Armature AI Labs

RESEARCH PAPER / ENGINEERING + BUSINESS

Robotic actuators: technology, innovation and manufacturing in India

What robots use today, what limits actuator performance, and how to develop a competitive Indian joint.

Research cut-off: 25 October 2026. Edition 1.

Read the executive brief first. The detailed chapters connect technology choices to thermal limits, materials, Indian suppliers, development experiments and batch economics.

Evidence distinction: manufacturer claims, measured research, engineering calculations, proposed targets and unknowns remain separate. Blue reference IDs open original sources; the appendix gives precise locators.

No supplier outreach, procurement, fabrication or public publication was performed. This is a decision paper, not product certification.

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Executive brief

This paper evaluates how Armature AI Labs could develop compact, serviceable robot actuators in India. The first objective is a well-characterised V0 joint with a competitive mass and package, followed by improvements in sustained operation, heat rejection and precision. Matching catalogue mass alone is not an equivalent actuator: output support, electronics, sensing, connectors and cooling must fit inside the same comparison boundary.

The intended arm remains a general-purpose manipulator for grasping, pick-and-place and object positioning. Laboratory work, test tubes, fine assembly, biological experiments, soldering and PCB handling are additional development goals. They are not validated capabilities. A dexterous hand is a separate actuator, sensing and software programme that also adds wrist mass and contact complexity.

Decision recommendation - begin with one instrumented medium rotary joint and a small wrist demonstrator. Preserve the existing RS-based reference study and compare Chinese actuators as engineering benchmarks. Pursue Indian design, assembly, testing and service; disclose imported components individually. Do not freeze a complete arm around unqualified catalogue torque.

- Measure stationary holding and friction first. A joint may achieve a short peak torque yet be unsuitable for sustained gravity compensation or delicate contact.

- Prioritise winding-to-housing heat flow, current/torque calibration, dual-encoder diagnostics, repairable construction and a documented thermal estimator before pursuing exotic motor concepts.

- Treat OEM demonstrations as evidence of a robot task, not proof of undisclosed actuator life, thermal margins or supplier identity.

- Localise processes in stages: housings, shafts, harnesses, winding and assembly are different industrial problems from precision gears, encoders and sintered rare-earth magnets.

- Use the cost model to identify what quotations and yield data would change the decision. Its numbers are editable planning assumptions, not market prices.

How to review: engineering reviewers should challenge the load cases, thermal boundaries and test criteria; suppliers should correct specific capability or origin entries; business reviewers should replace cost assumptions with written quotations. Every referenced statement links to its source. Source IDs also resolve in the evidence appendix and spreadsheet. No supplier outreach or public publication was performed for this paper.

Scope and evidence rules

Research cut-off: 25 October 2026. Public primary documentation, manufacturer disclosures and research publications underpin the evidence tables. A source date is retained where available; an undated webpage is identified as such. “Undisclosed” means the cited public material does not establish the fact, not that the manufacturer lacks the capability. Reported supplier capability is not a completed vendor audit.

Label	Meaning	What it does not prove
Published claim	Manufacturer or institution statement with clickable source and locator	Independent performance or availability
Measured research	Result from an identified experiment and setup	Performance outside that mass/cooling/load boundary
Calculation	Reproducible formula and stated inputs	Physical qualification
Proposed target	Engineering starting point for a test or design	A validated product requirement
Unknown / conflict	Insufficient or inconsistent public evidence	Zero capability or zero cost

A complete joint boundary includes motor, reduction, output bearings, encoders, driver, housing, harness exits, lubrication and any brake. Compare bare motors separately from complete joints. For cooled designs, also report the allocation of pumps, fans, radiators, coolant, hoses, power and structural heat sinks. Peak torque per kilogram, continuous torque per kilogram and installed arm mass answer different questions.

Platform mapping deliberately stops where public evidence stops. Patents describe possible embodiments; photographs suggest geometry; simulation files expose controller or modelling assumptions. None alone establishes a production supplier, gearbox topology or a guaranteed physical rating. A later generation is not automatically evidence about an earlier deployed fleet.

No paid supplier quotations, physical teardown, dynamometer measurements or component-origin audits were performed. Documented uncertainty is part of the result. The linked 24-entry comparison remains a separate specification reference; its exploratory arm load assumptions are not frozen requirements for this paper.

The actuator as a complete system

A joint actuator is a controlled load path and a thermal system. A supplier may sell a bare motor, a gear unit, an integrated drive or a supported joint. Those are different procurement boundaries. The electronics, output bearing, encoder and brake can change mass and packaging as much as the motor choice. [E02] [E06] [E12] [E24]




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Encoders + torque feedback -> controller -> commands

Losses -> housing / mounting / cooling -> ambient
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The complete joint includes sensing, firmware, bearings and a defined thermal path. Brake and external cooling are explicit additions.

Four different time claims. Warm-up time to a limit, sustainable operation at thermal equilibrium, duration/recovery of a short peak, and accumulated wear life are different questions. Running for eight hours at one light duty neither validates all loads nor establishes a thousands-of-hours service life. [E01] [E21] [E27]

Thermal limiting chain. Copper heating depends on current; magnetic losses rise with operating conditions including speed; the inverter contributes conduction/switching loss; gearbox/bearings/seals/lubricant dissipate mechanical losses. Windings, magnets, encoder, inverter, grease and touch surfaces can have different limits. [E01] [E02] [E11] [E14] [E17]

Holding is a separate operating point. At stationary output, mechanical output power is zero while energized torque can still generate copper and inverter heat. A running torque rating therefore does not automatically establish continuous zero-speed holding torque. Test multiple electrical rotor angles and the real mounting thermal path. [E01] [E11]

Precision and sensitivity. Backlash, elastic deflection, friction, cogging, energized ripple, encoder errors and thermal drift are distinct. Current-based torque estimation is not an actual output torque transducer; motor encoder resolution is not output positioning accuracy. [E04] [E06] [E13] [E18] [E26]

Installed mass and reflected inertia. For a simple reduction N = motor speed/output speed, rotor inertia referred to the output scales as N squared times rotor inertia; load inertia referred to the motor scales inversely. Distal mass also contributes gravity moment and link inertia. Comparisons should use a full robot model, not just module mass. [E03] [E02]

Architecture comparison

Direct drive

Principle: Motor rotor directly drives output; no reduction transmission.

Strengths: Eliminates gear backlash and gear friction; frameless integration can make the structure part of the motor package.

Limits: Motor must produce full joint torque; cooling, bearings and structural mass remain. No gearbox does not mean zero cogging or infinite precision.

Best fit: Engineering assessment: Low-torque precise axes, gimbals and some wrists; compare complete supported assembly.

Sources: [E02] [E13]

Quasi-direct drive (QDD)

Principle: High-torque motor with low-ratio reduction, commonly planetary. QDD describes an architecture, not a universal ratio standard.

Strengths: Low reflected rotor inertia and comparatively transparent force transmission support impact interaction.

Limits: Requires substantial motor current for output torque; continuous hold remains thermally constrained. Gear friction still affects current-based torque inference.

Best fit: Engineering assessment: Dynamic arms and legs where force interaction matters, with separately qualified precision and thermal behavior.

Sources: [E03] [E01]

Conventional planetary geared servo

Principle: Sun, planets, carrier and ring form one or more reduction stages.

Strengths: Configurable reduction and compact coaxial motor/gear packages.

Limits: Stage count affects efficiency and length; backlash, shaft support and running torque must be qualified by exact variant.

Best fit: Engineering assessment: Cost-conscious arm joints when externally supported and calibrated to task requirements.

Sources: [E24]

Strain-wave geared servo

Principle: Wave generator elastically deforms flexspline against circular spline.

Strengths: Compact high reduction and manufacturer-specified zero backlash at gear mesh.

Limits: Finite torsional stiffness, hysteresis and backdriving torque persist; zero backlash is not zero loaded error. Flexspline life requires load-cycle qualification.

Best fit: Engineering assessment: Compact positioning shoulders/elbows/wrists with output sensing and verified fatigue margins.

Sources: [E05] [E06] [E27]

Cycloidal/RV geared servo

Principle: Eccentric cycloidal reduction; Nabtesco RV adds an input reduction stage and integrated support bearings.

Strengths: Manufacturer emphasizes shock capacity, stiffness and moment support.

Limits: Precision contact geometry, preload and bearing installation need control; do not transfer one vendor’s ratings to a locally made reducer.

