loop before deploying to the robot.
- On-robot runtime for the 8 GB Standard model: keep real-time control deterministic. Run stereo perception, ToF, balance, ROS control and the behavior layer locally. Use a compact VLM/reasoner or an offboard world-model service to score candidate high-level actions. Never let a generative world model issue raw servo commands.
- Upgrade path: if a future MOXIE Standard/XL uses Jetson AGX Orin or Thor, evaluate Cosmos 3 Edge as a local predictive-policy layer. Its output should remain a bounded action proposal or trajectory objective passed through MOXIE safety checks, ros2_control and the Teensy real-time controller.
- World-model bridge package. Add moxie_world_model as a ROS 2 package that accepts timestamped perception snapshots plus a small set of candidate actions and returns predicted outcomes, confidence/risk scores, and optional future-state representations. The behavior manager can then choose among safe candidates without coupling the rest of the stack to a specific vendor model.
- Synthetic-data use. Generate difficult but safe-to-create training scenarios offboard: poor lighting, partial occlusion, cluttered floors, unusual object positions, slips, near-falls, and failed grasp setups. Use generated data to harden perception and policy evaluation, not as a substitute for real sensor calibration and real-world validation.

- Safety rule. World-model output is advisory. Hard joint limits, fall detection, contact checks, collision constraints, watchdog timers and the emergency stop remain deterministic and outside the generative model.

7N.2 Suggested software interfaces

moxie_world_model/
 msg/WorldState.msg
 msg/PredictedOutcome.msg
 srv/EvaluateAction.srv
 action/PredictTaskOutcome.action
 launch/world_model_bridge.launch.py

Inputs: stereo/depth, ToF, IMU, FSR/contact, joint_states, candidate action

Outputs: predicted future state, risk score, success score, explanation/metadata

Execution: offboard first; optional local deployment only on validated hardware

7O. Software research references

- NVIDIA Cosmos prerequisites: <https://docs.nvidia.com/cosmos/latest/prerequisites.html>
- NVIDIA Cosmos 3 model matrix: https://docs.nvidia.com/cosmos/latest/cosmos3/model_matrix.html
- NVIDIA Cosmos 3 announcement: <https://nvidianews.nvidia.com/news/nvidia-launches-cosmos-3-the-open-frontier-foundation-model-for-physical-ai/>
- NVIDIA Isaac ROS overview: <https://developer.nvidia.com/isaac/ros>
- NVIDIA Isaac ROS 5.0 Getting Started:
https://nvidia-isaac-ros.github.io/v/release-5.0/getting_started/index.html
- NVIDIA Isaac ROS 5.0 release notes: <https://nvidia-isaac-ros.github.io/v/release-5.0/releases/index.html>
- NVIDIA JetPack 6.2.2: <https://developer.nvidia.com/embedded/jetpack-sdk-622>
- NVIDIA Isaac ROS 3.2 Getting Started:
https://nvidia-isaac-ros.github.io/v/release-3.2/getting_started/index.html
- Isaac ROS Common / Dev Docker:
https://nvidia-isaac-ros.github.io/v/release-3.2/repositories_and_packages/isaac_ros_common/index.html
- ROS 2 apt-source repository setup: https://github.com/ros2/ros2_documentation/blob/rolling/source/Get-Started/Installation/_Apt-Repositories.rst
- ros2_control Humble documentation: <https://control.ros.org/humble/>
- MoveIt 2 Humble Getting Started:
https://moveit.picknik.ai/humble/doc/tutorials/getting_started/getting_started.html
- MoveIt Setup Assistant:
https://moveit.picknik.ai/humble/doc/examples/setup_assistant/setup_assistant_tutorial.html
- Nav2 documentation: <https://docs.nav2.org/>
- Pinocchio: <https://github.com/stack-of-tasks/pinocchio>
- MuJoCo: <https://github.com/google-deepmind/mujoco>
- mujoco_ros2_control Humble: https://control.ros.org/humble/doc/mujoco_ros2_control/doc/index.html

7P. Build options: budget through advanced

The software stack is intentionally modular so the same Moxie behaviors can run on different mechanical and sensor configurations. Builders can reduce cost by simplifying mechanics and sensing first, while

keeping the ROS 2 package interfaces stable. This makes it possible to start with a cheaper robot and add stereo vision, active toes, tactile sensing, or higher-torque joints later without rewriting the whole system.

Figure 7P-1. Moxie build-option overview covering size, cost, component choices, software architecture, and customization.

Build	Mechanical / sensor strategy	Compute	Approx. cost*	Tradeoff
Budget	Mini or simplified Compact; lower-cost smart servos; passive/fixed toe groups; one camera; IMU; reduced FSR count	Raspberry Pi 5 or existing Jetson used offboard	\$600-\$1,800	Lowest cost, but less dynamic walking, depth perception, and grasp feedback
Standard (recommended)	610 mm baseline; stereo cameras + ToF; 32 actuators; three-group toes; three-servo hands; IMU + FSRs	Existing Jetson Orin NX	\$2,400-\$3,200	Best balance of cost, capability, and compatibility with this document
Advanced	Stronger servos or selected Dynamixels; richer tactile sensing; higher-quality bearings; more machined aluminum; depth/perception upgrades	Orin NX / Orin AGX	\$4,500-\$6,500	Higher performance and durability, with more integration work
Premium / XL	850 mm class; BLDC integrated lower-body actuators; industrial structure; expanded sensors; stronger battery and safety hardware	Orin AGX class optional	\$8,000-\$12,000+	Research-grade capability, much higher cost and safety burden

**These are planning ranges, not vendor quotes. Final cost depends heavily on actuator choice, printer ownership, fabrication method, number of batteries, and how much of the current hardware is reused.*

Practical cost-reduction priorities

- Reuse the existing Jetson Orin NX and camera kit rather than buying another onboard AI computer.
- Prototype one leg, one foot, and one hand before ordering every actuator. This catches torque, geometry, and tendon problems before the largest purchases are made.
- For Mini/Compact versions, reduce active toe actuation before reducing ankle DOF. Ankle pitch/roll is more important to stable biped walking than individually powered toes.
- Use printed PETG/PA-CF shells and commercially available metal servo brackets wherever possible; reserve CNC parts for the pelvis, high-load leg brackets, and interfaces that fail printed testing.
- Start with one M18 battery and a standard charger during development. Add the multi-pack full-day battery kit only when runtime becomes a real requirement.
- Keep the software package APIs identical across variants so a lower-cost build can later inherit perception, speech, behaviors, simulation, and tools from the Standard platform.

8. Procurement list (orderable parts)

Prices and stock below are snapshots from 26 September 2026 and should be rechecked before ordering. Shipping, tax, brackets, wiring and fabrication are not included unless stated.

Subsystem	Part	Qty	Unit	Extended	Ref	Purchase
Already owned	Yahboom Jetson Orin NX Super 8GB Camera Advanced Kit	1	Owned	—	R5	See Ref
Leg actuators	Hiwonder HTD-45H 45 kg·cm HV serial bus servo	12	\$24.99	\$299.88	R3	Buy / source
Upper/toe/ hand actuators	Hiwonder HTS-20H 20 kg·cm HV serial bus servo	20	\$17.99	\$359.80	R13	Buy / source
Real-time MCU	Teensy 4.1	1	\$31.50	\$31.50	R7	Buy / source
IMU	Adafruit BNO085 9-DOF orientation breakout	1	\$29.50	\$29.50	R14	Buy / source
Foot + hand tactile sensing	SparkFun 0.5 in FSR	24	\$10.95	\$262.80	R10	See Ref
Analog mux	SparkFun CD74HC4067 16-channel mux breakout	2	\$6.50	\$13.00	R11	Buy / source
Voice input	Seeed reSpeaker XVF3800 USB 4-mic array with case	1	\$59.90	\$59.90	R15	Buy / source
Audio amp	Adafruit MAX98357A I2S 3W amplifier	1	\$5.95	\$5.95	R16	Buy / source
Speaker	Adafruit 3W 4Ω enclosed speaker	1	\$3.95	\$3.95	R17	See Ref

Subsystem	Part	Qty	Unit	Extended	Ref	Purchase
Primary battery	Milwaukee M18 REDLITHIUM FORGE XC8.0 (48-11-1881)	1 required / 4 day-kit	\$199	\$199 / \$796	R8	Buy / source
Servo regulation	Pololu D42V110F12 12 V / 9 A regulator (prototype branch use only)	3 prototype	\$59.95	\$179.85 prototype set	R21	Buy / source
Servo setup tool	Hiwonder serial bus servo controller/debugger	1	\$39.99	\$39.99	R18	Buy / source
Frame stock	2 mm 6061-T6 aluminum sheet/strip	1 lot	est. \$80–150	\$120 est.	Generic	Buy / source
Printed structure	PETG/PA-CF for torso/head/covers/hands; TPU for sole and fingertip pads	1 lot	est. \$100–170	\$135 est.	Generic	Buy / source
Fasteners/bearings	M2/M3 screws, locknuts, shoulder bolts, small bearings	1 lot	est. \$100–160	\$130 est.	Generic	Buy / source
Toe + hand tendons	1.0–1.5 mm Dyneema/Spectra + PTFE guide tube	1 lot	est. \$35–60	\$45 est.	Generic	Buy / source
Power safety	XT60 harness, 60–80A main fuse, branch fuses, E-stop, TVS/filter parts	1 lot	est. \$80–130	\$105 est.	Generic	Buy / source

Subsystem	Part	Qty	Unit	Extended	Ref	Purchase
Wiring/ connectors	Servo leads, JST/PH, ferrules, silicone wire, heat shrink	1 lot	est. \$70–120	\$95 est.	Generic	Buy / source
Compute regulator	Validated 19 V-class buck- boost converter for Jetson, >=65 W continuous	1	TBD	TBD	R28 / validation	Buy / source
Hot-swap power OR	Pololu Power ORing Ideal Diode Pair, 4–60 V, 6 A/channel	1	\$7.95	\$7.95	R23	Buy / source
Keep-alive battery	TalentCell YB1203000 11.1 V / 3000 mAh Li-ion, 3 A max	1	~\$50	\$50 est.	R24	Buy / source
Full-day charger	Milwaukee M18 Dual Bay Simultaneou s Super Charger (48- 59-1815)	1	\$229	\$229	R9	Buy / source
M18 robot dock	Commercial M18 battery adapter/cont act dock + custom guarded latch	1	est. \$25–40	\$30 est.	Generic	Buy / source
Stereo camera #2	Yahboom IMX219 8MP CSI camera, 22-pin; same FOV as existing camera	1	\$20.90	\$20.90	R25	Buy / source

Subsystem	Part	Qty	Unit	Extended	Ref	Purchase
Central ToF sensor	VL53L5CX 8x8 multizone ToF breakout/evaluation board	1	~\$23-35	~\$23-35	R26	Buy / source

Estimated cost note. The BOM is now intentionally split between known catalog items and validation-dependent power hardware. Expect roughly \$2.3k for the concept-stage robot parts excluding the Jetson already owned, and roughly \$3.3k with spares plus a four-pack M18 demo-day rotation. These are planning estimates, not a quoted build cost; the final total depends on measured servo-current needs, the selected 19 V mobile Jetson converter, fabrication rework, and current market pricing.

9. Parts that should be fabricated

Assembly	Recommended material	Notes
Pelvis frame	2 mm 6061 aluminum, box structure	Carries both hip assemblies and internal keep-alive battery; reinforced for added M18 mass
Thigh/shin side plates	2 mm 6061 aluminum	Pairs of plates with standoffs; slotted prototype holes useful
Torso cage	Aluminum lower tray + printed shell	Jetson, MCU, regulators, power ORing; removable rear panel; route M18 dock conductors away from sensor wiring
Feet	Nylon/PETG skeleton + TPU sole pads	Embedded FSR pockets and tendon channels
Toe links	Nylon or PA-CF	Pin-jointed; replaceable wear components
Head	PETG shell	Camera window + mic acoustics
Servo brackets	Prefer vendor metal brackets where possible	Only custom-fabricate geometry not available off-the-shelf
Hand palm and finger links	PA-CF/nylon or PETG prototype; TPU/silicone pads	Five visible fingers; tendon channels and replaceable fingertip pads
Hand tendon manifold	Aluminum/printed pulley block + PTFE guides	One servo distributes pull to middle/ring/pinky while preserving per-finger compliance
M18 rear dock / guard	2 mm 6061 aluminum + printed contact shroud	Low rear-pelvis mount, positive latch, protected contacts, quick one-hand battery removal

9A. Staged purchasing to reduce prototype risk

- Stage 1: purchase enough leg servos and hardware for one complete leg plus one adaptive foot, one hand set, the MCU/IMU, and bench power components.

- Stage 2: complete static-load, current, thermal, backlash, tendon, and foot-contact tests. Freeze joint geometry and confirm the HTD-45H torque class is adequate before buying the remaining leg actuators.
- Stage 3: order the balance of the servos, frame material, second camera, ToF sensor, and final wiring only after the lower-body design passes its gate.
- Stage 4: buy the full M18 battery rotation and final mobile compute DC/DC hardware after measured robot power is available.

9B. Fastener, attachment, and hole-making standard

This section freezes the Standard 610 mm MOXIE prototype around a small metric fastener set so a builder can order hardware, drill parts, and assemble repeatably. The installed counts below are the Rev-A build target; order quantities include normal development spares. Where vendor-supplied servo horn screws are specified, use the vendor hardware and do not re-tap the servo output unless the physical part is measured and the vendor documentation agrees.

Verified vendor facts used here: Hiwonder specifies M3x6 for the HTD-45H main horn center screw and M2x5 for horn retention; Hiwonder lists the HTD-45H at 51.1 x 20.14 x 40 mm and the HTS-20H at 54.38 x 20.04 x 45.50 mm. NVIDIA recommends M2.5/M3 hardware for Orin-series module mounting and notes 3.5 mm module mounting holes. The custom frame and printed-part hole standards below are MOXIE design decisions, not vendor-provided dimensions.