Best fit: Engineering assessment: High-load proximal arm, hip or knee joints after mass and efficiency are measured.

Sources: [E07]

Series-elastic actuator (SEA)

Principle: A designed elastic element lies in the force path; spring deflection supports force feedback.

Strengths: Compliance provides force-control and interaction benefits.

Limits: Deflection, spring travel, resonances and control bandwidth must be designed together; stored energy must be managed.

Best fit: Engineering assessment: Contact-rich arms, leg joints and tools where compliance has a defined purpose.

Sources: [E04]

Ball/planetary-roller screw linear actuator

Principle: Motor rotation becomes linear travel through rolling balls or threaded planetary rollers.

Strengths: High force from a suitable screw lead; mature precision-screw manufacturing routes.

Limits: Preload raises rigidity and friction; guides, support bearings, end joints, buckling checks, braking and stroke envelope are system requirements.

Best fit: Engineering assessment: Linear knees/ankles, grippers and industrial push/pull axes; choose by full linkage geometry.

Sources: [E08] [E09] [E19]

Remote tendon/cable actuation

Principle: Cable or tendon transmits motor effort to a joint; antagonist arrangements can control tension and stiffness.

Strengths: Motor placement can reduce distal mass; DLR documents distinct antagonistic hand mechanisms.

Limits: Routing, tension, elastic stretch and hysteresis complicate sensing and maintenance; remote mass is relocated, not removed.

Best fit: Engineering assessment: Hands and wrists where a lighter distal assembly outweighs transmission complexity.

Sources: [E10] [E04]

Architecture selection is an engineering assessment. Start from the joint duty and acceptable impedance, then size motor, transmission, bearing and thermal path together. High reduction can improve compact torque production but adds friction and reflected inertia; compliance can protect the mechanism but needs sensing and bandwidth analysis. [E03] [E04] [E05]

Who leads, and what robots actually use

There is no evidence-based universal ranking. Commercial integration, sensitive torque control, precision gearing, miniature motors, field service and manufacturing scale reward different designs. The following specialist map describes evidence-backed niches, while the robot table distinguishes disclosed mechanisms from unknown joint details.

Specialists and application-specific leadership

CubeMars

Niche: Commercial integrated robot-joint modules and integration tools

Evidence: Official portal supplies separate product/driver manuals, versioned setup tools and CAN/UART demonstrations.

Decision: Benchmark documentation, integration time and measured complete-module duty; listed firmware does not establish reliability or local stock.

Sources: [E20]

RobStride

Niche: Compact integrated QDD reference family

Evidence: Official product repository gives model-level manuals, torque/speed/mass data and heat-sink conditions.

Decision: Use revision-locked RS references for V0 equivalence. Avoid promoting peak torque or heatsink-conditioned running torque into indefinite hold.

Sources: [E21]

DAMIAO

Niche: Documented integrated geared modules for compact research manipulators

Evidence: Pinned DM-J4310-2EC hardware V1.2/manual V1.4 separates specification, protection, mechanical and command sections.

Decision: Maintain hardware/manual/P-variant identity. Provenance is useful; independent life/holding evidence is still required.

Sources: [E22]

Harmonic Drive

Niche: Precision strain-wave reducer/component benchmark

Evidence: Operating-principle documentation and product-specific stiffness, backdriving and separate overload tables.

Decision: Evaluate as transmission technology, not a ready-made drop-in full actuator; finite stiffness still matters.

Sources: [E05] [E06]

Nabtesco

Niche: Cycloidal/RV reduction for high-load support and stiffness

Evidence: Official two-stage architecture and support-bearing design disclosures.

Decision: Manufacturer shock claims need exact model selection and installed-mass comparison for humanoids.

Sources: [E07]

maxon

Niche: Small precision motor/gear component routes and motor-characterization documentation

Evidence: Stage-specific GPX gearhead data and accessible motor thermal/cogging guidance.

Decision: A matched motor/gear/encoder/drive assembly must be sized and weighed as a complete route.

Sources: [E01] [E13] [E24]

Kollmorgen

Niche: Frameless torque-motor integration and servo application engineering

Evidence: Detailed robotic-joint thermal/interface guidance and holding-brake documentation.

Decision: Strong component-integration reference; custom housing, bearings, reducer and controller remain the builder's engineering work.

Sources: [E02] [E19]

Moog

Niche: Integrated hydraulic robotic actuation and motion-control components

Evidence: Integrated Smart Actuator brochure documents servo valve, electronics, sensing and bus communication.

Decision: Include pump, reservoir, hose and cooling mass before comparison with an electric module; no humanoid supplier relationship inferred.

Sources: [E23]

NSK / Rollvis

Niche: Precision screw transmission benchmarks

Evidence: NSK publishes friction/preload engineering; Rollvis describes precision-ground planetary screw geometry.

Decision: Select by force/stroke/support geometry and life model, not motor torque alone.

Sources: [E08] [E09]

SKF

Niche: Bearing selection, friction models and support engineering

Evidence: Separates rolling, sliding, seal and lubricant drag contributions.

Decision: A low-friction motor cannot compensate for unsuitable bearing preload or lubrication.

Sources: [E14]

For industrial mobile inspection, Spot and ANYmal offer more useful maturity evidence than isolated peak-torque records: Boston Dynamics reports a customer fleet above 1,500, while ANYbotics documents modular torque-controlled drives and a named maxon development/production partnership. This makes them informative references for integration and serviceability, not purchasable drop-in joint specifications. Individual lifetime and actuator mass remain qualification gaps. [R27] [R23] [R22]

For cost-sensitive dynamic platforms, Unitree exposes helpful joint-level limits and real packaging measures, including Go2 heat pipes and G1 dual encoders. OpenArm makes a named commercial motor-family mix inspectable, and explicitly uses a higher-reduction 4340 series where payload and packaging justify it. These are practical benchmarking routes; neither family maximum torque nor robot battery runtime establishes sustainable

torque density. [R01] [R03] [R04] [R26]

For dexterous hands,1X's July 2026 forearm-motor/tendon disclosure is a strong architecture reference for reducing distal mass; Figure 03 instead supplies useful evidence about integrated tactile sensing and the industrialization of many actuator SKUs. Neither disclosure provides a common mass, cooling, accuracy and lifetime test from which to declare a universal winner. Their value to an India program is in identifying system-level experiments, not copying an unverified performance headline. [R21] [R11] [R13]

For high-load humanoids, compare generation-specific approaches: electric Atlas is distinct from its hydraulic predecessor; Apollo's disclosed linear architecture must be separated from current Apollo 2 claims; Digit 5's planned cycloidal drives are not Digit 4 hardware. Tesla's accessible recruiting disclosures establish rotary/linear development expertise but cannot substantiate a shipped joint BOM. Leadership in this category should be judged after comparable duty-cycle, field-reliability and service data exist. [R05] [R06] [R14] [R15] [R16] [R17] [R10]

Read robot-level specifications at robot level. Payload, IP rating, ambient range and operating hours are not automatically ratings of each joint. Announced next-generation hardware is kept separate from delivered or deployed revisions.

Robot - generation - joint - actuator evidence

Unitree H1

Generation: Original H1,2023; do not merge with H1-2

Joint: Knee / hip / ankle / arm

Actuation: Unitree electric joint actuators; individual SKU map undisclosed

Developer supplier: Unitree self-developed; component suppliers undisclosed

Known spec: Published joint limits approx 360 /220 /45 /75 Nm respectively; five leg axes and four arm axes

Unknowns: Continuous holding/running torque, peak duration, per-joint mass, reduction and thermal map

Evidence level: Manufacturer specification, not independent measurement

Sources: [R01]

Unitree H1-2

Generation: H1-2 live specification

Joint: Arm / leg

Actuation: Electric joints; M107 family shown but exact assignment not established

Developer supplier: Unitree

Known spec: Arm maximum 120 Nm; leg maximum 360 Nm;7 axes per arm and 6 per leg; cross-roller output bearings

Unknowns: Which axis receives each model; continuous duty and actuator installed mass

Evidence level: Manufacturer specification with incomplete joint mapping

Sources: [R02]

Unitree G1

Generation: 2024-introduced family; configuration-dependent

Joint: Knee; body joint infrastructure

Actuation: Electric joint motor; exact SKU undisclosed

Developer supplier: Unitree; component origins undisclosed

Known spec: Knee maximum 120 Nm in cited family specification; dual encoders and local air cooling

Unknowns: Per-variant mapping; continuous torque; winding temperature, fan power and installed cooling mass

Evidence level: Manufacturer family specification

Sources: [R03]

Unitree Go2

Generation: Go2 Pro/X/EDU product table, retrieved 2026

Joint: Leg joints; knee cooling

Actuation: Integrated electric joint drive

Developer supplier: Unitree; exact motor/reducer SKU not given

Known spec: Approx 45 Nm maximum for cited configurations; heat-pipe cooling;12 joint units

Unknowns: Continuous output, peak duration, individual actuator mass and thermal resistance

Evidence level: Manufacturer configuration-specific claims

Sources: [R04]

Boston Dynamics Atlas

Generation: Electric Atlas 2024 to industrial product 2026; separate from hydraulic Atlas

Joint: Arms, hands and legs; individual allocation undisclosed

Actuation: All-electric proprietary system; detailed transmissions undisclosed

Developer supplier: Boston Dynamics; external actuator suppliers not established

Known spec: 2026 whole robot:56 DoF,90 kg,30 kg sustained /50 kg instantaneous payload; -20-40 deg C and IP67

Unknowns: Actuator mass, supplier/model, torque-speed and thermal-life data by joint; payload figures are not joint ratings

Evidence level: Manufacturer product specification and program announcement

Sources: [R05] [R06]

Boston Dynamics Spot

Generation: Hardware described in SDK 5.2.0

Joint: Hip HX/HY and knee

Actuation: Two hip drives plus one knee drive per leg; knee ball-screw/push-rod described by OEM

Developer supplier: Boston Dynamics system; motor/screw suppliers undisclosed

Known spec: 12 leg DoF; knee transmission leverage changes with angle

Unknowns: Actuator part numbers and continuous limits; simulation table is not treated as hardware certification

Evidence level: Manufacturer hardware description; simulation-oriented limits excluded

Sources: [R07] [R08]

Boston Dynamics Spot Arm

Generation: SDK 5.2.0 arm specification

Joint: Shoulder, elbow, wrist and gripper

Actuation: Six-axis arm plus gripper; coupled SH1/EL0 input drives

Developer supplier: Boston Dynamics system; component suppliers undisclosed

Known spec: 8 kg arm including gripper; continuous 5 kg at 0.5 m extension at 22 deg C

Unknowns: Individual motor masses, gear types, lifetime and joint thermal limits

Evidence level: Manufacturer assembly specification and transmission description

Sources: [R08] [R09]

Tesla Optimus

Generation: Program-level disclosure retrieved 2026; hardware revision not identified

Joint: Rotary and linear axes; exact arm/leg/hand allocation unverified

Actuation: Tesla engineering program explicitly develops rotary and linear electromechanical actuators

Developer supplier: Tesla actuator team; shipped component suppliers unknown

Known spec: No revision-specific actuator datasheet recovered from accessible primary evidence

Unknowns: Installed model, screw/reducer topology, force/torque, mass, duty and life for each generation

Evidence level: Primary recruitment disclosure only; not deployed BOM proof

Sources: [R10]

Figure 02

Generation: BMW deployment reportedNovember 2025

Joint: Forearm/wrist subsystem

Actuation: Wrist actuators; hardware model undisclosed and forearm communications electronics

Developer supplier: Figure; lower-tier components undisclosed

Known spec: OEM reports 1250+robot operating hours; forearm was leading hardware failure location

Unknowns: Joint SKU/torque/mass and individual actuator lifetime; robot-hours do not equal fatigue life

Evidence level: Manufacturer deployment report, unaudited

Sources: [R12]

Figure 03

Generation: October 2025 launch;2026 production update

Joint: Body actuators and wrist electronics

Actuation: In-house actuator designs; Figure 03 wrist controllers connect directly to main computer

Developer supplier: Figure design/manufacturing with unnamed component suppliers

Known spec: OEM reports more than 10 actuatorSKUs and 9000+units produced byApril 2026

Unknowns: Per-joint SKU assignments, reducer topology, continuous duty, mass and MTBF

Evidence level: Manufacturer architecture/production disclosures, unaudited

Sources: [R11] [R12] [R13]

Apptronik Apollo

Generation: August 2023 platform as described in 2024 announcement

Joint: Body actuation; individual axes undisclosed

Actuation: Linear actuator and force-control architecture disclosed

Developer supplier: Apptronik custom technology; component supplier map unknown

Known spec: No model-level force/speed/mass table disclosed in cited source

Unknowns: Screw type/lead, force sensor topology, rotary exceptions, stationary-hold envelope

Evidence level: Manufacturer architecture disclosure

Sources: [R14]

Apptronik Apollo 2

Generation: Current Apollo 2 webpage retrieved 2026

Joint: Whole-body actuator platform; joint assignments not disclosed

Actuation: Apptronik proprietary actuator platform; do not automatically inherit all 2023 mechanisms

Developer supplier: Apptronik; supplier details undisclosed

Known spec: 90%+energy-efficiency and 7 x 22 operation are design claims without common test boundary

Unknowns: Torque/force and mass by axis, thermal conditions and full efficiency denominator

Evidence level: Manufacturer design targets, not a duty-specific qualification report

Sources: [R15]

Agility Digit

Generation: Digit 3 versus commercially deployed Digit 4

Joint: Leg links and compliant elements

Actuation: OEM identifies leaf-spring-to-rigid-link evolution; complete actuator BOM not disclosed

Developer supplier: Agility; component suppliers unknown

Known spec: 2026 Q&A explains removal of spring dynamics for manipulation-oriented design

Unknowns: Digit 4 per-joint transmission/torque sensor details; cannot assign Digit 5 gearbox backward

Evidence level: Manufacturer retrospective engineering explanation

Sources: [R16]

Agility Digit 5

Generation: Announced developmentOctober 2026; early access expectedH1 2027

Joint: Ankle / knee; higher-load body joints

Actuation: Planned proprietary cycloidal reductions; winding-current torque control; staged impact handling

Developer supplier: Agility proprietary design; components undisclosed

Known spec: Small low-inertia ankle intended to buffer larger knee drives

Unknowns: Final production BOM, ratio, efficiency, mass and endurance; not deployed qualification evidence

Evidence level: Announced design intent

Sources: [R16] [R17]

Fourier GR-2

Generation: FSA 2.0; webpage versusMay 2025 brochure

Joint: Body joints; seven actuator variants

Actuation: Fourier Smart Actuator modules with dual encoders

Developer supplier: Fourier; per-component sourcing unknown

Known spec: Webpage says family peak>380 Nm;2025 brochure says>436 Nm; retain both source boundaries

Unknowns: Revision causing difference; per-axis SKU, continuous torque and mass; do not apply family maximum to every joint

Evidence level: Manufacturer claims with unresolved revision discrepancy

Sources: [R18] [R19]

1 X NEO Gamma

Generation: February 2025 Gamma

Joint: Body joints

Actuation: 1 X Tendon Drive with soft covers

Developer supplier: 1 X; component sourcing undisclosed

Known spec: Tendon architecture explicitly disclosed; no absolute life from relative reliability claim

Unknowns: Joint reduction, mass, torque and duty profile; laterNEOhand data not transferable

Evidence level: Manufacturer generation-specific announcement

Sources: [R20]

1 X NEO hand

Generation: July 2026 hand announcement

Joint: Fingers/palm and wrist

Actuation: Forearm-mounted in-house motors; tendon transmission approximately 5:1-15:1

Developer supplier: 1 X integrated motor, tendon, electronics and firmware

Known spec: 22 finger/palmDoF plus 3 wristDoF; force-controlled/backdrivable claimed; >2 million wrist cycles under unspecified high load

Unknowns: Each joint's motor mass/torque, tendon pretension, replacement interval and cycle test protocol

Evidence level: Manufacturer architecture and endurance claims

Sources: [R21]

ANYmal

Generation: 2018 ANYdrive description; do not silently map to currentD/X

Joint: Hip ab/adduction, hip flexion, knee flexion

Actuation: Three sealed series-elastic ANYdrive modules per leg

Developer supplier: ANYbotics historical design

Known spec: Integrated electronics; position, torque and impedance regulation

Unknowns: 2018 module mass/life not established here; current generation mechanism must be separately verified

Evidence level: OEM-hosted technical article

Sources: [R23]