ID	Fastener / attachment	Installed	Order	Primary use	Driver / tool
F1	M2 x 5 socket-head, class 10.9 or stainless	64	100	Small sensor brackets, finger shells, small covers; substitute only where CAD calls M2	1.5 mm hex
F2	M2 x 8 socket-head	24	50	Camera/ToF retainers, cable-guide retainers, small printed brackets	1.5 mm hex
F3	M2.5 x 8 socket-head	16	25	Jetson/Teensy/ electronics tray mounting	2.0 mm hex
F4	M3 x 6 socket-head	32 vendor sets	40 spare	HTD-45H primary horn center screw; use vendor-specified size	2.5 mm hex
F5	M2 x 5 horn-retaining screw	HTD-45H vendor sets	40 spare	HTD-45H horn retention; use supplied/vendor equivalent	1.5 mm hex / supplied

F6	M3 x 8 socket-head	148	180	Servo clamp brackets, cable clips, small structural brackets	2.5 mm hex
F7	M3 x 10 socket-head	96	120	Printed shell panels into M3 heat-set inserts	2.5 mm hex
F8	M3 x 12 socket-head	48	60	Hand/foot structural printed joints and tray brackets	2.5 mm hex
F9	M3 nyloc nut	96	120	Through-bolted M3 metal/PA-CF joints	5.5 mm wrench
F10	M3 flat washer, 7 mm OD	180	250	Load spread under M3 screw heads/nuts	-
F11	M3 brass heat-set insert, M3x0.5, 5.7 mm length	96	120	Reusable threads in PETG/PA-CF shells and printed brackets	Heat-set tip
F12	M4 x 12 socket-head	56	70	Pelvis, hip/knee/ankle structural plates, torso spine	3.0 mm hex
F13	M4 x 16 socket-head	16	25	Battery dock, thicker stacked structural joints	3.0 mm hex
F14	M4 nyloc nut	72	100	M4 through-bolted structure	7 mm wrench
F15	M4 flat washer, 9 mm OD	144	200	Load spread on 2 mm aluminum / composite structure	-
F16	M4 brass heat-set insert, M4x0.7, 8.2 mm length	16	25	Battery guard / heavy printed service panels only	Heat-set tip
F17	3 mm x 20 mm stainless dowel pin	10	16	Five toe hinge pins per foot, one per toe	Arbor press / soft mallet

F18	3 mm E-clip or shaft collar	20	30	Retention on both ends of toe hinge pins	E-clip pliers
F19	2 mm x 12 mm shoulder screw/pivot pin	30	40	Finger joint pivots; three per finger	1.5 mm hex
F20	M2 nyloc nut	30	50	Finger shoulder-screw retention where through-bolted	4 mm wrench
F21	Medium-strength removable threadlocker (blue)	1 bottle	1	Metal-to-metal threaded joints only; keep off plastics and electronics	-
F22	Low-profile cable tie, 2.5 mm width	~60	100	Harness strain relief; never use as structural retention	Flush cutter

9B.1 Drill, tap, ream, and printed-insert hole sizes

Feature	Use this tool size	Result / notes
M2 x 0.4 tapped hole in aluminum	1.6 mm tap drill	Tap M2x0.4; deburr both faces.
M2 clearance hole	2.2 mm drill	Normal clearance through metal/printed bracket.
M2.5 x 0.45 tapped hole in aluminum	2.05 mm tap drill	Tap M2.5x0.45. If 2.05 mm unavailable, 2.0 mm can be used carefully in soft aluminum.
M2.5 clearance hole	2.7 mm drill	Electronics standoff clearance.
M3 x 0.5 tapped hole in aluminum	2.5 mm drill	Tap M3x0.5; use cutting fluid and back tap out often in 6061.
M3 normal clearance	3.2 mm drill (1/8 in is acceptable at 3.175 mm)	Preferred through-hole for M3 bolts.
M4 x 0.7 tapped hole in aluminum	3.3 mm drill	Tap M4x0.7.
M4 normal clearance	4.3 mm drill	Use 4.5 mm only where alignment slots/tolerance require extra clearance.
M3 heat-set insert pocket	Model/finish at 4.0 mm nominal	For the specified M3 5.7 mm insert; pocket depth ≥ 6.5 mm. Print a calibration coupon first.
M4 heat-set insert pocket	Model/finish at 5.6 mm nominal	For the specified M4 8.2 mm insert; pocket depth ≥ 9.0 mm. Print a calibration coupon first.
3 mm toe hinge press/slip fit	Drill 2.9 mm then ream 3.0 mm	Use on the fixed side. For a free-rotating printed knuckle, ream

		3.1 mm and validate play.
2 mm finger pivot	Drill 1.9 mm then ream 2.0 mm	Use shoulder screw/pin as bearing surface; do not let threads run in the joint.
Cable pass-through, small servo lead	6.0 mm drill / printed slot	Add 0.5 mm radius/chamfer and grommet where wire rubs.
PH2.0-3P servo connector passage	8 x 5 mm printed slot minimum	Verify actual plug orientation before freezing CAD.

- Drill-order rule for aluminum: center punch -> pilot 2.0 mm -> final drill -> deburr -> tap/ream. Do not tap through burrs or bent sheet.
- Printed-part rule: do not chase heat-set insert pockets with a metal drill unless a calibration coupon proves the printed hole is undersized. Install inserts with a temperature-controlled iron/press at roughly filament print temperature +10 to +20 C and keep the insert square.
- All structural metal-to-metal M3/M4 joints use a washer under the rotating screw head and either a nyloc nut or removable threadlocker. Do not use both unless the joint is explicitly marked as critical.
- Use no permanent threadlocker on service covers, electronics, heat-set insert screws, or plastic-adjacent joints. Use mechanical locking instead.

9B.2 Installed hardware by subsystem

Subsystem	Exact Rev-A installed hardware	Hole preparation / notes
Head shell + sensor carrier	8 x F7 M3x10 into F11 inserts; 8 x F1 M2x5; 4 x F2 M2x8	M3 insert pockets 4.0 mm; M2 clearance 2.2 mm. Camera/ToF holes must follow measured modules.
Neck (2-DOF)	8 x F6 M3x8 servo clamps; vendor horn screws per servo; 4 x F10 washers	Use clamp-style custom bracket so servo case is not drilled. Verify horn neutral before tightening.
Torso shell / rear access	20 x F7 M3x10 into F11 inserts	Service panels use heat-set inserts only; no self-tapping screws.
Torso inner frame / spine	16 x F12 M4x12 + 16 x F14 + 32 x F15	4.3 mm clearance holes in 2 mm 6061 unless joint is intentionally tapped.
Pelvis / hip frame	20 x F12 M4x12 + 20 x F14 + 40 x F15	Use through-bolts on primary load paths.
M18 battery dock + guard	8 x F13 M4x16 + 8 x F14 + 16 x F15; 8 x F7 M3x10 into inserts for guard	Metal dock uses M4; removable printed guard uses M3 inserts.
Each leg (x2), servo/body brackets	24 x F6 M3x8 per leg = 48 total; vendor horn screws; 10 x F12 M4x12 per leg = 20 total	M3 clamp screws secure servo bodies to brackets; M4 through-bolts join major plate stacks.
Each foot (x2)	12 x F8 M3x12 per foot = 24; 5 x F17 + 10 x F18 per foot = 10 pins/20 clips total	Toe fixed knuckle 3.0 mm reamed; moving knuckle 3.1 mm. Verify free motion before tendon install.
Each arm (x2)	20 x F6 M3x8 per arm = 40 total; vendor horn screws	Use 4 clamp screws per actuator module. Route servo bus before closing covers.

Each hand (x2)	12 x F8 M3x12 per hand = 24; 15 x F19 + 15 x F20 per hand = 30 pivots/nuts total	Finger pivot holes reamed to 2.0 mm. Tendon anchors are not structural screws.
Jetson / compute tray	4 x F3 M2.5x8 + 4 nylon/metal standoffs; 4 x F7 M3x10 tray-to-frame	Use measured Yahboom carrier hole pattern from its STEP/3D model. Do not infer NVIDIA reference-carrier spacing.
Teensy / low-voltage electronics	4 x F3 M2.5x8 for tray/clamp + 8 x F1 M2x5 for sensor/breakout clips	Teensy 4.1 has plated pin holes, not dedicated mechanical mounting holes; mount in a printed edge-clamp or carrier rather than drilling the PCB.
Cable clips / strain relief	20 x F6 M3x8 into F11 inserts + ~60 F22 ties	Minimum bend radius and service loop at every moving joint.

9B.3 Minimum mechanical tool kit

- Metric drill bits: 1.6, 2.0/2.05, 2.2, 2.5, 2.7, 2.9, 3.0, 3.1, 3.2, 3.3, 4.0, 4.3, 5.6, 6.0 mm.
- Metric taps: M2x0.4, M2.5x0.45, M3x0.5, M4x0.7; use a tap guide for square threads.
- Metric reamers: 2.0 mm, 3.0 mm, 3.1 mm for finger/toe pivots.
- Hex drivers: 1.5, 2.0, 2.5, 3.0 mm; nut drivers/wrenches: 4, 5.5, 7 mm.
- Calipers (0.01 mm readout), center punch, deburring tool, countersink/chamfer tool, small torque driver, heat-set insert press/tip, E-clip pliers, flush cutters.

9B.4 Assembly torque targets

Joint type	Initial torque target	Notes
M2 steel screw into nut / metal	0.20-0.30 N.m	Finger/sensor hardware; use very light hand torque.
M2.5 electronics fastener	0.30-0.45 N.m	Do not bow PCBs; use standoffs.
M3 into brass heat-set insert	0.45-0.60 N.m	Service covers / printed brackets; stop if insert starts to rotate.
M3 through-bolt + nyloc	0.70-0.90 N.m	Servo clamp / small structure.
M4 through-bolt + nyloc, aluminum structure	1.5-1.8 N.m	Primary frame. Recheck after first 30 minutes of walking tests.
Vendor servo horn screws	Use vendor-tight / hand snug; do not exceed vendor guidance	Mark with torque paint after final neutral-position validation.

10. Assembly guide

The illustrated build sequence below provides a visual map of the complete assembly process. Use it together with the detailed numbered instructions that follow; the drawings are concept-level and final hole patterns, fastener sizes, tendon lengths, and cable routes must be verified against the released CAD before fabrication. Before starting physical assembly, complete Section 9B and sort all hardware into labeled F1-F22 bins. Every step below references that standardized fastener system.

Figure 10-1. MOXIE detailed build and assembly sequence: printed/mechanical parts, adaptive feet, lower legs, hips, pelvis and M18 battery mount, torso electronics, arms, head, final wiring, shells, and calibration.

The roadmap below provides a simplified build-and-validation sequence with explicit safety and quality gates. It complements the longer assembly procedure and can be used as the practical shop-floor checklist when planning the physical build.

10A. Build and validation roadmap

Figure 10A-1. Build and validation roadmap showing recommended assembly order, safety checks, calibration gates, and staged commissioning activities.

- The recommended order is intentional: prove one foot and one hand first, then one leg, then the lower body, before adding the full torso, arms, head, and higher-level autonomy.
- Do not skip the bench-test, static-stand, and assisted-walk stages; these are the highest-value checkpoints for protecting hardware and identifying design weaknesses early.
- The safety side panel should be treated as mandatory, especially the E-stop, fusing, battery isolation, cable strain relief, and fall-prevention harness during early walking tests.

Detailed assembly procedure

15. Bench-test all 32 servos before assembly. Use the Hiwonder debugger to assign unique IDs, verify feedback, set safe angle limits and record neutral positions. Reject any servo with noisy gears, unstable feedback or abnormal current.
16. Build one leg only. Assemble hip yaw/roll/pitch, knee pitch and ankle pitch/roll. Keep wiring external and accessible. Attach temporary long test leads. Use F6 M3x8 for servo clamp brackets and F12 M4x12/F14/F15 for the primary aluminum plate stack. Drill M3 clearance at 3.2 mm and M4 clearance at 4.3 mm; do not drill the servo cases.
17. **Validate one-leg torque.** Clamp the pelvis end of the leg to a fixture. Add progressively larger loads at the ankle while logging current and servo temperature. Verify the knee and hip-pitch axes have useful margin before duplicating the leg.
18. Build the pelvis and second leg. Make the pelvis torsionally stiff and symmetric. Add the reinforced rear/lower M18 dock structure and reserve a protected internal pocket for the keep-alive battery. Use ballast equal to the XC8.0 pack mass during early gait testing if the actual battery is not installed. Do not install the Jetson yet. Use F12 M4x12 through-bolts for pelvis structural plates and F13 M4x16 only where the battery-dock stack is thicker. Use washers on both sides of 2 mm aluminum.
19. Build one adaptive foot. Print/machine the foot skeleton, five toes and hinge pins. Install passive springs/elastomers. Route three tendons to three HTS-20H servos mounted in the lower shin. Calibrate tendon slack so toes return to neutral mechanically. Use five F17 3 mm hinge pins per foot. Ream the fixed leaf to 3.0 mm and the moving knuckle to 3.1 mm; retain each pin with two F18 clips. Use F8 M3x12 for printed structural joints.
20. **Install foot sensors.** Place one FSR under each toe, two under the forefoot and one at the heel. Cover each with a small compliant puck so pressure reaches the active sensor area consistently. Route signals to a local 16-channel mux.
21. **Duplicate the foot.** Only after the first foot survives repeated load/terrain testing. Match spring constants and tendon lengths left-to-right.

22. **Install Teensy + IMU.** Mount the IMU near the pelvis/torso centerline on a stiff plate. Isolate it from loose cable motion. Connect Teensy to Jetson by USB and to servos by UART through a proper level/interface stage if required by the selected bus wiring.
23. Wire power and emergency stop. M18 dock -> main fuse -> physical E-stop -> star distribution node. For early bench work, use separately fused 12 V prototype servo branches and current logging. Do not treat the initial three 9 A modules as the final full-robot supply. Power the Jetson from its supplied adapter during first integration; only move to the M18-fed mobile compute rail after a 19 V-class ≥ 65 W buck-boost solution has passed bench load, brownout, and thermal tests. Mount the power-distribution plate with four F12 M4x12 through-bolts and isolating standoffs. Do not use self-tapping screws through high-current power hardware.
24. Validate hot swap before walking. Seat or support the robot, disable all servo rails, place the Jetson in ≤ 20 W swap mode, and use the validated mobile compute converter plus keep-alive boost/ORing path. Remove the M18 pack and verify that Jetson, Teensy, network, and telemetry remain alive without a large input-voltage step. Reinsert the M18 pack, confirm stable compute voltage, then re-enable actuator power only after the main source is healthy.
25. First powered stance in a safety frame. Suspend the robot from an overhead tether so its feet can touch the floor but it cannot fall. Use the validated power configuration, bring up the MCU first, verify every branch voltage and current limit, command a neutral crouched stance, then energize servo branches one at a time while logging voltage, current, and temperature.
26. **Tune standing before walking.** Tune ankle roll/pitch response, then hip corrections. Add FSR-derived center-of-pressure correction only after the IMU-only loop is stable.
27. **Tune weight shifting.** Move center of mass laterally until one foot can unload. Validate toe-group assistance at the support-foot edge.
28. **Single step.** Lift the swing foot 10–20 mm, move it 20–30 mm forward, place it, and verify contact before transferring weight. Keep step length tiny.
29. **Continuous quasi-static gait.** Build up from single steps to slow continuous walking. Log every fall or near-fall and keep all servo temperature/current telemetry.
30. Add torso, arms and head. Install Jetson, camera, microphone array, speaker and arm joints only after the lower body can walk under ballast approximating the final upper-body mass. Leave the hands off until shoulder/elbow current margins are confirmed. Install removable shells with F7 M3x10 screws into F11 heat-set inserts. Arm/neck servo clamps use F6 M3x8. Electronics must be mounted on standoffs, never directly against printed plastic.

Build one hand. Fabricate the palm and five finger chains. Mount three HTS-20H servos in the forearm/palm region, route the thumb and index tendons independently, and route the middle/ring/pinky group through a compliant tendon manifold. Verify all fingers return fully when released. Use F19 2 mm shoulder screws/pins at finger pivots and F20 nyloc nuts; ream pivot holes to 2.0 mm. Use F8 M3x12 for palm/manifold structure.

Calibrate grip sensing. Install four FSR channels per hand (thumb, index, grouped-finger contact zone, palm). Record unloaded and contact values, then tune `close_soft()`, `pinch()`, `power_grip()`, `point()`, and `release()` behaviors. Limit grip force in firmware before attaching the second hand.

Duplicate and install the second hand. Match tendon lengths, spring preload and neutral finger angles left-to-right. Recheck shoulder and elbow current with a 300 g test object held close to the torso.

31. **Enable AI behaviors last.** Expose high-level ROS2 actions to the local agent. Require the real-time controller to enforce joint limits, speed limits, fall detection and an unconditional stop command.

11. Commissioning / acceptance checklist

- ☐ All 32 actuator IDs unique and readable
 - ☐ Neutral pose mechanically symmetric
 - ☐ No servo exceeds safe temperature during 2-minute static hold
 - ☐ E-stop removes actuator power but leaves telemetry/Jetson available where practical
 - ☐ Foot FSR baseline and full-load values recorded
 - ☐ IMU axes verified against physical roll/pitch/yaw
 - ☐ Robot stands tethered for 60 seconds without drift
 - ☐ Robot performs controlled ± 20 mm lateral CoM shift
 - ☐ Each toe group can modulate contact pressure without binding
- ☐ Thumb, index, and grouped middle/ring/pinky actuators move through full range without tendon binding
- ☐ Each hand can perform pinch, power grip, point, and controlled release
- ☐ Hand FSRs detect contact and stop further grip-force increase at configured threshold
- ☐ Robot takes ten tethered single steps without missed contact
 - ☐ Jetson survives servo transients and M18 battery removal/reinsertion without brownout
 - ☐ All ROS2 motion commands are bounded by MCU-side safety limits
 - ☐ Robot automatically blocks gait commands while main M18 pack is absent
 - ☐ Backup battery never energizes the servo rails
 - ☐ Main pack can be swapped while the Jetson/Teensy/network remain alive for at least 2 minutes
 - ☐ M18 dock latch positively retains battery under walking shock and contacts cannot be touched accidentally

12. Recommended development phases

Phase 0 – CAD/simulation: Create URDF; estimate mass/inertia; verify joint ranges; simulate simple standing and foot placements.

Phase 1 – lower body: Two legs, pelvis, rigid prototype feet; establish safe stand and weight shift.

Phase 2 – adaptive feet: Add five-toe mechanism, FSR sensing, toe-group control and uneven-terrain test fixtures.

Phase 3 – complete body/power: Add torso ballast, M18 dock, keep-alive battery and power ORing; prove hot-swap behavior; then add Jetson, stereo cameras/depth sensor, arms, five-finger hands and head. Validate 200–300 g grasping loads and retune gait for the final battery mass.

Phase 4 – embodied AI: Vision, speech, semantic map, high-level action interface, local LLM/VLM.

Phase 5 – rough terrain: Depth sensing, terrain classification, foothold scoring and pre-shaping of the toes before contact.

12A. Action behavior showcase

The MOXIE concept is intended not only as a static research platform, but as a small embodied system capable of expressive social behavior, simple manipulation, and basic inspection tasks. The following action sheet shows six representative behaviors that the robot should be able to perform once the mechanical build, calibration, and software stack are complete.

Figure 13. MOXIE action behavior sheet showing six representative actions: walking, greeting, pointing, picking up an object, carrying an object, and inspecting/scanning.

The expanded action gallery below provides additional complete-body poses that can serve as targets for simulation, animation, and hardware validation. Social gestures can be developed early; crouching, pickup, carrying, and walking should only be attempted after static balance and tethered motion tests are stable.

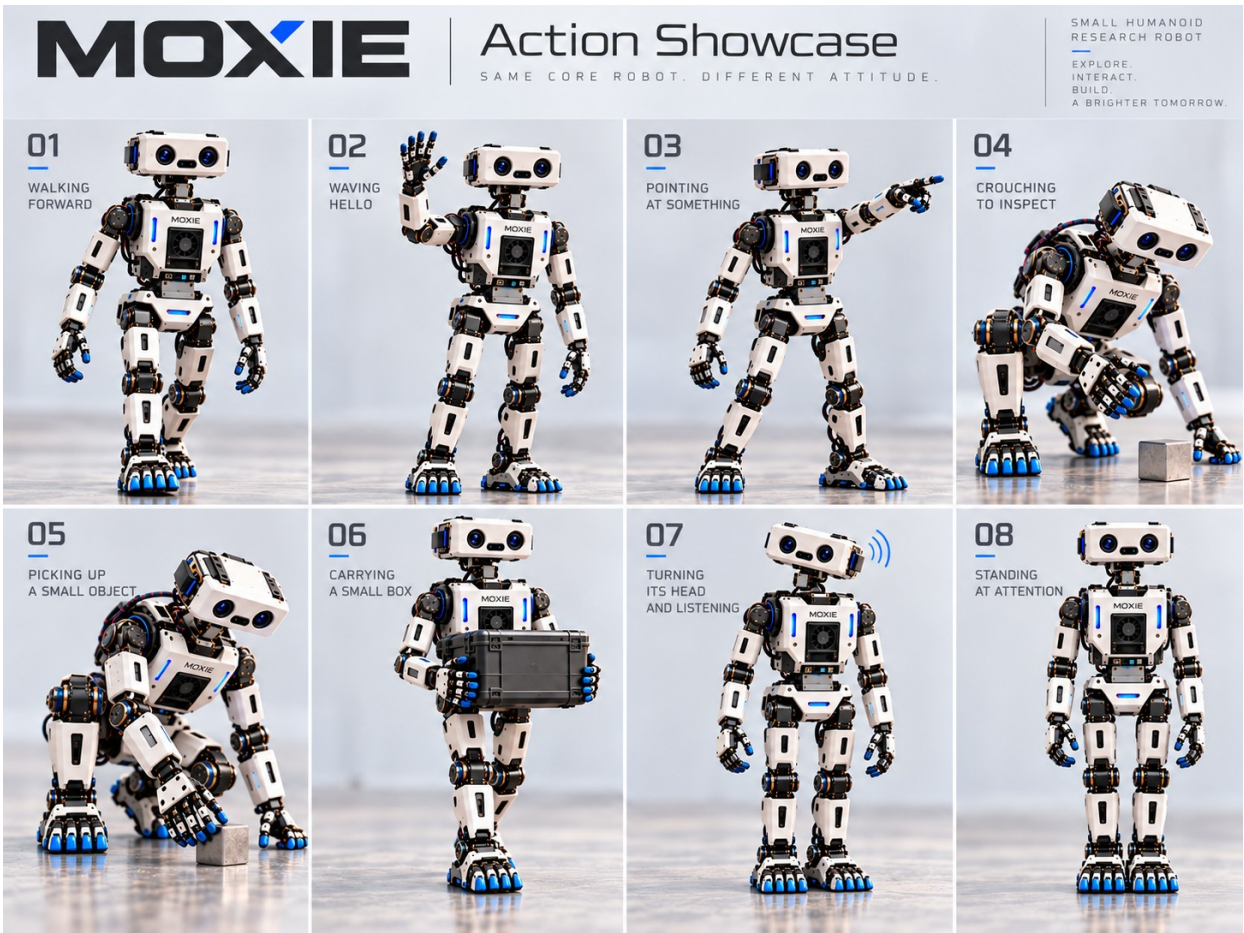


Figure 12A-2. Expanded MOXIE action showcase: walking, waving, pointing, crouching, picking up an object, carrying, listening, and standing at attention.

Representative actions and expected behavior

32. 1. Walking forward

- The robot walks in a stable forward gait using the adaptive five-toe feet, IMU feedback, and whole-body balance control. This is the baseline locomotion behavior used for navigation and repositioning.

33. 2. Waving hello

- The robot raises one arm and performs a friendly wave using shoulder pitch/roll, elbow pitch, and the five-finger hand. This is an expressive target behavior; gesture speed and range should remain within validated joint limits.

34. 3. Pointing at something

- The robot extends an arm and points with the index finger toward a target of interest. This is useful for explanation, guided interaction, object indication, or user-directed tasks.

35. 4. Picking up a small object

- The robot kneels or crouches, reaches toward a nearby object, and closes the adaptive five-finger hand around it. This demonstrates low-height reach, balance while crouched, and fine grasping.

36. 5. Carrying a box

- The robot holds a small box or payload with both hands close to the torso and transports it while standing or walking slowly. This behavior demonstrates cooperative arm use and center-of-mass management during handling.

37. 6. Inspecting or scanning

- The robot kneels or lowers its body and uses the stereo cameras and central ToF sensor to examine a nearby object or area. This behavior demonstrates perception-led interaction, close-range inspection, and sensor-directed attention.

12B. Detailed movement study and pose sequencing

The movement study breaks representative behaviors into intermediate poses so they can be implemented as state machines or time-parameterized trajectories. These sequences are particularly useful for MuJoCo validation, center-of-mass analysis, collision checking, and tuning the handoff between Jetson-level planning and Teensy-level joint control.

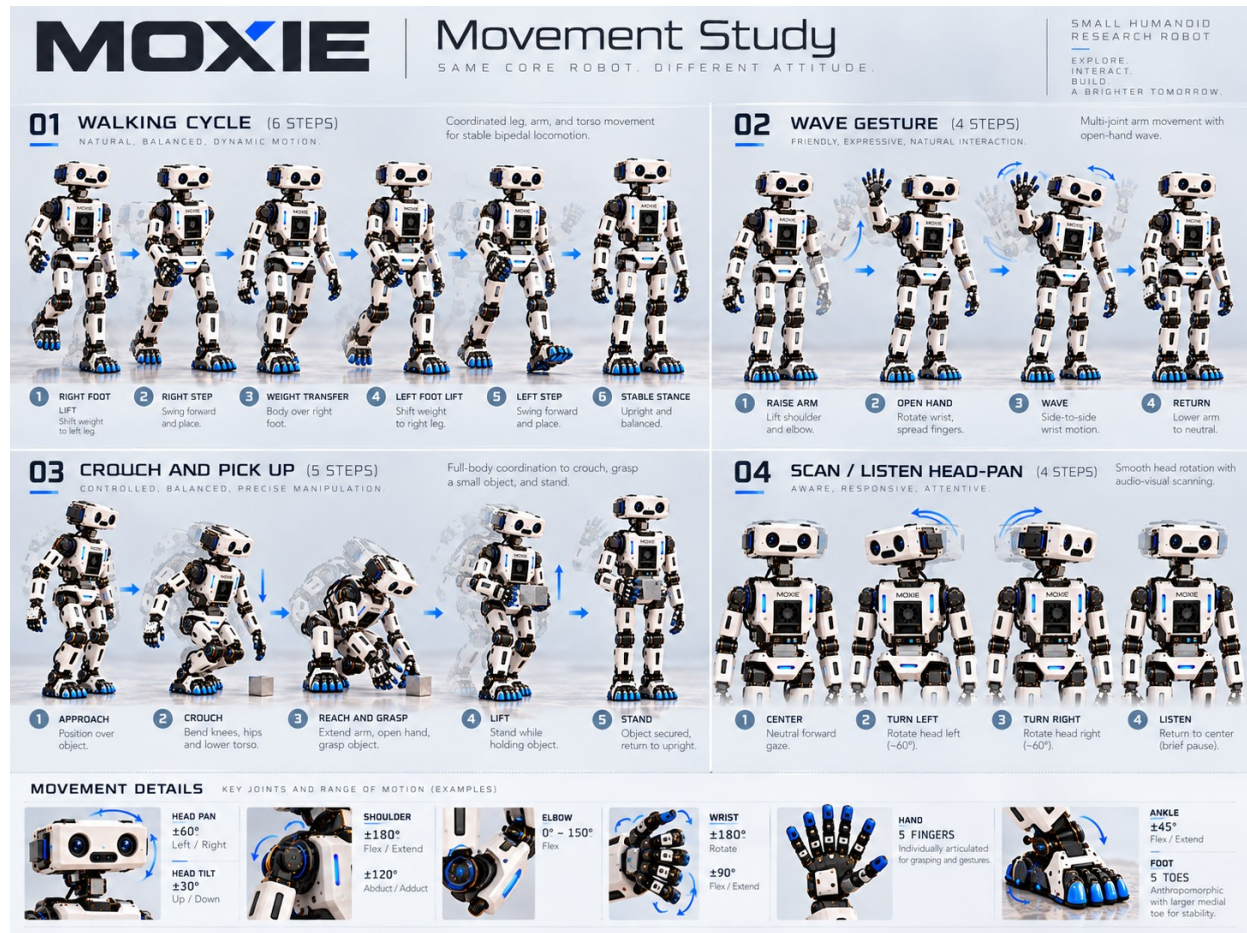


Figure 12B-1. Detailed MOXIE movement sequences for walking, waving, crouch-and-pick-up, and sensor-directed head scanning.

- Walking should move through stable support states with verified foot contact before weight transfer.
- Crouch-and-pick-up should be separated into approach, crouch, reach, grasp, lift, and recovery states so failures are diagnosable.
- Head pan/tilt gestures can be developed independently, then integrated with perception and attention behaviors.
- Any joint angles shown in artwork are illustrative; final limits must come from measured mechanical clearances, servo limits, tendon travel, and collision tests.

Behavior implementation notes

- Walking and crouching behaviors depend primarily on successful IMU tuning, foot-pressure sensing, and careful center-of-mass management.
- Waving and pointing depend on accurate upper-body kinematics and coordinated finger/hand control.
- Pick-and-carry actions require grasp planning, calibrated hand closure, and conservative payload limits appropriate for the small humanoid size.
- Inspection and scanning behaviors are enabled by the dual stereo camera “eyes” and the center ToF “nose” sensor, together with perception software on the Jetson Orin NX.

13. Financial plan and total system cost

This section consolidates the current MOXIE bill of materials into a financial view. Prices are working estimates in USD as of 26 September 2026 and should be rechecked immediately before ordering. Taxes, shipping, outsourced machining, failed prints, and the final validated Jetson mobile regulator are not included unless explicitly listed. The existing Yahboom Jetson Orin NX Super 8GB Camera Advanced Kit is treated as already owned and therefore has \$0 incremental project cost.

Scenario	Estimated cost	Notes
Baseline robot - one M18 battery, no actuator/FSR spares	\$2,475.97-\$2,487.97	Excludes final Jetson mobile regulator; includes one M18 battery and charger.
Recommended purchase package - servo/FSR spares + four M18 batteries	\$3,224.63-\$3,236.63	Preferred package for development and intermittent full-day demos.
15% project reserve on recommended known-cost package	~\$484	Covers small price movement, shipping, reprints, replacement fasteners, and minor fabrication overruns.
Recommended cash budget before optional printer	\$3,700-\$4,000	Practical target including reserve and room for the still-TBD validated Jetson regulator.
Optional QIDI Plus5 printer	+\$749	Capital tooling; not part of the robot itself.
Optional Prusa CORE One+ Gen 2	\$999 kit / \$1,299 assembled	Capital tooling; not part of the robot itself.
Optional Bambu Lab H2D	~\$1,750-\$1,900	Premium capital tooling; not part of the robot itself.

Financial summary

Figure 13-1. Estimated MOXIE cost by subsystem. The recommended package increases power and actuation/sensing costs primarily because it includes four M18 batteries and development spares.

13.1 Itemized robot cost

The table below is the working financial BOM for one complete robot. "Baseline" shows the minimum planned quantity for one functioning prototype; "Recommended" reflects the development order quantity with key spares and the four-battery day kit. The ToF line is a price range; the Jetson mobile regulator remains intentionally unpriced until a specific converter passes bench validation.