ANYmal C / later ANYmal program

Generation: C launched 2019;2020 maxonpartnership is program-level

Joint: Leg torque-controlled joints

Actuation: C torque-controlled drives; maxon announced future actuator development/production

Developer supplier: ANYbotics and maxon partnership; exact currentSKU unknown

Known spec: C actuator design claim >1 million cycles, profile unpublished

Unknowns: Which revisions use which maxon assembly; exact SEA implementation on currentD/X; cycle load/temperature

Evidence level: Manufacturer C specification plus partnership announcement

Sources: [R22] [R24]

MIT Mini Cheetah

Generation: Original modular platform described inMay 2020 thesis; distinguish thesis redesign

Joint: All leg joints

Actuation: Replaceable BLDC + internal planetary gearbox + controller + position sensor modules

Developer supplier: MIT Biomimetic Robotics Lab; hobby-motor basis

Known spec: Same module used throughout simplifies replacement; thesis proposes newer custom-rotor module

Unknowns: Production support and duty/lifetime qualification; new thesis prototype not assumed installed in original robot

Evidence level: Primary MIT thesis abstract; no unsupported numeric ratings

Sources: [R25]

OpenArm

Generation: OpenArm 2.0 hardware documentation

Joint: Shoulder/proximal motors; intermediate joints; wrist/end-effector region

Actuation: Diagram labels DAMIAODM8009P,DM4340P,DM4340,DM4310; assignment follows annotated motor-location drawing

Developer supplier: DAMIAO motors; enactic/OpenArm integration

Known spec: 8009 P/43 series mix; cross-roller units at one-sided supports;4340 series explicitly not QDD

Unknowns: Exact delivered motor hardware/manual revision; joint-number-to-P-variant BOM must be pinned before mass sum

Evidence level: Official hardware architecture and motor-location diagram

Sources: [R26]

Scope is public primary evidence reviewed25 October 2026. A missing detail means it was not established in the reviewed evidence, not that the manufacturer has no internal data.

Manufacturer webpages, technical documentation, OEM engineering reports and a primary university thesis are separated by evidence_level. None of the manufacturer peaks or endurance figures in this matrix is independently verified here.

Joint-to-actuator rows deliberately stop at the source's disclosure level. Patents, external appearance, speculative supplier lists and simulation actuator limits are not used to infer installed production hardware.

Spot SDK supplemental documentation explicitly describes physical transmission mechanisms; those prose disclosures are retained. Its simulation-oriented torque/ratio table is not promoted to continuous hardware ratings. [R08]

A historical architecture remains historically useful without being attributed to a current generation:2018 ANYdrive SEA evidence is not automatically current ANYmal D/X evidence; Apollo 2023 linear disclosures do not closeApollo 2 joint-mapping gaps. [R23] [R14] [R15]

Commercial battery hours, robot fleet operating hours, actuator thermal equilibrium and component fatigue life answer different questions. Figure 02reported robot-hours, ANYmal C cycles andNEO hand cycles use different boundaries and cannot be ranked as equivalent lifetime data. [R12] [R24] [R21]

All Chinese platforms/actuators remain engineering benchmarks for the India-developed direction. This section is not a recommendation to buy finished Chinese actuators. Component origin disclosure and procurement decisions remain separate.

Why heat, mass and precision interact

Thermal equilibrium and hours of operation



Heat flows through thermal resistances; capacitance delays change

Measure winding, inverter and housing; protect the limiting component

Conceptual thermal network. Arrows represent heat flow, not equal temperatures. Parallel paths and local hotspots need a multi-node model.

Engineering model: at zero speed, mechanical output power is zero even while the motor produces holding torque. Electrical and inverter losses can still be substantial. A simple thermal model is Cth dT/dt = Ploss - (T - Tamb)/Rth. For constant losses it approaches a steady rise of Ploss x Rth, with time constant Rth x Cth. More thermal mass delays heating; lower thermal resistance improves steady operation. These are different interventions. [E28]

```
Copper loss = sum over phases k of Rk(T) x Ik,rms^2. This becomes 3 x Rphase(T) x Iphase,rms^2 for balanced equal-phase RMS conditions. Thermal rise at equilibrium approx. Ploss x Rth. Time constant = Rth x Cth.
```

These equations are an analytical starting point. Do not substitute DC bus current for phase RMS current, or phase-to-phase resistance for per-phase resistance without the winding connection and measurement convention. Motor torque constant conventions must match the current convention. Add inverter, iron, mechanical and gearbox losses for the tested operating point; temperature-dependent resistance creates feedback that a constant-loss model misses. [E01] [E11] [E17]

Illustrative calculation, not a component rating: with 30 W total heat and a 1.5 K/W system thermal resistance, steady temperature rise is 45 K. At 40 C ambient, the modelled node reaches 85 C. Halving thermal resistance lowers that node to 62.5 C. Doubling thermal capacitance only slows the rise. A winding hotspot may exceed that node, so a safe surface temperature does not establish winding or magnet safety.

Four distinct specifications are required: permissible continuous steady load; an intermittent peak envelope with recovery time; mission operating hours at a defined trajectory; and service life at defined loads and maintenance. A battery-runtime statement is not a joint-life statement. Eight hours of intermittent operation is not eight hours at peak torque. A short burn-in is not evidence for thousands of service hours. [E01] [E21] [E27]

Mass propagates upstream

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Added shoulder gravity torque = sum(delta mass x g x horizontal offset). Added point-mass inertia = sum(delta mass x radius^2).
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Illustrative calculation: adding 0.5 kg at 0.6 m horizontal offset adds 2.943 Nm of gravity torque and 0.18 kg m2 of point-mass inertia about that axis. At 5 rad/s2 it adds 0.9 Nm of acceleration torque in this simplified model. Adding the same mass near the shoulder axis contributes much less. Thus distal driver, brake, wrist and hand mass can trigger a larger shoulder actuator, which then increases structure and support requirements. [E03]

A complete arm calculation must include link distributed inertia, motor rotor inertia reflected through the square of gear ratio, joint geometry, payload centre of mass, counterbalances, contact loads and cable forces. The simple example is a sensitivity demonstration, not an arm payload rating. A light motor with a heavy external bearing or cooling plate may lose its apparent system advantage. [E02] [E03]

Accuracy is a chain, not an encoder resolution

An encoder quantises angle; it does not remove mechanical compliance, transmission error, friction, thermal drift or mounting error. A motor-side encoder cannot directly observe all output-side deflection or backlash. An output encoder improves observability but still needs calibration. A physical torque sensor measures strain or displacement through a calibrated load path; current-based torque estimation includes uncertain friction, ratio efficiency and temperature effects. [E13] [E18]

For delicate contact, test both directions near zero speed. Report breakaway torque, hysteresis, minimum repeatable controllable output torque, noise, bias drift and closed-loop stability. A high command rate is not the measured torque bandwidth; timestamps, filtering, transport, controller update and mechanics all contribute latency. Tool-level force sensitivity also depends on kinematics and the tool contact geometry. [E03] [E04] [E18]

Speed, energy and wear

```
Mechanical power = torque x angular speed. Linear power = force x velocity. Screw motoring
torque approx. force x lead / (2 pi x forward efficiency). Lowering/backdriving needs
reverse-efficiency and friction analysis; self-locking must be checked.
```

For illustration, 20 Nm at 40 rpm is about 83.8 W of mechanical output. A 2 kN linear force at 0.1 m/s is 200 W. These are not electrical-input ratings. High torque and maximum no-load speed must never be multiplied as if simultaneously available. Back-EMF, bus voltage, current limits, winding temperature and transmission speed limits shape the envelope. [E01]

Deceleration and lowering a load can return energy to the DC bus. Specify how much the battery or power supply can absorb, and design bus clamps, braking resistors or a coordinated motion strategy where necessary. A bench supply that sources current may not sink it. Power-loss tests must distinguish motor shutdown, controlled stop, brake engagement and stored elastic/gravitational energy. [E12]

Transmission wear, bearing preload, lubrication and sealing can change friction and accuracy before a joint fails completely. Endurance acceptance should include drift in lost motion, efficiency, temperature rise, vibration and noise, not merely continued rotation. An accelerated test is credible only when it preserves the relevant failure mechanism. [E14] [E27]

More thermal mass can delay a temperature rise without improving the eventual sustainable load. Improved steady cooling requires a better path to the environment. A heat pipe moves heat; it still needs an effective condenser/sink. The published heat-pipe experiment varies orientation and airflow, which are especially relevant when a robot joint changes posture. A phase-change insert should be rated by finite absorbed energy and its reset time, not advertised as indefinite cooling. The phase-change proposal and its test gate are engineering recommendations. [E28] [E30]

The limiting temperature can belong to the gearbox lubricant, encoder, drive electronics or exposed surface instead of the motor insulation. Kollmorgen explicitly discusses neighboring component limits in frameless robotic joints. Use the actual selected parts and their mounting conditions; do not reuse the example temperatures from that application note as universal design limits. A proposed component temperature register should list normal limit, protection threshold, measurement location, uncertainty and required margin for each part. [E02]

Four application classes: provisional requirements

All numerical values below are proposed study targets for trade-off and fixture design, not established actuator specifications or final Armature product requirements. Each torque or force point must be paired with speed, duration, ambient, mounting and cooldown. Targets may be revised after the first measured joint.