Category	Part	Baseline qty	Rec. qty	Unit est.	Extended	Notes
Compute	Yahboom Jetson Orin NX Super 8GB Camera Advanced Kit	Owned	Owned	\$0 incremental	\$0 incremental	Already owned; replacement value excluded

Category	Part	Baseline qty	Rec. qty	Unit est.	Extended	Notes
Actuation	Hiwonder HTD-45H 45 kg.cm HV serial bus servo	12	14	\$24.99	\$299.88 / \$349.86	Legs; recommended package includes 2 spares
Actuation	Hiwonder HTS-20H 20 kg.cm HV serial bus servo	20	22	\$17.99	\$359.80 / \$395.78	Upper body, toes, hands; 2 spares recommended
Control	Teensy 4.1	1	1	\$31.50	\$31.50	Real-time gait/servo controller
Sensing	Adafruit BNO085 9-DOF orientation breakout	1	1	\$29.50	\$29.50	Torso IMU
Sensing	SparkFun 0.5 in force-sensitive resistor	24	30	\$10.95	\$262.80 / \$328.50	Feet + hands; recommended includes 6 spares
Sensing	SparkFun CD74HC4067 16-channel mux breakout	2	2	\$6.50	\$13.00	FSR multiplexing
Audio	Seed reSpeaker XVF3800 USB 4-mic array	1	1	\$59.90	\$59.90	Voice input
Audio	Adafruit MAX98357A I2S 3 W amplifier	1	1	\$5.95	\$5.95	Speaker amplifier
Audio	Adafruit 3 W 4-ohm enclosed speaker	1	1	\$3.95	\$3.95	Voice output
Power	Milwaukee M18 FORGE XC8.0 battery	1	4	\$199	\$199.00 / \$796.00	One onboard; four-pack rotation recommended

Category	Part	Baseline qty	Rec. qty	Unit est.	Extended	Notes
Power	Milwaukee M18 Dual Bay Simultaneous Super Charger	1	1	\$229	\$229.00	Required unless compatible charger already owned
Power	Pololu D42V110F12 12 V / 9 A regulator - prototype branches	3	3	\$59.95	\$179.85	Final capacity/count remains subject to measured load tests
Power	Validated 19 V-class >=65 W buck-boost converter for Jetson	1	1	TBD	TBD	Do not order until carrier-input and thermal validation are complete
Power	Pololu power-ORing ideal-diode pair	1	1	\$7.95	\$7.95	Main/backup compute-source transfer
Power	TalentCell YB1203000 11.1 V / 3000 mAh keep-alive battery	1	1	~\$50	\$50 est.	Keeps compute alive during M18 swap
Power	M18 battery adapter/contact dock + guarded latch	1	1	~\$30	\$30 est.	Rear pelvis hot-swap dock
Setup	Hiwonder serial bus servo controller/debugger	1	1	\$39.99	\$39.99	Servo ID/setup/testing
Structure	2 mm 6061-T6 aluminum sheet/strip	1 lot	1 lot	~\$120	\$120 est.	Pelvis, leg, torso structural parts
Fabrication	PETG / PA-CF / TPU printing material	1 lot	1 lot	~\$135	\$135 est.	Covers, hands, feet, compliant pads

Category	Part	Baseline qty	Rec. qty	Unit est.	Extended	Notes
Hardware	M2/M3 screws, locknuts, shoulder bolts, bearings	1 lot	1 lot	~\$130	\$130 est.	Mechanical assembly
Tendons	1.0-1.5 mm Dyneema/Spectra + PTFE guide tube	1 lot	1 lot	~\$45	\$45 est.	Hands and adaptive toe routing
Safety	XT60 harness, 60-80 A fuse, branch fuses, E-stop, TVS/filter parts	1 lot	1 lot	~\$105	\$105 est.	Main power safety/distribution
Wiring	Servo leads, JST/PH connectors, ferrules, silicone wire, heat shrink	1 lot	1 lot	~\$95	\$95 est.	Full robot harness
Vision	Yahboom IMX219 8MP CSI camera - second stereo eye	1	1	\$20.90	\$20.90	Matches existing camera
Vision	VL53L5CX 8x8 multizone ToF breakout/evaluation board	1	1	~\$23-\$35	~\$23-\$35	Central depth/proximity sensor

Known-cost baseline total: \$2,475.97-\$2,487.97. Known-cost recommended package total: \$3,224.63-\$3,236.63. These totals intentionally exclude the already-owned Jetson and the still-unselected compute buck-boost regulator. They also exclude taxes, shipping, outsourced CNC/laser cutting, and optional 3D-printer capital equipment.

13.2 Optional fabrication tooling

Tool	Current working price	Use in project	Included in robot total?
QIDI Plus5	\$749	Recommended value printer for PETG/TPU/PA-CF custom parts	No

Tool	Current working price	Use in project	Included in robot total?
Prusa CORE One+ Gen 2	\$999 kit / \$1,299 assembled	Serviceability/ documentation-focused printer	No
Bambu Lab H2D	~\$1,750-\$1,900	Premium printer for large/engineering-material parts	No

If no capable printer is already available, the QIDI Plus5 gives the lowest current entry price among the three recommended printers. Adding it to the recommended robot package brings the known project acquisition cost to approximately \$3,974-\$3,986 before the TBD Jetson converter, taxes, shipping, and fabrication contingency.

Price-control note: the actuator prices (\$24.99 HTD-45H and \$17.99 HTS-20H), BNO085 price (\$29.50), Milwaukee XC8.0 list price (\$199), and QIDI Plus5 price (\$749) were spot-checked against current vendor pages during this revision. Other generic line items remain planning estimates from the engineering BOM and should be quoted before purchase.

14. Online references and order links

[R1] ROBOTIS OP3 introduction/specifications: ~510 mm, ~3.5 kg, 20 DOF, XM430 actuators, OpenCR sub-controller. [Link](#)

[R2] ROBOTIS OpenCR 1.0 controller: Cortex-M7, TTL/RS-485/CAN, 5–24 V input. [Link](#)

[R3] Hiwonder HTD-45H high-voltage serial bus servo: 9–12.6 V, 64 g, 45 kg·cm max torque, feedback. [Purchase / source](#)

[R4] HTEC foot research (Defence Technology, 2025): rigid-elastic humanoid foot with improved terrain adaptability on lawn/cobblestone/obstacles. [Link](#)

[R5] Yahboom Jetson Orin NX Super development kit: 8/16 GB, 117/157 TOPS, SSD, ROS/AI tutorials. [Purchase / source](#)

[R6] Yahboom Orin carrier-board information: MIPI CSI-2 multi-camera support and Orin NX compatibility. <https://category.yahboom.net/products/jetson-carrier-board>

[R7] SparkFun Teensy 4.1: 600 MHz Cortex-M7, 8 serial ports, 3 CAN buses, 18 analog inputs; current listed price \$31.50. [Purchase / source](#)

[R8] Milwaukee M18 REDLITHIUM FORGE XC8.0 (48-11-1881): 8 Ah; 5.3 × 3.4 × 3.5 in; 2.38 lb; 35 min to 80% with compatible super charger. <https://www.milwaukeeetool.com/products/details/m18-redlithium-forge-xc8-0-battery-pack/48-11-1881>

[R9] Milwaukee M18 Dual Bay Simultaneous Super Charger (48-59-1815): simultaneously charges two M18 packs; XC8.0 reaches 80% in about 35 min. <https://www.milwaukeeetool.com/products/details/m18-dual-bay-simultaneous-super-charger/48-59-1815>

[R10] SparkFun 0.5-inch force-sensitive resistor (FSR), ~0.1–10 kg force range; current listed price \$10.95.

[Purchase / source](#)

[R11] SparkFun CD74HC4067 16-channel analog/digital multiplexer breakout; current listed price \$6.50.

[Purchase / source](#)

[R12] ROBOTIS OP3 ROS packages and walking modules (useful software architecture reference). [Link](#)

[R13] Hiwonder HTS-20H high-voltage bus servo: 9–12.6 V, 58 g, 20 kg·cm, feedback; baseline actuator for upper body, toe tendons and three hand groups per hand. [Purchase / source](#)

[R14] Adafruit BNO085 9-DOF sensor-fusion breakout; current listed price \$29.50. [Purchase / source](#)

[R15] Sreed reSpeaker XVF3800 USB 4-mic array with case; 360° far-field processing; current listed price \$59.90. [Purchase / source](#)

[R16] Adafruit MAX98357A 3 W I2S mono amplifier; current listed price \$5.95. [Purchase / source](#)

[R17] Adafruit 3 W 4 Ω enclosed speaker; current listed price \$3.95. [Purchase / source](#)

[R18] Hiwonder serial bus servo controller/debugger; current listed price \$39.99. [Purchase / source](#)

[R19] ROBOTIS XM430-W350 benchmark actuator: 4.1 N·m stall torque, 82 g, used by OP3; current listed price \$310.39. [Link](#)

[R20] Research example adding foot force sensors to ROBOTIS OP3 for ground-plane/pressure estimation. [Link](#)

[R21] Pololu D42V110F12: fixed 12 V step-down regulator, input up to 60 V, typical max output around 9 A. <https://www.pololu.com/product/5677>

[R22] Pololu D42V110F15 fixed 15 V buck regulator. Retained as a historical prototype reference only; Revision 2.2 no longer treats 15 V as the production Jetson rail. <https://www.pololu.com/product/5679>

[R23] Pololu Power ORing Ideal Diode Pair: 4–60 V operation, 6 A per channel, reverse-current blocking; intended for redundant/backup power supplies. <https://www.pololu.com/product/5398>

[R24] TalentCell YB1203000: 11.1 V 3000 mAh Li-ion, 12.6–9 V output, 3 A max, about 190 g; baseline keep-alive battery. <https://talentcell.com/lithium-ion-battery/12v/yb1203000.html>

- [R25] Yahboom IMX219 8MP CSI camera for Orin NX Super: 22-pin option; selectable 77°, 120°, or 160° FOV; direct price \$20.90 on 26 Sep 2026. <https://category.yahboom.net/products/jetson-nano-camera>
- [R26] VL53L5CX multizone ToF reference: 4x4 or 8x8 ranging and up to about 4 m. https://github.com/adafruit/Adafruit_VL53L5
- [R27] Yahboom carrier board: MIPI CSI-2 multi-camera support for Jetson Orin modules. <https://category.yahboom.net/products/jetson-carrier-board>
- [R28] Yahboom Jetson Orin NX Super kit: 8GB Super listed at 117 TOPS and supplied with a 65 W power adapter; vendor page does not publish a general battery-input range. <https://category.yahboom.net/products/jetson-orin-nx>

[R29] Rama naming reference: Rama Revealed describes Moxie as a super-robot; MOXIE is the project name used from Revision 2.4 onward. [Kirkus review / reference](#)

Reference date: Online specifications, availability and prices checked 26 September 2026. Where a source is a reseller rather than the original manufacturer, verify the manufacturer’s electrical limits before wiring.

14A. Fastener and mechanical-reference sources

- Hiwonder HTD-45H product page and mounting screw Q&A:
<https://www.hiwonder.com/products/htd-45h>
- Hiwonder HTS-20H product page and physical dimensions:
<https://www.hiwonder.com/products/hts-20h>
- NVIDIA Jetson Orin NX hardware FAQ (mounting screw / hole guidance):
<https://forums.developer.nvidia.com/t/jetson-orin-nx-hw-faq/249117>
- PJRC Teensy 4.1 dimensions / finished-hole information: <https://www.pjrc.com/store/teensy41.html>
- McMaster M3 heat-set insert reference, M3x0.5 x 5.7 mm:
<https://www.mcmaster.com/product/94459A140/>
- CNC Kitchen heat-set insert design/calibration guidance: <https://www.cnckitchen.com/blog/tips-and-tricks-for-heat-set-inserts>

Appendix A - Purchase Parts List

This appendix converts the design BOM into a practical ordering list. “Required” is the minimum quantity needed for one MOXIE prototype; “Order” includes recommended spares and the four-pack M18 day-kit. Prices are planning estimates and should be rechecked before purchase.

Existing compute already owned	Yahboom Jetson Orin NX Super 8GB Camera Advanced Kit
Estimated minimum build parts	~\$2,300 concept-stage estimate excluding the owned Jetson; final mobile compute power hardware remains validation-dependent
Recommended order with spares + 4-pack M18 demo-day kit	~\$3,300 concept-stage estimate before tax/shipping; not a continuous-walking runtime guarantee

A.1 Orderable components

Category	Part / model	Required	Order	Unit est.	Order est.	Source	Notes	Purchase link
Actuation	Hiwonder HTD-45H 45 kg.cm HV serial bus servo	12	14	\$24.99	\$349.86	R3	12 legs + 2 spares	Open
Actuation	Hiwonder HTS-20H 20 kg.cm HV serial bus servo	20	22	\$17.99	\$395.78	R13	Upper body, toes, hands + 2 spares	Open

Category	Part / model	Required	Order	Unit est.	Order est.	Source	Notes	Purchase link
Control	Teensy 4.1	1	1	\$31.50	\$31.50	R7	Real-time gait/servo controller	Open
Sensing	Adafruit BNO085 9-DOF orientation breakout	1	1	\$29.50	\$29.50	R14	Torso IMU	Open
Sensing	SparkFun 0.5 in force-sensitive resistor (FSR)	24	30	\$10.95	\$328.50	R10	Feet + hands; includes 6 spares	Open
Sensing	SparkFun CD74HC4067 16-channel mux breakout	2	2	\$6.50	\$13.00	R11	FSR multiplexing	Open
Audio	Seeed reSpeaker XVF3800 USB 4-mic array with case	1	1	\$59.90	\$59.90	R15	Voice input	Open
Audio	Adafruit MAX98357A I2S 3 W mono amplifier	1	1	\$5.95	\$5.95	R16	Speaker amplifier	Open
Audio	Adafruit 3 W 4-ohm enclosed speaker	1	1	\$3.95	\$3.95	R17	Robot voice output	Open
Power	Milwaukee M18 REDLITHIUM FORGE XC8.0 (48-11-1881)	1	4	\$199	\$796.00	R8	One onboard; four-pack set supports intermittent demo-day rotation, not guaranteed continuous walking	Open
Power	Milwaukee M18 Dual Bay Simultaneous Super Charger (48-59-1815)	1	1	\$229	\$229.00	R9	Full-day battery rotation	Open

Category	Part / model	Required	Order	Unit est.	Order est.	Source	Notes	Purchase link
Power	Pololu D42V110 F12 12 V / 9 A step-down regulator (prototype branch use only)	3 prototype	3 prototype	\$59.95	\$179.85	R21	Final regulator count/capacity TBD after measured current tests	Open
Power	Validated 19 V-class buck-boost converter for Jetson, >=65 W continuous	1	1 after validation	TBD	TBD	R28 / validation	Do not order until carrier input and converter thermal behavior are bench-tested	Open
Power	Pololu Power ORing Ideal Diode Pair, 4-60 V, 6 A/channel	1	1	\$7.95	\$7.95	R23	Automatic main/backup transfer	Open
Power	TalentCell YB1203000 11.1 V / 3000 mAh Li-ion	1	1	~\$50	\$50 est.	R24	Keep-alive battery	Open
Power	M18 battery adapter/contact dock + custom guarded latch	1	1	~\$30	\$30 est.	Generic	Rear pelvis hot-swap dock	Supplier TBD
Setup	Hiwonder serial bus servo controller/debugger	1	1	\$39.99	\$39.99	R18	Servo ID/setup/testing	Open
Structure	2 mm 6061-T6 aluminum sheet/strip	1 lot	1 lot	~\$120	\$120 est.	Generic	Pelvis, leg, torso structural brackets	Open
Structure	PETG/PA-CF + TPU printing material	1 lot	1 lot	~\$135	\$135 est.	Generic	Covers, hands, feet, flexible pads	Supplier TBD
Hardware	M2/M3 screws, locknuts, shoulder bolts, small bearings	1 lot	1 lot	~\$130	\$130 est.	Generic	Mechanical assembly	Open
Tendons	1.0-1.5 mm Dyneema/Spectra + PTFE guide tube	1 lot	1 lot	~\$45	\$45 est.	Generic	Hands + toe tendon routing	Supplier TBD

Category	Part / model	Required	Order	Unit est.	Order est.	Source	Notes	Purchase link
Safety	XT60 harness, 60-80 A fuse, branch fuses, E-stop, TVS/filter parts	1 lot	1 lot	~\$105	\$105 est.	Generic	Main power safety and distribution	Supplier TBD
Wiring	Servo leads, JST/PH connectors, ferrules, silicone wire, heat shrink	1 lot	1 lot	~\$95	\$95 est.	Generic	Full robot harness	Supplier TBD
Vision	Yahboom IMX219 8MP CSI camera, 22-pin, same FOV as existing camera	1	1	\$20.90	\$20.90	R25	Second stereo eye	Open
Vision	VL53L5C X 8x8 multizon e ToF breakout /evaluation board	1	1	~\$23–35	~\$23–35	R26	Central mouth/n ose depth and proximit y sensor	Open

Recommended purchase sequence: start with six HTD-45H leg servos, three HTS-20H servos for one foot/hand test set, Teensy, IMU, servo debugger, one M18 pack/dock, and bench power hardware. Prove one leg + one adaptive foot and measure current/thermal behavior before ordering the remaining bulk servos. Add the second matching IMX219 camera and VL53L5CX ToF sensor when the head CAD is frozen. Delay the final Jetson mobile DC/DC purchase until carrier-board input requirements are validated.

A.2 Already owned / do not reorder

Item	Qty	Use
Yahboom Jetson Orin NX Super 8GB Camera Advanced Kit	1	Primary onboard AI/vision computer; existing camera kit is reused as part of the stereo/depth head architecture where practical.

A.3 Fabricated parts not included as direct catalog purchases

- Pelvis frame and reinforced M18 rear battery guard/dock structure
- Thigh, shin, ankle, shoulder, forearm, torso, and neck brackets
- Five-toe adaptive foot bodies, toe links, compliant arch elements, and TPU pads
- Five-finger hand frames, tendon manifolds/differentials, palms, and compliant fingertip pads
- Torso/head covers and internal electronics trays
- Cable guides, strain reliefs, battery guards, and custom sensor mounts

Purchasing note: exact seller availability, shipping, and pricing can change. Reconfirm every linked/reference component before ordering, especially servo versions, regulator current ratings, battery charger compatibility, and connector pinouts.

A.4 Fastener and attachment purchase list

The following replaces the earlier generic “M2/M3 screws, locknuts, shoulder bolts, bearings” allowance for the Standard 610 mm Rev-A prototype. Quantities include development spares. Buy metric socket-head hardware from a reputable supplier; avoid mixed low-grade assortments for structural joints.

Order item	Order qty	Specification / note
M2x5 socket-head screws	100	ISO metric, 1.5 mm hex
M2x8 socket-head screws	50	ISO metric, 1.5 mm hex
M2 nyloc nuts	50	DIN 985 or equivalent
M2x12 shoulder screws / precision pivots	40	2 mm shoulder diameter; use for finger joints
M2.5x8 socket-head screws	25	Electronics / standoffs
M3x8 socket-head screws	180	Servo clamps, brackets, cable clips
M3x10 socket-head screws	120	Shells and service panels
M3x12 socket-head screws	60	Hands/feet/trays
M3 nyloc nuts	120	Through-bolts
M3 flat washers	250	Approx. 7 mm OD
M3 heat-set inserts, 5.7 mm length	120	M3x0.5; 4.0 mm nominal pocket
M4x12 socket-head screws	70	Primary frame
M4x16 socket-head screws	25	Battery dock / thick stacks
M4 nyloc nuts	100	Primary frame
M4 flat washers	200	Approx. 9 mm OD
M4 heat-set inserts, 8.2 mm length	25	M4x0.7; 5.6 mm nominal pocket
3 mm x 20 mm stainless dowel pins	16	Toe pivots; 10 installed
3 mm E-clips / collars	30	Toe hinge retention
M3x6 + M2x5 servo horn screw spares	40 sets	HTD-45H vendor-specified horn hardware; verify HTS-20H supplied screw bag before substitution
2.5 mm cable ties	100	Harness only, not structural

Appendix B - Parts Visual Reference Gallery

This appendix adds representative purchase-reference images for the major components listed in Appendix A. The images are organized by subsystem so the build team can quickly identify what each purchased item should look like during sourcing, receiving, and assembly.

Figure B1. Visual reference sheet 1 of 3: compute, actuation, control, sensing, setup, and audio components.

Figure B2. Visual reference sheet 2 of 3: audio and power components, battery system, regulators, hot-swap hardware, and safety power hardware.

Accuracy update for Revision 2.2: the 15 V Pololu regulator pictured on this visual sheet is a legacy prototype reference only. The current design requires a validated 19 V-class ≥ 65 W mobile buck-boost solution for the Jetson, selected after carrier-board input testing.

Figure B3. Visual reference sheet 3 of 3: structural materials, printing materials, hardware, tendons, wiring supplies, and fabricated bracket/shell references.

Appendix C - Custom Parts CAD and 3D Printing Guide

This appendix documents how the custom MOXIE parts are created. It shows the major fabricated parts, the intended CAD structure, recommended materials, typical print orientations, post-processing steps, and the general fabrication workflow for getting from CAD to assembly-ready parts.

Figure C1. Custom parts CAD overview showing the main fabricated parts, exploded views, dimensions, materials, and fabrication methods for shells, feet, hands, brackets, and routing parts.

Key custom part families

- Head shell: PETG printed shell around the stereo cameras and central ToF sensor nose opening, with heat-set inserts and internal mounting features.
- Torso shell and inner cage: printed cosmetic shell panels around a structural inner cage that carries compute, power, and spine hardware.
- Pelvis and battery dock guard: structural aluminum pelvis members plus a printed rear guard around the M18 battery dock and wiring.
- Feet and hands: printed outer shells and compliant elements combined with metal pins/brackets and tendon routing features.
- Servo brackets and routing parts: CNC-cut or bent aluminum brackets plus printed tendon guides, cable clips, and strain-relief parts.

Figure C2. 3D printing and fabrication guide showing slicer build plates, print orientation, material settings, post-processing steps, aluminum bracket fabrication, and the end-to-end custom-part workflow.

Recommended fabrication workflow

38. Create 3D CAD for all printed parts and 2D flat-pattern CAD for all laser-cut/CNC-cut aluminum brackets.
39. Export STL/3MF for printed parts and DXF/STEP for metal parts, then organize by subsystem: head, torso, pelvis, leg shells, feet, hands, and routing components.
40. Print PETG shell parts first to confirm fit, then print high-load parts such as toe links and structural routing parts in PA-CF or similar nylon-carbon-fiber material.
41. Laser cut or CNC machine the aluminum brackets and structural plates, then bend and deburr where required.
42. Post-process all printed parts by removing supports, deburring, installing heat-set inserts, drilling/reaming critical holes, and test-fitting mating parts.
43. Do a dry-fit of each subassembly before final assembly, especially the foot modules, hand tendon paths, and battery dock interfaces.
44. Only after the custom parts fit correctly should the servos, sensors, electronics, tendons, and outer shells be installed for final assembly.

Print notes

- Use PETG for most exterior shell parts because it balances durability, ease of printing, and surface finish.
- Use PA-CF or another reinforced engineering filament for toe links, tendon guides, and heavily loaded custom printed parts.
- Use TPU for flexible soles, cable grommets, and strain-relief parts where compliance is useful.
- Install M3/M4 heat-set inserts in printed parts wherever repeated assembly/disassembly is expected.

Appendix C.1 - Custom Color Options for Printed and Fabricated Parts

The custom shell and cosmetic parts for MOXIE can be produced in multiple colorways by changing the filament color for printed covers, pads, and trim pieces while keeping the underlying metal structure, actuators, and electronics the same. This gives the project flexibility for branding, team colors, demonstration variants, or functional use cases such as high-visibility industrial colors.

Figure C3. Updated MOXIE custom color lineup showing six printed colorways with the refined head design, two stereo camera eyes, central mouth sensor, and anatomically mirrored left and right five-toe feet.

Suggested production colorways

- Arctic White: white shell panels with blue accents; ideal for a clean research-lab appearance and the default design language used throughout this document.
- Graphite Black: dark charcoal shell panels with cyan accents; useful for a stealth or premium-tech appearance and less visually prominent wear marks.

- Industrial Orange: orange shell panels with dark trim; useful for high visibility in workshops, labs, and demonstration spaces.
- Racing Red: red shell panels with dark trim; good for demonstration impact and team-branded versions.
- Olive Green: olive shell panels with tan accent parts; suitable for field-robotics or ruggedized demonstration variants.
- Silver / Gray: metallic gray shell panels with yellow accents; useful for a neutral engineering prototype look with high-visibility highlights.

Color manufacturing notes

- Most visible shell parts can be printed directly in the target PETG color rather than painted, which simplifies production and replacement.
- High-load PA-CF structural printed parts can remain black or dark gray regardless of the cosmetic shell color.
- TPU sole pads, fingertip pads, and bumpers can be color-matched or intentionally printed in accent colors for visibility and style.
- If exact corporate or team colors are required, shell parts can also be printed in a neutral color and painted or wrapped after post-processing.

Appendix D - 3D Printer Selection and Production Workflow

This appendix compares three enclosed FDM printers that are well suited to the MOXIE custom parts. The project needs reliable PETG for shells, TPU for compliant pads and grommets, and nylon/carbon-fiber materials such as PA-CF for stronger toe links, tendon guides, and selected structural printed parts. Prices and availability below were checked on 26 September 2026 and can change.

Recommended role	Printer	Current price	Build volume	Hotend / chamber	Why it fits MOXIE
Premium / least compromise	Bambu Lab H2D	~\$1,750-\$1,900	325 x 320 x 325 mm single-nozzle	350 C / 65 C active chamber	Large enough for every planned printed part; hardened extrusion path; dual-nozzle option is useful for support material; strong automation and dimensional repeatability.
Best value for engineering materials	QIDI Plus5	\$749	320 x 320 x 300 mm	370 C / 65 C active chamber	Very strong value for PA, PC, PETG, TPU and fiber-reinforced filaments; large chamber; hardened gears; enclosed and actively heated.

Recommended role	Printer	Current price	Build volume	Hotend / chamber	Why it fits MOXIE
Best long-term serviceability / open workflow	Prusa CORE One+ (Gen 2)	\$1,299 assembled / \$999 kit	250 x 220 x 270 mm	290 C / 55 C active chamber	Build volume is sufficient for the current MOXIE custom parts; excellent serviceability, documentation and PrusaSlicer workflow. Add the appropriate hardened/high-temp nozzle setup for abrasive PA-CF.

Project recommendation. If one printer is being purchased mainly for MOXIE, the QIDI Plus5 is the strongest cost/performance choice because it combines a large build volume, 370 C hotend, and 65 C actively heated chamber at \$749. The Bambu H2D is the premium choice when ease of use, dual-nozzle support workflows, and dimensional automation are worth the higher cost. The Prusa CORE One+ is the best fit when repairability, documentation, and a highly maintainable long-term platform are the priority.

D.1 Bambu Lab H2D

The H2D provides a 325 x 320 x 325 mm single-nozzle build volume, hardened steel nozzle and extruder gears, a 350 C maximum nozzle temperature, and an actively heated chamber up to 65 C. For MOXIE, use it for PETG outer shells, PA-CF or PET-CF structural printed parts, TPU pads, and support-intensive hand/foot components. A dual-nozzle configuration is especially useful when printing support interfaces in a different material.

Figure D1. Bambu Lab H2D enclosed CoreXY printer recommended as the premium engineering printer for MOXIE shells, structural polymer parts, and general prototype production.

D.2 QIDI Plus5

The Plus5 provides a 320 x 320 x 300 mm build volume, 370 C nozzle, 120 C bed, 65 C actively heated chamber, hardened extruder gears, automatic leveling, and stated support for PLA, ABS, ASA, PETG, TPU, PA, PC, and carbon/glass-fiber reinforced polymers. Its large volume can print all current MOXIE shells and most batches of smaller parts in one job.

Figure D2. QIDI Plus5 enclosed high-temperature printer recommended as the strongest value option for MOXIE PETG, TPU, and PA-CF custom parts.

D.3 Prusa CORE One+ (Gen 2)

The CORE One+ provides a 250 x 220 x 270 mm enclosed CoreXY build volume and active chamber control up to 55 C. The current MOXIE shell geometry fits within this envelope. For abrasive carbon-fiber nylon, use a wear-resistant nozzle and the appropriate engineering-material profile; Prusa also offers higher-temperature options on the CORE platform. The main advantage is maintainability and a mature, transparent slicer/workflow ecosystem.

Figure D3. Prusa CORE One+ (Gen 2) enclosed CoreXY printer recommended as the serviceability and documentation-focused option for MOXIE custom-part production.

D.4 How to create the MOXIE custom parts on the printer

45. **Finish the CAD model:** Model the part in CAD with final screw holes, heat-set-insert pockets, cable channels, tendon passages, sensor pockets, and mating clearances. Keep the master model in STEP format and create a revision-controlled 3MF/STL for printing.
46. **Choose material by function:** Use PETG for cosmetic shells and covers; PA-CF for toe links, tendon guides, high-load brackets, and selected hand components; TPU 95A for sole pads, fingertip pads, grommets, bumpers, and strain relief.
47. **Prepare and dry filament:** PETG should be dry enough to print cleanly. Nylon/PA-CF must be dried thoroughly and kept in a dry box while printing. Moist nylon causes bubbles, poor surface finish, weak layers, and dimensional drift.
48. **Install the correct nozzle:** Use a 0.4 mm nozzle for shell detail. For PA-CF, a 0.6 mm hardened nozzle is preferred where geometry allows because it reduces clog risk and improves fiber-filled extrusion consistency.
49. **Orient the part:** Orient shells to minimize visible supports and maximize surface quality. Orient PA-CF load-bearing parts so the dominant mechanical load runs in the XY plane rather than trying to pull layers apart in Z. Print toe links flat on their side when possible so pin holes remain round and layer lines resist bending.
50. **Slice using the project baseline:** For PETG shells start near 0.20 mm layers, 4 walls, and 15-20% gyroid infill. For PA-CF structural parts start near 0.16-0.20 mm layers, 5-6 walls, and 30-40% gyroid infill. For TPU pads use about 0.20 mm layers, 3 walls, and 20-30% gyroid. Final temperatures and speeds must follow the filament manufacturer profile for the selected printer.
51. **Print calibration coupons first:** Before a full robot batch, print a hole/insert coupon, a tendon-channel coupon, and one representative joint/link. Measure hole diameter, insert fit, wall thickness, and mating clearance. Correct CAD or slicer compensation before committing to large prints.
52. **Print shells and low-load parts:** Print head, torso, forearm, thigh/shin covers, battery guard, cable clips, and other PETG components. Label each part with revision and left/right orientation in the CAD model where practical.
53. **Print structural polymer parts:** Switch to the dried PA-CF material and hardened nozzle for toe links, hand linkages, tendon guides, and any printed structural brackets. Keep the chamber closed and stable throughout the job.
54. **Print compliant parts:** Use TPU for the foot sole pads, finger pads, grommets, and bumpers. Print these slower than rigid materials and use the direct-drive filament path recommended by the printer manufacturer.

55. **Post-process:** Remove supports carefully, deburr edges, drill or ream precision holes to final size, and install heat-set inserts with a temperature-controlled soldering iron. Do not force screws directly into printed plastic where the joint will be serviced repeatedly.
56. **Dry fit before final assembly:** Assemble each printed subsystem without electronics first. Verify servo clearance, tendon paths, cable bend radius, battery latch clearance, and shell-to-frame spacing. Reprint any part that binds rather than compensating with excessive force or oversized holes.
57. **Record final print profiles:** Once a part passes fit and load testing, save the exact slicer profile, material lot, nozzle size, orientation, and CAD revision. Treat these as the manufacturing recipe for replacement parts.

D.5 Baseline print settings for MOXIE parts

Part family	Material	Nozzle	Layer height	Walls	Infill	Special notes
Head/torso/limb shells	PETG	0.4 mm	0.20 mm	4	15-20% gyroid	Optimize orientation for visible surface; heat-set inserts after printing.
Toe links / tendon guides / structural printed brackets	PA-CF	0.6 mm hardened preferred	0.16-0.20 mm	5-6	30-40% gyroid	Dry filament; heated enclosure; orient loads in XY where possible.
Foot sole pads / finger pads / bumpers	TPU 95A	0.4 mm	0.20 mm	3	20-30% gyroid	Slow print; minimize retractions; direct-drive feed path.
Cable clips / strain relief / sensor mounts	PETG or TPU	0.4 mm	0.20 mm	3-4	20-30%	Use TPU where flex is required; PETG where dimensional rigidity matters.

D.6 Current purchase and technical references

- Bambu Lab H2D technical specifications: https://cdn1.bambulab.com/documentation/h2d/en/H2D_Laser_Full_Combo_20250305.pdf
- Bambu Lab H2D launch/specification overview: <https://blog.bambulab.com/bambu-lab-launches-h2d-to-rethink-personal-manufacturing/>
- QIDI Plus5 product page and current \$749 US price: <https://us.qidi3d.com/products/plus5>
- QIDI Plus5 technical specifications: <https://us.qidi3d.com/pages/qidi-plus5-techspecs>
- Prusa CORE One+ (Gen 2) product page: <https://www.prusa3d.com/product/prusa-core-one/>
- Prusa CORE One+ technical overview: <https://www.prusa3d.com/p/core-one-plus/>

Price note: QIDI listed the Plus5 at \$749 on 26 September 2026. Prusa listed the CORE One+ at \$1,299 assembled / \$999 kit. Bambu H2D retail pricing varies by configuration and reseller; current retail examples were around \$1,750-\$1,900 for the printer/AMS-combo tier. Verify price and stock immediately before purchase.