The classes prevent a low-friction wrist from being judged by the same priorities as an impact-loaded knee. For wrists and hands, moving mass and contact sensitivity are central. Shoulders need sustained gravity support; hips and knees need energy handling and impact tolerance; ankles combine support and contact transitions. Linear actuators must be evaluated through the linkage moment arm, including near-singular positions.

A proposed development screen is an eight-hour mission at stated ambient, with repeated motion/hold/idle segments and logged sensor data. Independently test stationary holding to equilibrium. A provisional near-steady screening criterion is less than 1 C total drift over the final 30 minutes at all measured winding, housing and driver nodes. Even this does not prove equilibrium: use a fitted thermal model and sufficient settling time, with predicted remaining rise below a declared margin. Stop at any predeclared component limit. Passing a particular mission does not qualify arbitrary trajectories.

Provisional application requirement matrix

Small wrist / interchangeable tool

Purpose: Low distal mass and gentle contact; general grasping plus laboratory and electronics development.

Mass: 0.35-0.65 kg installed joint target; count encoder, driver, output support and connectors. Tool and adapter separate.

Envelope: Initial study envelope: 80 mm diameter x 70 mm axial; cable bend and tool clearance additional.

Running: 3-6 Nm at 60 rpm study point; verify torque-speed envelope.

Peak: 10-15 Nm for 1 s, initially one event per minute; qualification required.

Holding: 2-4 Nm until thermal equilibrium at zero speed; brake-assisted holding is a separate mode.

Profile: Eight-hour mission: 60% motion, 30% hold, 10% idle; actual task histogram must replace this assumption.

Thermal: Characterise at 25, 35 and 40 C ambient. Start with passive mounting; specify mounting conductance.

Loads: Calculate tool centre-of-mass and contact moments; qualify radial, axial and overturning loads separately.

Precision: Provisional bidirectional lost motion <=0.1 degree; report friction and minimum controllable torque, not encoder bits alone.

Control: Proposed 1 kHz joint command interface; measure end-to-end delay and torque bandwidth separately. Dual encoder and output torque sensing considered.

Life: 100 h development screen, then mission-derived endurance. Commercial life and maintenance intervals remain TBD.

Cost: Target cost not frozen; compare installed cost with equivalent sensing and support.

Evidence status: proposed / engineering assessment.

Medium arm joint

Purpose: Shoulder / elbow positioning and sustained gravity compensation.

Mass: 0.7-1.5 kg installed joint study range; a brake or larger bearing may exceed it.

Envelope: Initial study envelope: 110 mm diameter x 100 mm axial; confirm hollow bore and cable routing.

Running: 15-25 Nm at 40 rpm study point; not a full-speed continuous guarantee.

Peak: 40-60 Nm for 1 s, initially one event per minute; voltage and gearbox limits apply.

Holding: 10-15 Nm to equilibrium without motion; test brake and counterbalance as separate system options.

Profile: Eight-hour motion/hold mission as above; record payload and joint angle because gravity torque changes.

Thermal: 25 / 35 / 40 C chamber tests with defined link or heat sink. Do not reuse bench cooling as an installed rating.

Loads: Shoulder bearing design must include arm moment and tool loads; specify fatigue and static limits.

Precision: Provisional <=0.1 degree lost motion; measure output deflection under load and thermal drift.

Control: 1 kHz interface study target. Calibrated output torque measurement or characterised estimate; document current conventions.

Life: 100 h development screen followed by accelerated, mechanism-relevant endurance; no service-life claim from burn-in.

Cost: Economics example in this paper is a cost model for this class, not a supplier quotation.

Evidence status: proposed / engineering assessment.

High-load leg joint

Purpose: Hip / knee propulsion, impacts, regeneration and repetitive loading.

Mass: 1.2-2.0 kg installed joint study range; impact support and cooling count.

Envelope: Initial study envelope: 120 mm diameter x 120 mm axial; structural stiffness may dominate.

Running: 40-70 Nm at 40 rpm study point; walking/running operating clouds determine real requirements.

Peak: 120-200 Nm for 0.3 s, initially one event per 10 s; gearbox and DC bus limits require testing.

Holding: 20-40 Nm static screening point; a parked standing posture requires a separate power-loss strategy.

Profile: Eight-hour mission is a programme goal, not eight hours of peak torque or uninterrupted walking.

Thermal: 25 / 35 / 40 C with realistic enclosure. Include fan/pump energy and mass if adopted.

Loads: Impact spectrum, bearing preload, axial thrust and overload stops must be defined from robot dynamics.

Precision: Provisional <=0.2 degree lost motion; prioritise repeatable torque, low reflected inertia and impact tolerance.

Control: 1 kHz interface study target; assess closed-loop impedance, torque tracking and stability with contact.

Life: Cycle spectrum and damage accumulation required. Record impacts and thermal cycles, not hours alone.

Cost: Price target depends on volume, torque sensor, transmission and cooling; not fixed here.

Evidence status: proposed / engineering assessment.

Linear joint / screw actuator

Purpose: Compact force generation where linkage geometry favours a linear drive.

Mass: 1.5-3.0 kg installed assembly study range; count joints, guides, brake and sensing.

Envelope: 100-200 mm stroke; initial retracted length <=450 mm subject to screw support and linkage geometry.

Running: 1-2 kN at 0.1 m/s study point; check screw critical speed, buckling and duty.

Peak: 3-5 kN for 0.1 s, initially one event per 10 s; do not combine with maximum speed automatically.

Holding: 1 kN equilibrium screen; verify backdrive and brake behaviour under power loss.

Profile: Stroke-dependent force/speed histogram; reversal and end-stop events explicitly counted.

Thermal: 25 / 35 / 40 C; measure nut, screw, motor and inverter temperatures. Lubrication affects losses.

Loads: Side loads go through guides or spherical joints unless actuator is rated for them.

Precision: Provisional <=0.1 mm bidirectional lost motion at actuator; joint-angle accuracy depends on linkage.

Control: Force sensor and linear encoder preferred for qualification; map actuator force through moment arm.

Life: Track travel, reversals, load cycles and lubricant condition; motor hours alone insufficient.

Cost: Include guide, screw support bearings, nut, brake, linkage joints and controller in comparison.

Evidence status: proposed / engineering assessment.

Materials, processes and manufacturing controls

The following materials are engineering candidates, not a released bill of materials. Selection depends on magnetic frequency, flux, temperature, fatigue, tolerance, contamination and corrosion requirements. A trade name or grade is insufficient without a process drawing and inspection plan. Shafts/axles are load-bearing components; robot joint axes are kinematic coordinates, not interchangeable material specifications.




```
Material lot -> process record -> component inspection -> joint serial

Origins retained through magnets, gears, electronics and final assembly
```

Proposed manufacturing traceability chain. Local assembly alone does not establish domestic origin of all materials.

Component-to-process matrix

Stator/rotor magnetic laminations

Candidate materials: Low-loss non-oriented electrical steel; grade and gauge chosen from frequency/flux-loss maps

Process: Slit; prototype cut or stamp; deburr; insulate; stack/bond/interlock; verify post-process loss

India capability gap: SAIL provides CRNO and Tempel laminations; exact thin gauge and low-loss availability must be demonstrated

Qualification tests: B-H and core-loss measurement after cutting/stacking; burr, interlaminar insulation, stack factor, runout

Sources: [I08] [I09]

Copper winding

Candidate materials: Enamelled round copper; rectangular copper where winding geometry supports it

Process: Wire qualification; controlled winding tension; termination; impregnation/cure

India capability gap: RR Shramik local wire; selected enamel/resin supply and batch origin to qualify

Qualification tests: Resistance at known temperature; surge/hipot; turn insulation; fill factor; thermal rise

Sources: [I10] [I32]

Insulation and potting

Candidate materials: Compatible wire enamel, varnish/epoxy and slot insulation as one system

Process: Clean; dry; impregnate/pot; control voids and cure

India capability gap: ELANTAS local compounds; grade-specific thermal and dielectric properties required

Qualification tests: Dielectric withstand; thermal cycling; adhesion; void fraction; repair/rework trials

Sources: [I32]

Rotor magnets

Candidate materials: Sintered NdFeB grade chosen using hot demagnetisation curves; SmCo alternative; ferrite requires redesign

Process: Specify Br/Hcj versus temperature, arc geometry, segmentation, coating and magnetisation

India capability gap: India NdFeB pilot and company claims exist; no audited small-arc production chain in this study

Qualification tests: Incoming flux mapping and dimensions; irreversible demagnetisation after hot overload; coating/corrosion tests

Sources: [I14] [I15] [I16] [I35] [I41]

Shafts / axles

Candidate materials: 42CrMo4-type quenched/tempered steel candidate; bearing-seat material depends on loads and surface requirements

Process: Turn; heat treat; straighten; grind journals; finish key/spline and inspection

India capability gap: Precision machining and heat-treatment capability exists; exact miniature-journal fatigue process unqualified

Qualification tests: Chemistry/heat certificate; hardness; journal runout; fatigue; balance and bearing fit

Sources: [I11] [I12] [I42]

Planetary / cycloidal gears

Candidate materials: 16MnCr5-type case-hardening steel candidate; reducer designer selects grade and case specification

Process: Cut teeth; carburise/heat treat; finish grind; inspect and match

India capability gap: Shanthi/Gleason ecosystem; small module, thin ring, and low-backlash economics require samples

Qualification tests: Tooth geometry; case depth/hardness; residual distortion; backlash, efficiency and endurance

Sources: [I11] [I13] [I42]

Strain-wave flexspline

Candidate materials: Fatigue-qualified alloy and heat-treatment route supplied by reducer designer; no generic gear-steel substitution

Process: Thin-wall forming/machining; tooth generation; heat treatment; surface/process control

India capability gap: No verified Indian source in this review demonstrated a complete flexspline process and life curve

Qualification tests: Full deflection fatigue and overload tests; tooth contact; wall variation; crack inspection

Sources: [I01] [I03] [I11]

Housing and heat spreading

Candidate materials: 6061-T6 / 6082-T6 aluminium candidates; separate property check for cast variants

Process: Machine billet/extrusion for prototypes; controlled surface finish; later casting only after qualification

India capability gap: Hindalco extrusion availability; CNC candidate supply; thermal interface and bearing fit not automatic

Qualification tests: Thermal resistance; bearing-bore alignment; preload change over temperature; stiffness/strength

Sources: [I12] [I33] [I43]

Output and motor bearings

Candidate materials: Bearing-steel rolling bearing; angular-contact/cross-roller/thin-section selection by load envelope

Process: Clean installation; controlled fits and preload; lubrication

India capability gap: SKF/Schaeffler/Timken local manufacture exists; exact joint bearing may be imported

Qualification tests: Radial/axial/moment loads; friction versus temperature; preload; endurance and noise

Sources: [I17] [I18] [I19]

Seals and grease

Candidate materials: NBR/FKM/PTFE candidates; compatible grease selected for gear and seal duty

Process: Select seal geometry and finish; controlled grease fill and assembly cleanliness

India capability gap: Trelleborg and Klüber local manufacturing; exact compounds/formulation origins still SKU-specific

Qualification tests: Low-speed drag; leak/dust ingress; grease compatibility; thermal ageing and wear

Sources: [I20] [I21]

Rotor adhesive / thermal interface

Candidate materials: Retention adhesive plus electrically suitable thermally conductive interface; select by actual joint gaps

Process: Surface prep; measured bondline; cure; inspect; design service removal

India capability gap: Henkel local factory does not identify origin of every chosen thermal compound

Qualification tests: Shear/pull tests at temperature; thermal cycling; dielectric test; thermal resistance and rework

Sources: [I22]

Position and torque sensing

Candidate materials: Absolute motor/output encoder; separate strain-gauge torque flexure if real torque sensing required

Process: Precision encoder location; flexure machining; gauging; electronics; calibration

India capability gap: Renishaw channel and Sushma custom sensor capability; joint-size integration remains development

Qualification tests: Angle accuracy across temperature; torque calibration/cross-axis rejection; hysteresis; bandwidth

Sources: [I23] [I34]

Brake and power-loss retention

Candidate materials: Spring-applied brake sized for static load and any specified emergency stopping energy

Process: Mount and align; power-loss sequence; release sensing; thermal path

India capability gap: Mayr local production exists; compact brake model country/mass/duty to confirm

Qualification tests: Holding under gravity; release time; coil heat; wear/cycle endurance; stop-energy qualification

Sources: [I25]

Power/control electronics

Candidate materials: MOSFET/driver/MCU/current sensing PCB; copper and substrate selected for electrical/thermal design

Process: Design for assembly/test; PCBA; firmware flashing; current-loop calibration; functional burn-in

India capability gap: Kaynes/Centum assembly; semiconductors through authorised channels, country declared by lot

Qualification tests: Switching overshoot; current accuracy; thermal soak; regenerative fault handling; EMI/EMC

Sources: [I26] [I27] [I28]

Harnesses and connectors

Candidate materials: Flexible conductors, shield/insulation and locked connectors selected for joint routing

Process: Cut/crimp/terminate; strain relief; bend/twist management; inspect

India capability gap: SASMOS/Kaynes assembly candidates; robot-specific flex wire and connectors may be imported

Qualification tests: Pull test; continuity; contact heating; repeated bend/twist; EMC/shield bonding

Sources: [I26] [I29]

A practical control plan follows the part through manufacture. Incoming material certificates do not establish the properties after machining, cutting, heat treatment, winding or bonding. Keep the material heat/lot, drawing revision, process recipe, inspection result, firmware and calibration version against the assembled serial number. This is a proposed traceability scheme.

Process gate	Record required	Release question
Magnetic and winding	Steel loss data, stack geometry, magnet batch, winding turns/connection, resistance, insulation results	Does the built motor match the electromagnetic and thermal model?
Mechanical	Gear inspection, heat treatment, runout, surface finish, preload, bearing fit	Can the assembly carry the load without excessive friction or lost motion?
Assembly	Magnet retention, balance, lubrication, fastener process, sealing, cable routing	Is the process repeatable and serviceable?
Calibration	Encoder alignment, torque map, temperature sensor checks, current sensing, firmware	Is the controller using the actual manufactured joint parameters?
End of line	Mass, no-load current, torque check, communication, thermal screen and power-loss behaviour	Does this serialised unit meet the released acceptance limits?

The Indian supplier and localisation network

This is a capability map for qualification, not an approved vendor list. It covers complete-joint developers, manufacturers, distributors, process partners and test facilities. Locations identify published business or facility evidence; they do not establish the origin of every part. Prices, MOQ and lead times remain quotation-dependent where public evidence is absent.