Appendix E - 3D-Printed Part CAD Reference Drawings

This appendix provides a CAD-style reference drawing for every custom part family intended to be 3D printed on the MOXIE Standard 610 mm prototype. These sheets are prototype envelopes and interface references, not final production drawings: exact hole spacing, servo clearances, cable paths, tolerances, and wall thicknesses must be updated in the parametric CAD model after the purchased hardware is measured and the first foot/leg prototype is validated.

E.1 Printed-parts inventory

Drawing	Part family	Qty	Material	Primary function
E1	Head shell / faceplate	1 set	PETG	Stereo cameras + ToF + cable routing
E2	Torso shell + rear access panel	1 set	PETG	Cosmetic shell / electronics service access
E3	Pelvis cover + M18 battery dock guard	1 set	PA-CF/PETG	Rear battery protection / shroud
E4	Shoulder + upper-arm covers	2 mirrored sets	PETG	Actuator/cable protection
E5	Forearm cover	2 mirrored	PETG	Hand-servo/ tendon enclosure
E6	Thigh cover	2 mirrored	PETG	Hip-to-knee shell
E7	Shin + ankle covers	2 mirrored sets	PETG	Lower-leg protection / service access
E8	Palm + finger shell set	2 hands	PA-CF/PETG	Five-finger protective shell set
E9	Hand tendon manifold / differential	2	PA-CF	3-finger grouped tendon distribution
E10	Adaptive foot base / arch body	2 mirrored	PA-CF/Nylon	Main printed foot structure
E11	Toe links + TPU contact pads	10 links + pads	PA-CF + TPU	Five toes per foot
E12	Tendon guides / cable clips / sensor mounts	~20-30	PETG/PA-CF/TPU	Routing, strain relief, sensor retention
E13	Electronics tray / compute mount	1 set	PA-CF/PETG	Jetson/Teensy/ power mounting
E14	Neck shroud + cable collar	1 set	PETG + TPU	Neck protection / harness management

E.2 Drawing conventions and tolerances

- All dimensions shown are in millimeters and represent initial CAD envelopes for the Standard 610 mm robot.
- Use nominal printed-hole undersizing and drill/ream critical hinge and fastener holes after printing; do not rely on raw FDM hole size for bearing, pin, or servo-axis fits.

- Maintain at least 0.4-0.6 mm clearance between printed moving parts for PETG prototypes and verify clearances again for PA-CF because shrinkage and printer calibration differ.
- Use heat-set inserts for repeatedly serviced M3/M4 interfaces. Structural actuator loads should transfer into aluminum or metal brackets wherever specified in the main design.
- Mirror left/right shells and foot bodies in CAD rather than reusing a single non-mirrored part; the big toe must remain medial on both feet.

Head shell / faceplate

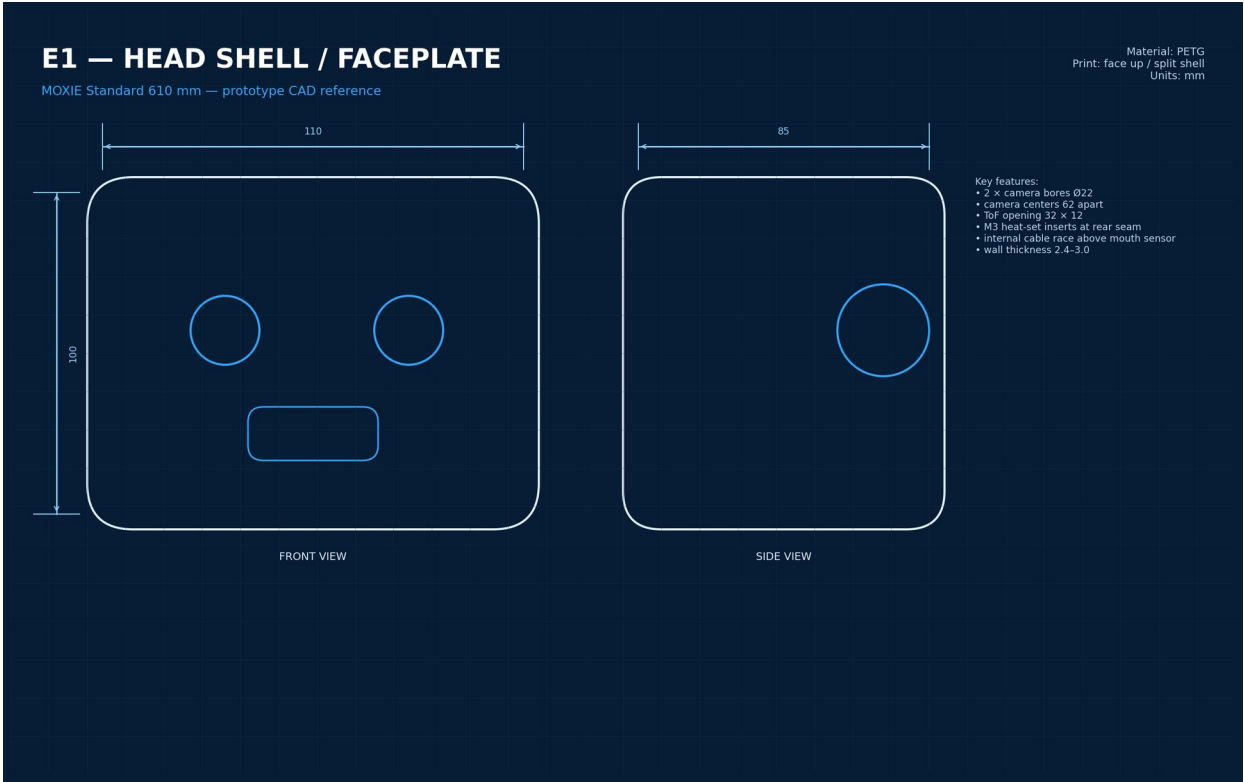


Figure E1. Head shell / faceplate CAD reference.

Torso shell and rear access panel

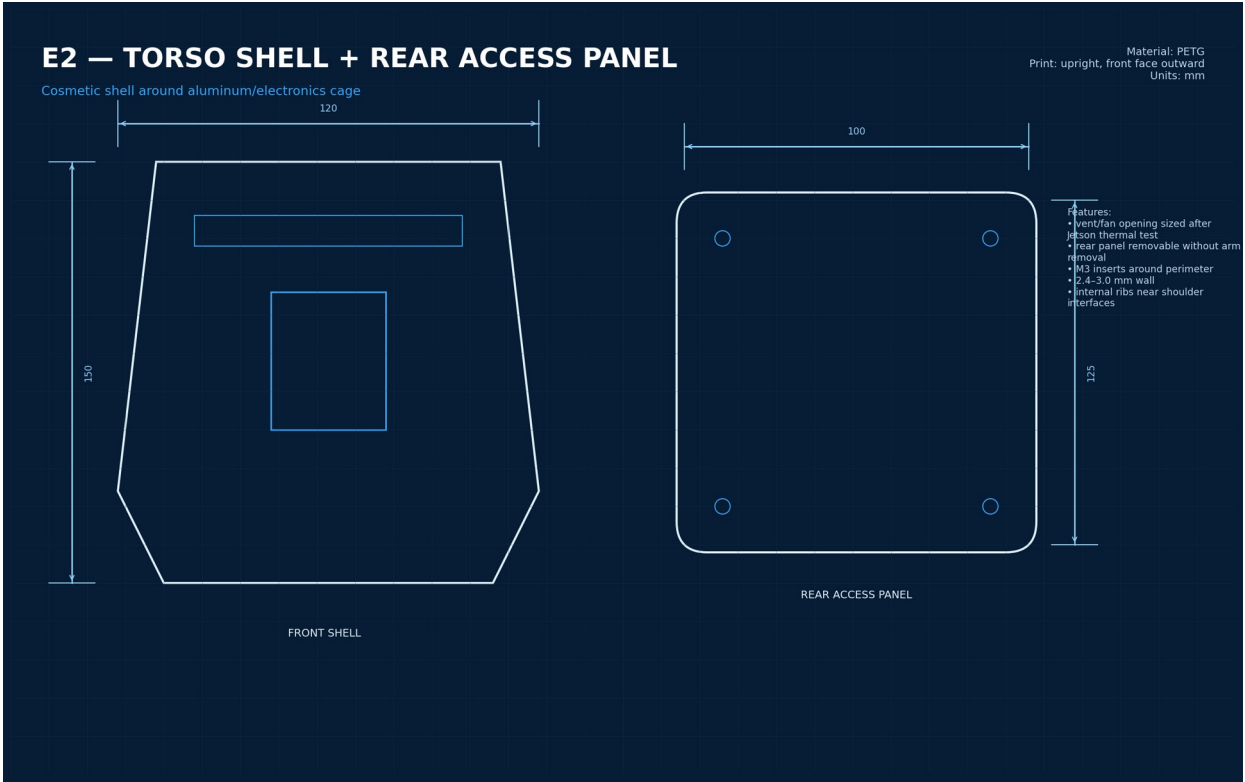


Figure E2. Torso shell and rear access panel CAD reference.

Pelvis cover and M18 battery dock guard

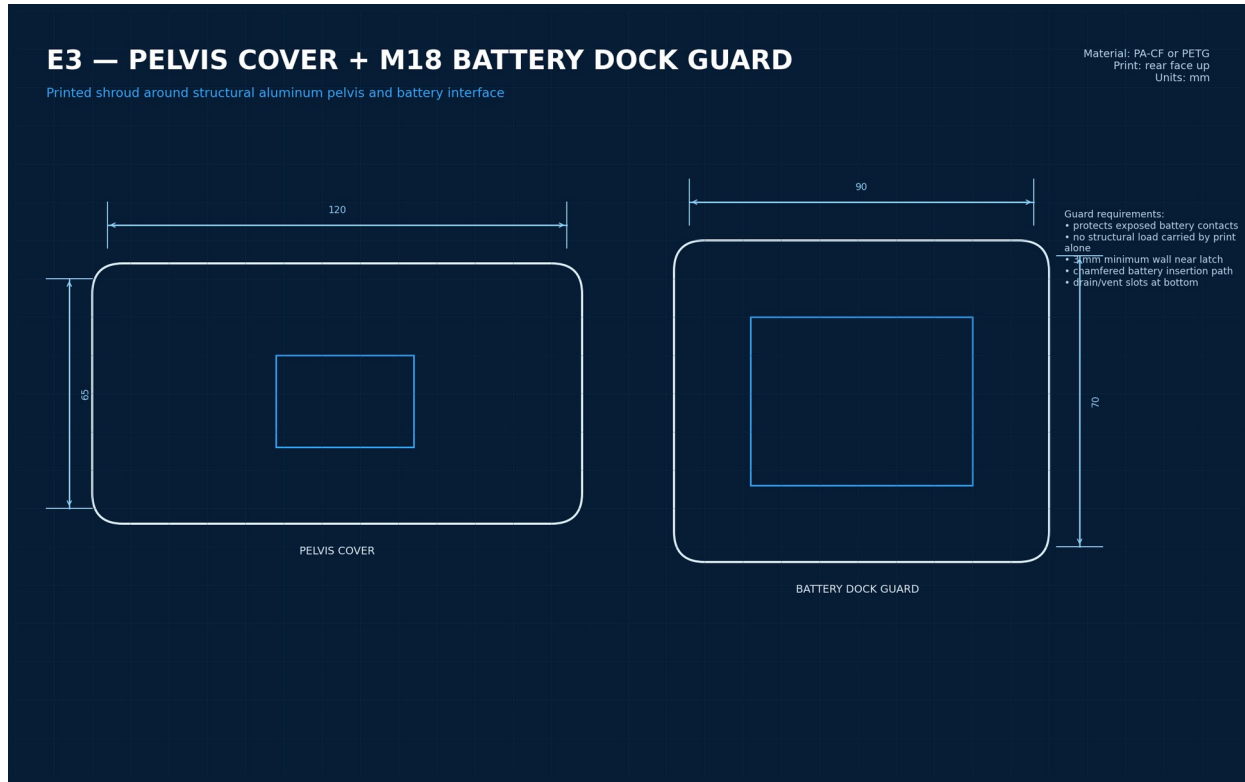


Figure E3. Pelvis cover and M18 battery dock guard CAD reference.

Shoulder and upper-arm cover

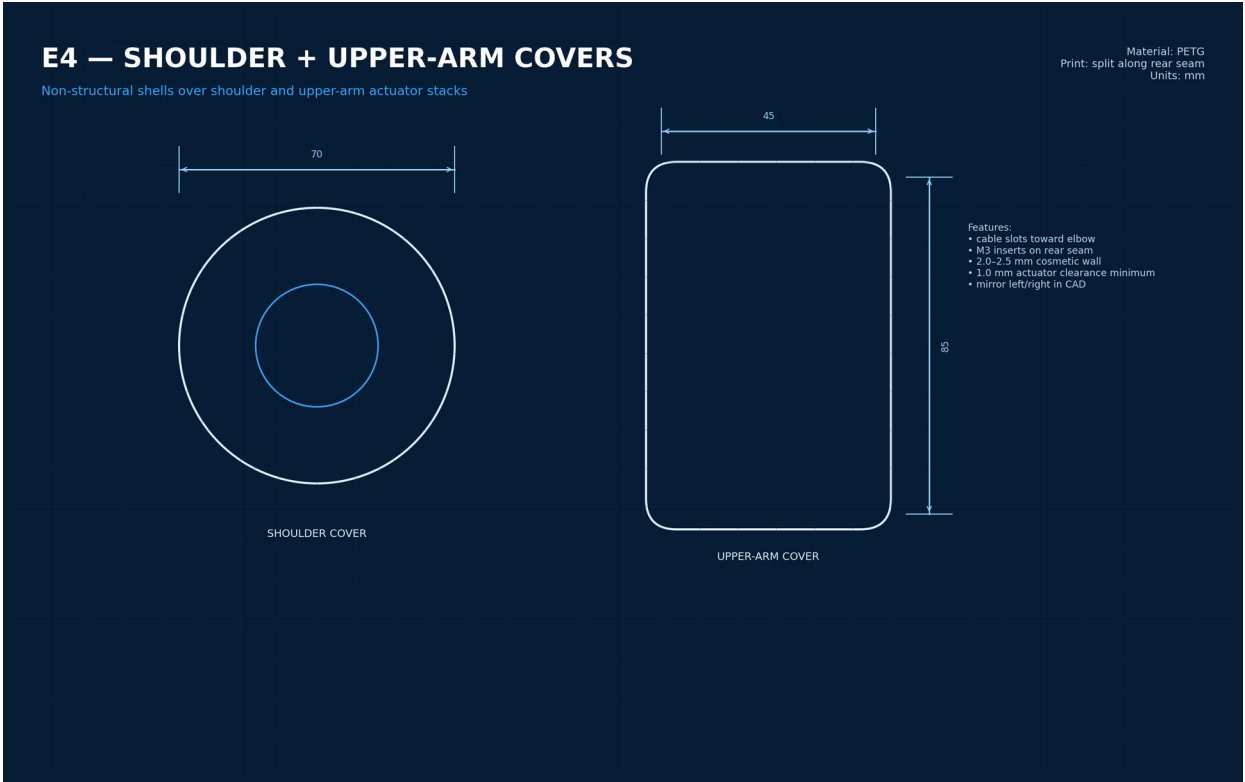


Figure E4. Shoulder and upper-arm cover CAD reference.