India can assemble a serious actuator supply chain now; a qualified complete joint is still a system project. Published capabilities cover motors, laminations, winding, machining, bearings, brakes, electronics and calibration. The unresolved work is model-specific qualification and integration, especially miniature reducers, bearing preload, encoder alignment and sustained thermal performance. This is an engineering synthesis, not a claim that any listed vendor can deliver an RS-equivalent joint today. [I05] [I09] [I11] [I17] [I25] [I26] [I30]

Do not describe India as having no NdFeB capability. ARCI has a government-confirmed sintered NdFeB pilot and PML now claims 2026 NdFeB production through Quantum Magnetics. Neither source establishes the requested motor arc grades, certified quantities, component origin, or delivery terms. Treat these as qualification leads. [I16] [I35]

Mineral sovereignty is not finished magnet supply. IREL oxide production, Bhopal metal mini-plants, strategic SmCo production, ARCI strip-cast-alloy pilot and the REPM industrial scheme are different stages. Obtain stage-by-stage country and facility declarations. Assembly, grinding, coating or magnetisation in India alone does not demonstrate Indian alloy or sintered-magnet manufacture. [I14] [I35] [I37] [I40]

Capacity discrepancy requires disclosure. The 25 March 2026 DAE release states 500 tonnes/year for the Vizag SmCo plant; the 2 April 2026 parliamentary release states 3 tonnes/year. This report does not reconcile them or use either value to promise supply. Request a plant-specific current production and commercial-allocation statement. [I38] [I39]

The 6,000-tonne REPM scheme is a future capacity target. The 13 August 2026 update describes bids and a two-year plant gestation period from award. It does not prove operating output or that a named bidder is an awardee. No scheme tonnage enters the near-term sourcing plan. [I37]

India invoices and India manufacture need separate columns. maxon, Renishaw and Mouser have official India channels, while SKF/Schaeffler/Timken/Mayr have local manufacturing evidence. Neither status proves the country of every SKU. Obtain supplier legal entity, ship-from location, country of manufacture and component/subassembly origin separately. [I06] [I17] [I18] [I19] [I23] [I25] [I28]

Test laboratories must match the measurand and drive technology. CPRI publishes an induction-motor scope; it cannot automatically be booked as a low-voltage BLDC joint qualification lab. Combine an agreed dynamometer/thermal fixture with reference torque measurement and calibrated dimensional inspection. Verify the current accreditation scope and measurement uncertainty. [I24] [I30] [I31] [I34]

Magnet supply chain: distinct industrial steps

Mineral concentration and rare-earth oxide separation

India evidence: IREL production officially stated

Gap: Oxide availability, purity, allocation and commercial terms

Sources: [I14]

Oxide reduction to metal

India evidence: IREL Bhopal mini-plants; Midwest funded electrolysis development

Gap: Qualified production batch, capacity, cost and purity for the selected alloy

Sources: [I14] [I36]

Alloying and strip casting

India evidence: ARCI pilot starts with strip-cast alloy; upstream alloy origin not established by that statement

Gap: Require alloy melt/facility origin and composition certification

Sources: [I35] [I40]

Powder, alignment, pressing and sintering

India evidence: ARCI finished sintered-magnet pilot; PML subsidiary production claim

Gap: Audit actual plant/process, yields, hot coercivity, powder handling and repeated lots

Sources: [I16] [I35] [I40]

Precision grinding / shaping

India evidence: Needed downstream of sintering; India motor-arc qualification not verified here

Gap: Shape tolerance, brittle chipping/cracks, dimensional inspection

Sources: [I40]

Coating and corrosion protection

India evidence: Separate process; local finishing is not proof of upstream magnet origin

Gap: Specify coat chemistry/thickness, adhesion and humidity/salt-corrosion qualification

Sources: [I40]

Magnetisation, flux sorting and rotor assembly

India evidence: Distinct fixture/process following manufacture

Gap: Magnetisation direction/pole pattern, flux variation, bond integrity and hot irreversible loss

Sources: [I40] [I41]

Indian supplier capability and qualification register

NMotion / Nawe Robotics

Role: Indian developer / complete actuator supplier

Component process: BLDC + harmonic joint + electronics

Location: Kozhikode, Kerala

Origin evidence: Indian developer/contact; component countries undisclosed

Capability: Integrated smart joints with public SDK and dual encoders

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Obtain process-by-process origin, BOM access, holding/thermal-life evidence and joint bearing envelope

Sources: [I01] [I02]

Kikobot

Role: India-made claim / complete actuator supplier

Component process: KH harmonic actuator

Location: Pune, Maharashtra

Origin evidence: Product explicitly states Made in India; BOM origin unresolved

Capability: Integrated joints and optional brake; domestic repairs/spares advertised

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Distinguish local design, gear production, motor winding, imported subassemblies; verify duty/accuracy and warranty

Sources: [I03] [I04]

Mechtex

Role: Indian manufacturer / custom motor route

Component process: Motor, gearbox, machining, winding

Location: Navi Mumbai, Maharashtra

Origin evidence: Company publishes Indian manufacturing facilities; model-level materials origin undeclared

Capability: BLDC, geared motors, CNC/VMC, winding, lamination and testing

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Bare motor is not a joint; qualify thin high-torque motor, encoder, FOC controller, output bearing and total mass

Sources: [I05]

maxon India

Role: Indian sales/support channel / modular components

Component process: Motor, gearbox, encoder, controller

Location: Bengaluru, Karnataka

Origin evidence: Indian office confirmed; no Indian motor manufacture established

Capability: Configurable component combinations with specification support

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Select exact SKUs, production countries, completed assembly mass, landed domestic price and support terms

Sources: [I06]

Hical Technologies

Role: Indian motor design/manufacturing candidate

Component process: Custom motors and electromagnetic assemblies

Location: Bengaluru ecosystem; confirm factory for order

Origin evidence: Manufacturer describes high-reliability motor development; component origins undeclared

Capability: Special-purpose motor design and test resources

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Confirm low-volume robotic frameless motor interest, cost, winding/rotor limits and qualification plan

Sources: [I07]

SAIL Rourkela

Role: Indian material manufacturer

Component process: CRNO electrical steel

Location: Rourkela, Odisha

Origin evidence: Indian mill documented

Capability: Non-oriented electrical coils

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Obtain thin-gauge availability, loss curves at actual electrical frequency/flux, coating class and slitting MOQ

Sources: [I08]

Tempel India

Role: Indian lamination manufacturing / global material sourcing

Component process: Stator/rotor laminations and stacks

Location: Chennai, Tamil Nadu

Origin evidence: Chennai manufacturing location; feedstock mill country varies

Capability: Stamping, tooling, prototype and core assembly capability

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Confirm Chennai-specific minimum gauge, burr, stress-relief, stack factor, die cost and prototype process

Sources: [I09]

RR Shramik / Ram Ratna Wires

Role: Indian winding-wire manufacturer

Component process: Copper/aluminium magnet wire

Location: Silvassa

Origin evidence: Indian wire manufacturing documented; raw copper/enamel origins undeclared

Capability: Round/rectangular and fine enamelled winding wire

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Sample diameter and thermal class, enamel bend/scrape/hipot performance, traceable batch metallurgy

Sources: [I10]

Shanthi Gears

Role: Indian gear/process manufacturer

Component process: Gear cutting/grinding, heat treatment, metrology

Location: Coimbatore region; confirm job site

Origin evidence: In-house industrial gear manufacturing processes published

Capability: Hobbing, grinding, forging, heat treatment and inspection

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Small-module thin gear/flexspline capability not established; prove runout, tooth quality, distortion and fatigue

Sources: [I11] [I46]

Sansera Engineering

Role: Indian precision machining candidate

Component process: Shafts, housings and machined parts

Location: India aerospace division; site assignment to confirm

Origin evidence: Official aerospace machining capability; no robotic-joint qualification claimed

Capability: Precision machined aerospace parts

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Prototype access, thin-wall chatter, concentricity, material traceability and commercial minimums

Sources: [I12]

Gleason Works India

Role: Local equipment manufacture plus imported equipment channel

Component process: Gear production tools, machines, metrology

Location: Bengaluru; India service centres

Origin evidence: Local production plus distribution from global technology centres stated

Capability: Gear manufacturing and measurement ecosystem

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Not a finished reducer supplier; establish equipment/process route and low-volume job-shop partner

Sources: [I13]

IREL / DAE ecosystem

Role: Indian upstream producer / strategic magnet capability

Component process: Rare-earth oxides, metal pilot, SmCo magnets

Location: Vizag; Bhopal; mineral/refining sites

Origin evidence: Oxide production and strategic SmCo operation officially stated

Capability: Separate oxide, metal mini-plant, recycling and SmCo activities

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Commercial access, grade, arc geometry, coating, MOQ and origin; capacity conflicting, do not book supply

Sources: [I14] [I38] [I39]

Delta Manufacturing

Role: Indian hard-ferrite manufacturing candidate

Component process: Ferrite permanent magnets

Location: Nashik, Maharashtra

Origin evidence: Integrated ferrite process documented; NdFeB origin not established

Capability: Hard-ferrite production for magnetic applications

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Check motor-grade arcs, magnetisation pattern, batch curves; ferrite is not drop-in NdFeB at same envelope

Sources: [I15] [I45]