Forearm cover

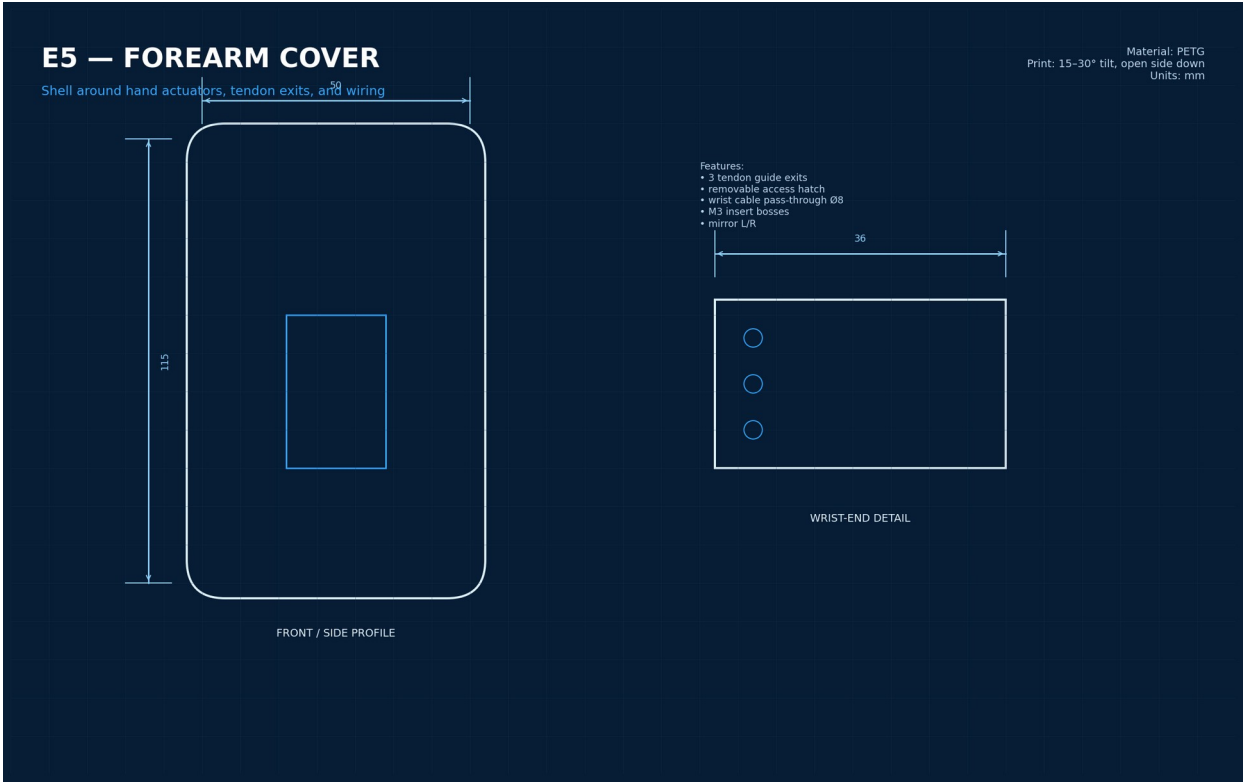


Figure E5. Forearm cover CAD reference.

Thigh cover

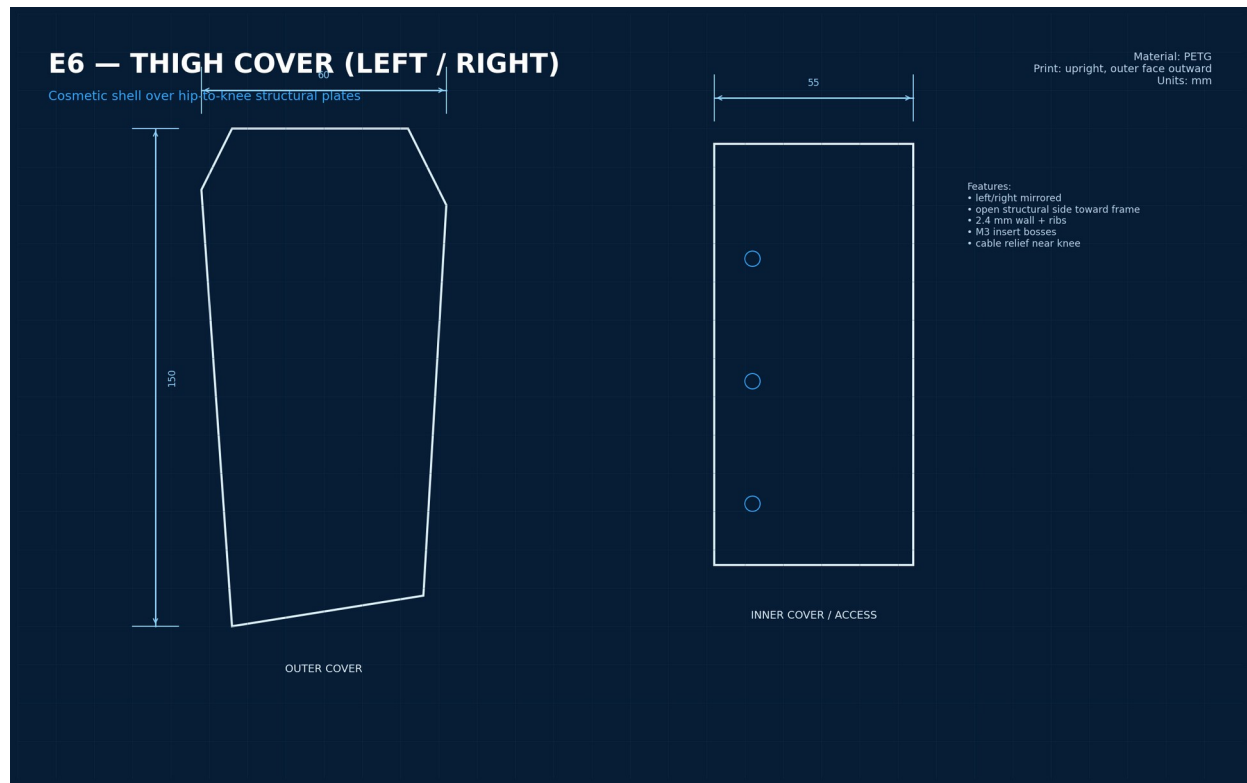


Figure E6. Thigh cover CAD reference.

Shin and ankle cover

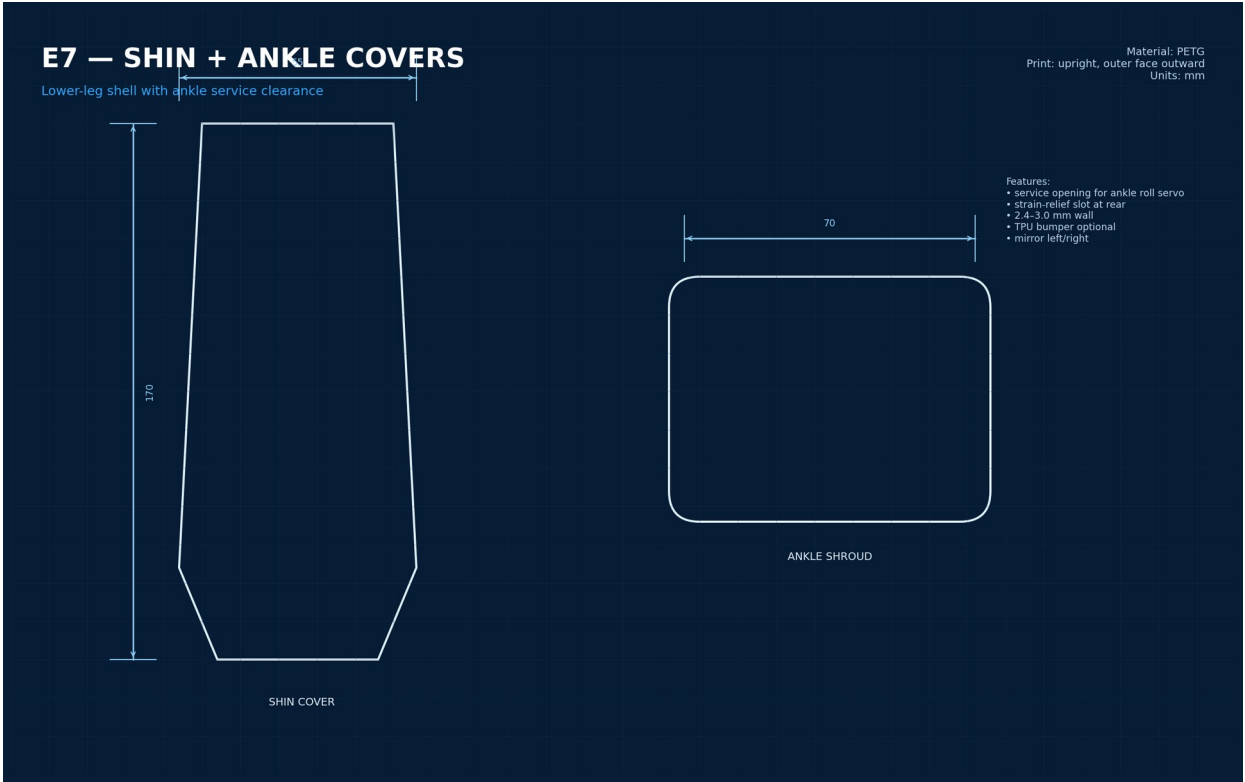


Figure E7. Shin and ankle cover CAD reference.

Hand palm and finger shell

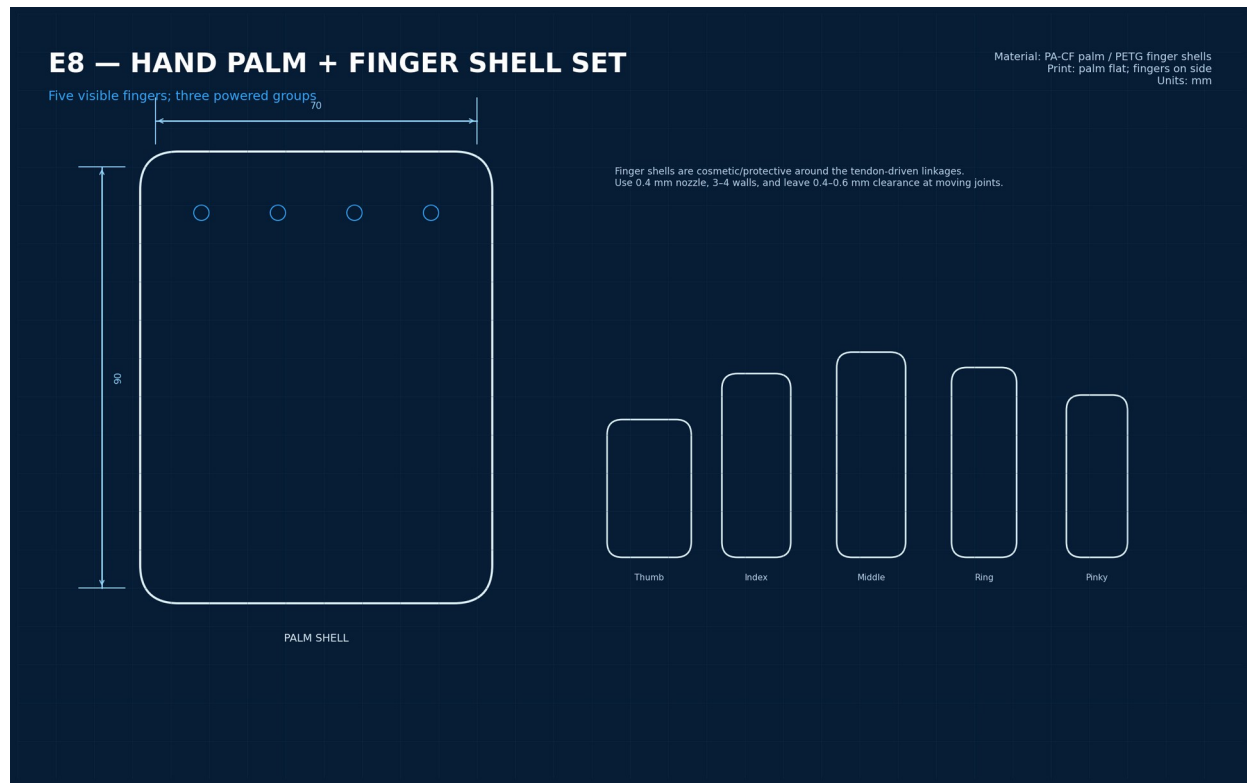


Figure E8. Hand palm and finger shell CAD reference.

Hand tendon manifold / differential

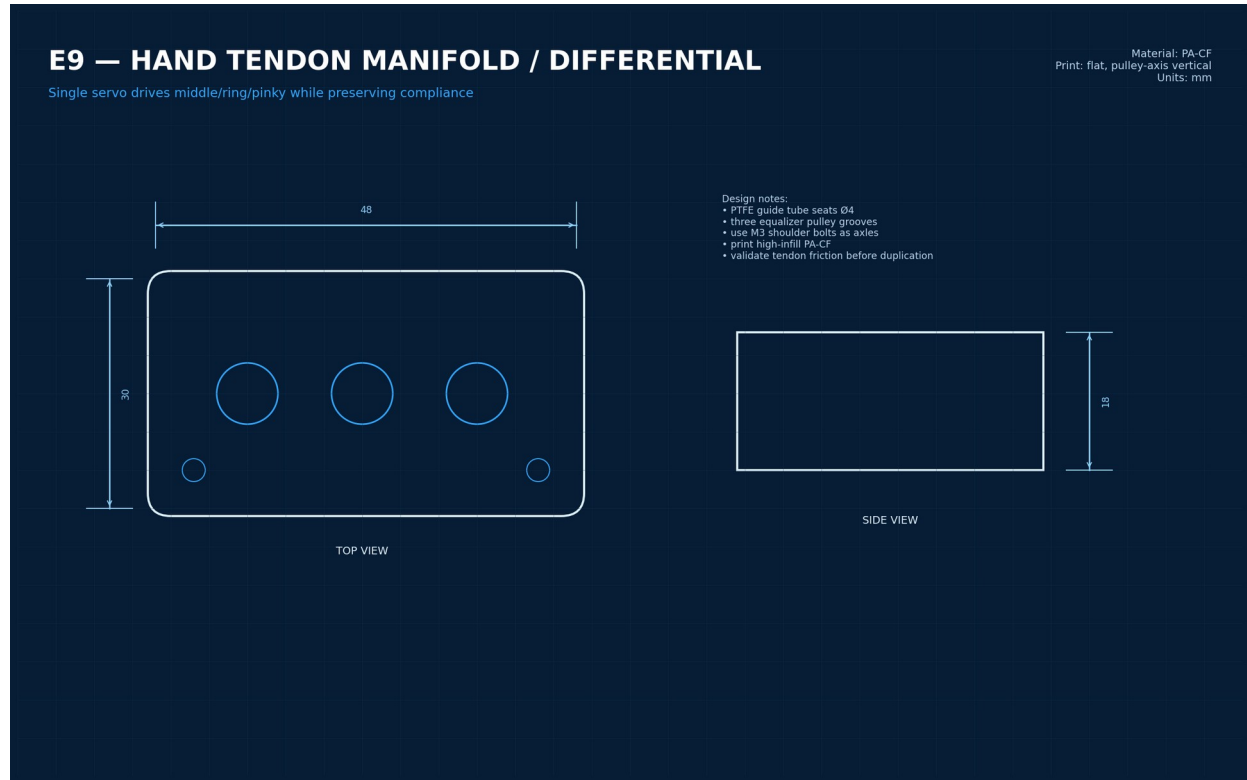


Figure E9. Hand tendon manifold / differential CAD reference.

Adaptive foot base / arch body

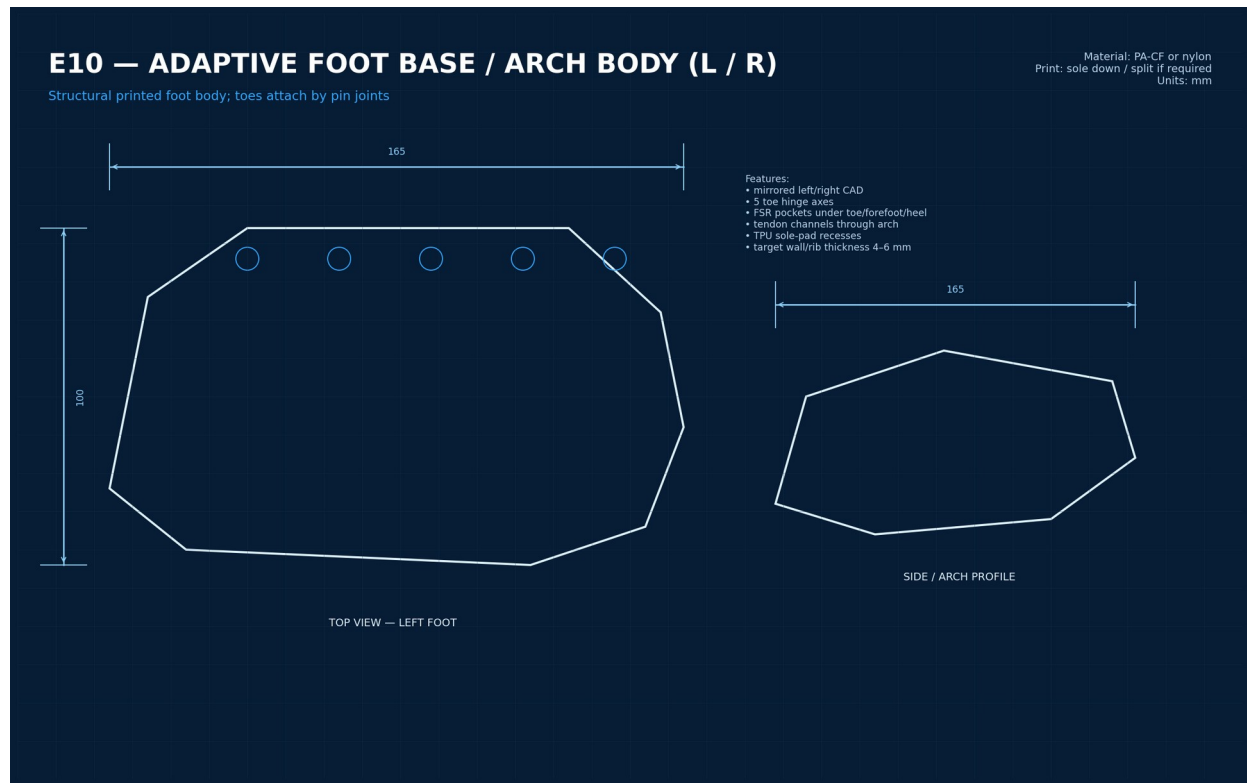


Figure E10. Adaptive foot base / arch body CAD reference.

Toe links and TPU contact-pad

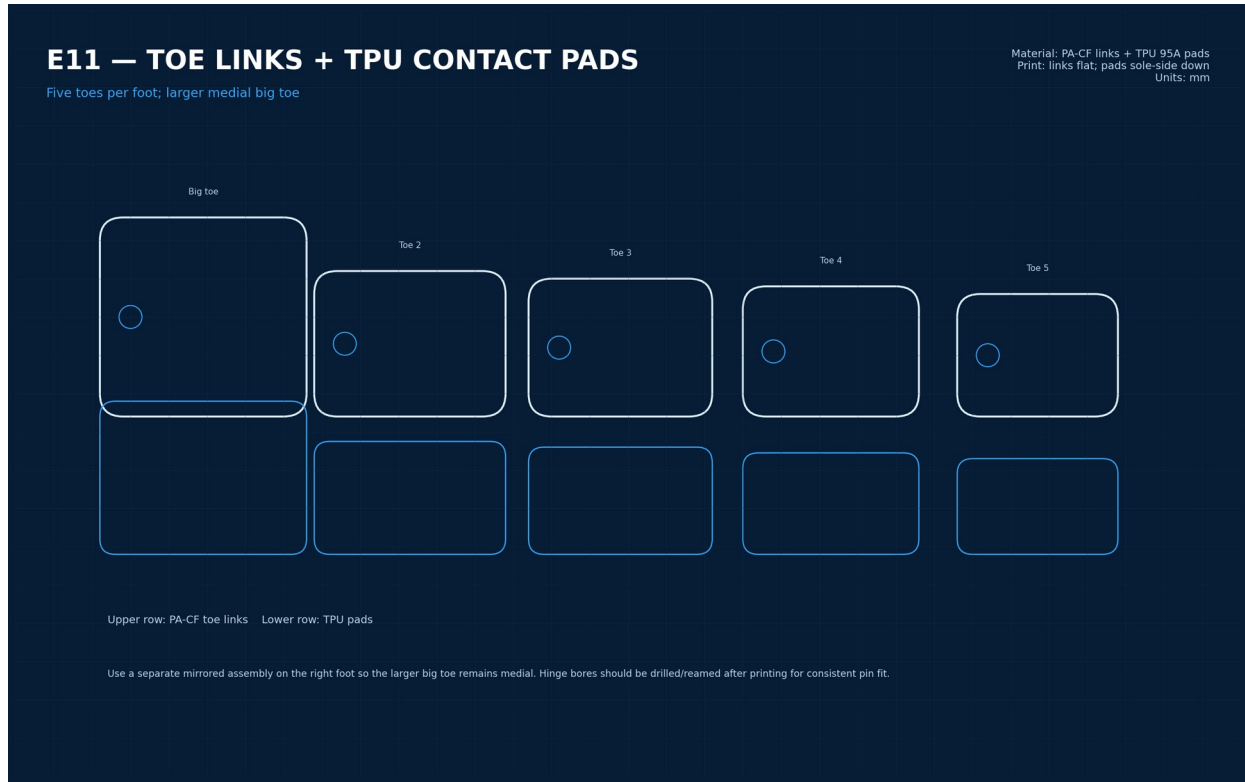


Figure E11. Toe links and TPU contact-pad CAD reference.

Tendon guides, cable clips, strain reliefs, and sensor mounts

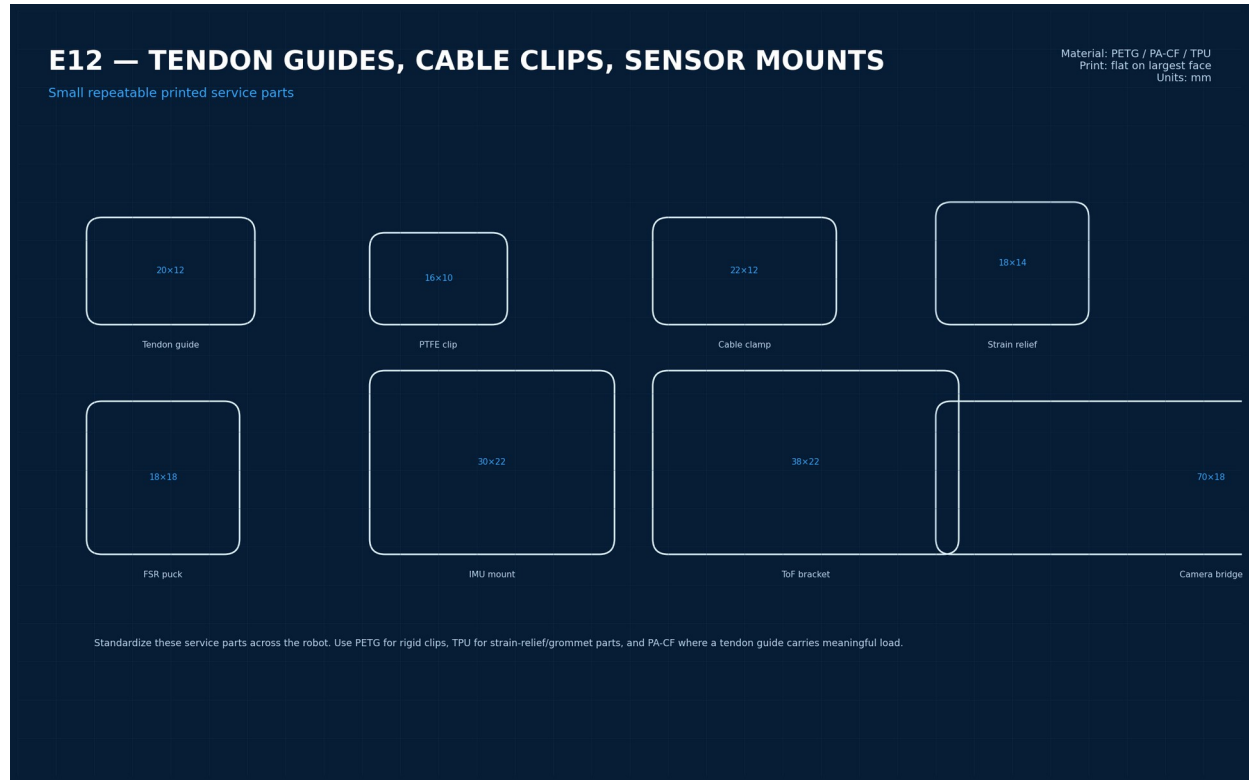


Figure E12. Tendon guides, cable clips, strain reliefs, and sensor mounts CAD reference.

Electronics tray and compute mount

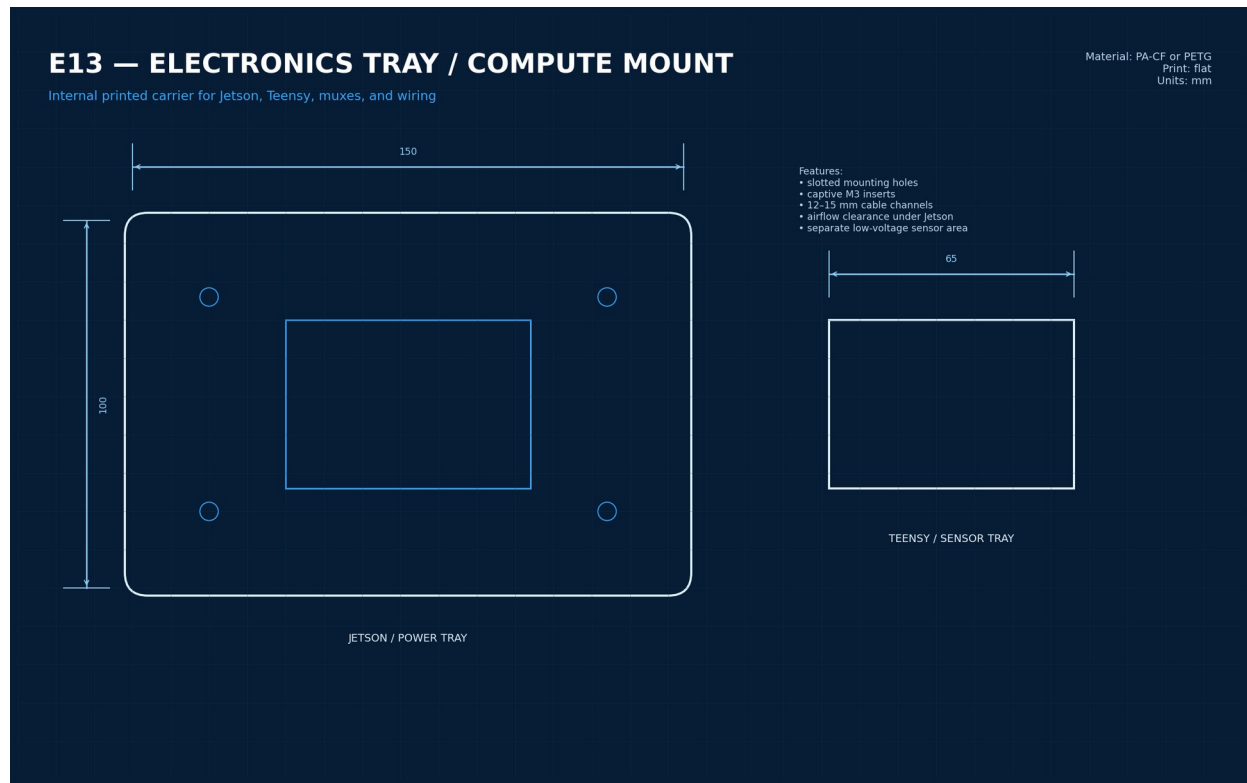


Figure E13. Electronics tray and compute mount CAD reference.

Neck shroud and TPU cable-collar

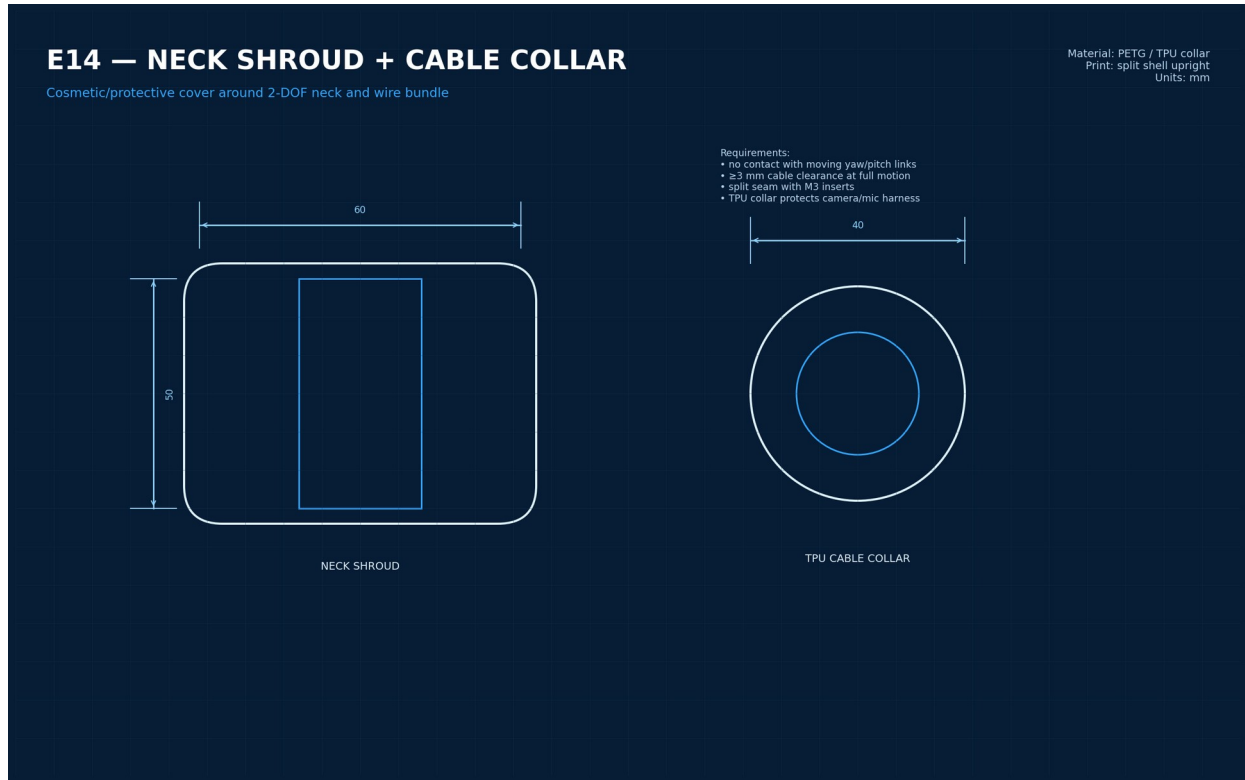


Figure E14. Neck shroud and TPU cable-collar CAD reference.

Appendix F - Open-Source License Agreement

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