Permanent Magnets Ltd / Quantum Magnetics

Role: Indian magnetic components; emerging NdFeB production claim

Component process: Magnetic assemblies, soft magnetics, NdFeB

Location: Mira Road, Thane corporate office; subsidiary production site to confirm

Origin evidence: Company timeline says NdFeB production in 2026 through Quantum; not independently factory-audited

Capability: Magnetic component and assembly capability

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Verify operating line, oxide/alloy origin, sintering versus finishing, grade certification, shipments and small arcs

Sources: [I16] [I47]

SKF India

Role: Indian bearing manufacturer plus distribution

Component process: Bearings, seals, lubrication

Location: Multiple India plants; order-specific site

Origin evidence: Domestic manufacturing confirmed; exact SKU may be imported

Capability: Bearing engineering and domestic distribution

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Do not assume thin-section/cross-roller Indian origin; qualify preload, friction, moment envelope and traceability

Sources: [I17]

Schaeffler India

Role: Indian bearing manufacturer plus group channel

Component process: Bearings and rolling elements

Location: Indian manufacturing footprint

Origin evidence: Domestic plants documented; exact product origin unresolved

Capability: Ball/roller-bearing ranges

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Joint-grade bearing size, moment load, preload, seals, precision and batch origin require confirmation

Sources: [I18]

Timken India

Role: Indian bearing manufacturer

Component process: Bearings / friction management

Location: Jamshedpur and Bharuch

Origin evidence: Indian production sites documented

Capability: Bearing manufacturing and support

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Compact joint fit, availability and origin by SKU; avoid projecting large-bearing capability to miniature joints

Sources: [I19]

Trelleborg Sealing Solutions India

Role: Indian seal/process manufacturer

Component process: PTFE/PEEK/elastomer seals; metal seal parts

Location: Bengaluru and Jigani

Origin evidence: Existing local manufacture documented

Capability: Polymer, elastomer and precision metal seal components

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Low-speed seal drag, dust/water target, grease compatibility, heat ageing and small-lot mould cost

Sources: [I20]

Klüber Lubrication India

Role: Indian lubricant manufacturer / tribology resource

Component process: Grease, specialty lubricants and testing

Location: Mysuru; Bengaluru office

Origin evidence: Existing plant confirmed; exact formulation country to declare

Capability: Specialty lubricant production, R&D and analytics

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Select grease against gear/bearing materials, low-temperature drag, bleed, seal compatibility and life tests

Sources: [I21]

Henkel India

Role: Indian adhesives manufacturer plus global portfolio

Component process: Structural adhesive, retaining compounds, thermal interface materials

Location: Kurkumbh near Pune

Origin evidence: Local adhesive manufacturing documented; individual thermal product origin unknown

Capability: Adhesives, sealants and surface treatment

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Qualify rotor bond, gap/thickness, cure, dielectric strength, thermal cycling; verify each SKU made-in country

Sources: [I22]

Renishaw India

Role: Indian encoder/metrology support channel

Component process: Position encoders and metrology

Location: Pune, Bengaluru, Chennai, Vadodara, Gurugram

Origin evidence: India offices confirmed; encoder SKU manufacture country not established

Capability: Encoder/application and measurement support

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Ring/readhead integration, air gap, contamination, absolute protocol, temperature drift and unit origin

Sources: [I23]

HBK / HBM India

Role: Indian measurement channel

Component process: Reference torque sensors and data acquisition

Location: India contact; laboratory/order site to confirm

Origin evidence: Sales/support route established; sensor country unconfirmed

Capability: Torque measurement product access

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Choose bench reference separately from embedded sensor; calibration range, uncertainty, overload and bandwidth

Sources: [I24]

Mayr India

Role: Indian brake/clutch manufacturer plus global portfolio

Component process: Power-loss holding brake / clutch

Location: Halol near Vadodara, Gujarat

Origin evidence: Production opened late 2024 per official March 2025 release

Capability: Local safety-brake/clutch manufacture

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Specific compact robotic brake origin, mass, coil heat, stopping versus static holding duty and cycle life

Sources: [I25]

Kaynes Technology

Role: Indian electronics design/manufacturing partner

Component process: PCBA, controller box build, harnesses, test fixtures

Location: Mysuru and other India facilities

Origin evidence: Domestic electronics manufacturing documented; semiconductors not presumed Indian

Capability: Prototype/design, PCBA, harness and end-of-line test development

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Confirm 10/100/1000-unit engagement, FOC expertise, power-loop layout, thermal/EMC validation and imported BOM

Sources: [I26]

Centum Electronics

Role: Indian electronics manufacturing partner

Component process: Controller PCBA and complex electronics

Location: Bengaluru

Origin evidence: Indian manufacturing confirmed; device origins vary

Capability: Complex assembly with electrical/functional inspection

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Robot servo firmware/design responsibility, power-stage test, reworkability and prototype commercial terms

Sources: [I27]

Mouser India

Role: Authorised component distribution / support

Component process: MOSFETs, gate drivers, MCUs, sensing, connectors

Location: Bengaluru India office; stock geography unresolved

Origin evidence: Channel is authorised; Indian office does not mean India-made parts or domestic stock

Capability: Traceable catalogue components

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: No minimum order value for normally stocked items; factory restrictions apply

Price: SKU/date/quantity dependent catalogue price; no frozen BOM quotation

Lead time: Stock and shipping origin must be checked per SKU

Qualification gap: Country per manufacturer lot, shipping origin, invoice entity, duties/GST, lifecycle and alternatives

Sources: [I28]

SASMOS

Role: Indian harness/assembly manufacturer

Component process: EWIS, wire bundles, electromechanical assemblies

Location: Bengaluru

Origin evidence: Local manufacturing evidence in official programme descriptions

Capability: Harness engineering, production and industrialisation

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Robot bend/twist cycles, connector locking, shielding, gauge temperature rise and prototype acceptance

Sources: [I29]

CMTI

Role: Indian public R&D / metrology facility

Component process: Dimensional and gear calibration

Location: Bengaluru; confirm service location

Origin evidence: Official institute services

Capability: Precision metrology and calibration

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Check accredited measurand/range/uncertainty and fixtures for actual parts; accreditation is scope-specific

Sources: [I30]

CPRI

Role: Indian public test facility

Component process: Motor electrical/thermal performance testing

Location: Bengaluru division; confirm booking

Origin evidence: Official motor laboratory; published induction-motor scope

Capability: Resistance, efficiency, thermal-rise and load tests

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Published 415 V induction scope is not acceptance of low-voltage BLDC robot joint; agree fixtures and accredited scope

Sources: [I31]

ELANTAS Beck India

Role: Indian insulation/compound manufacturer

Component process: Wire enamel, varnish, impregnation, resin systems

Location: Pune and Ankleshwar

Origin evidence: Local manufacturing and application labs documented

Capability: Enamels, varnishes, resins and compounds

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Whole insulation-system compatibility; cure process, thermal conductivity versus repairability and dielectric life

Sources: [I32]

Hindalco

Role: Indian aluminium material/extrusion manufacturer

Component process: Housings, heat spreader and structural stock

Location: India extrusion sites including Kuppam

Origin evidence: Indian extrusion capability documented

Capability: Alloy stock, extrusion and surface treatment

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: 6061/6082 temper certificates, thermal/mechanical properties, prototype machining yield and distortion

Sources: [I33] [I43]

Sushma Industries

Role: Indian sensor / test-system manufacturer

Component process: Strain-gauge torque sensors, motor test and calibration

Location: Peenya, Bengaluru

Origin evidence: Company says in-house strain-gauge sensor manufacture

Capability: OEM custom design, prototyping, validation and calibration

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Embedded annular sensor mass, cross-axis rejection, temperature drift, overload, bandwidth and uncertainty

Sources: [I34] [I44]

ARCI

Role: Indian R&D pilot / technology partner

Component process: NdFeB sintered-magnet process

Location: Hyderabad

Origin evidence: March 2026 government-confirmed pilot, not commodity production inventory

Capability: Strip-cast alloy to finished sintered magnets

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Prototype access, alloy/feedstock origin, coercivity, shape/coat processes and repeatable pilot batches

Sources: [I35]

Midwest Advanced Materials

Role: Funded emerging manufacturing / qualification candidate

Component process: Oxide-to-metal-to-rare-earth-magnet chain

Location: Hyderabad

Origin evidence: TDB-backed project; August 2026 scheme bidder; shipment status not verified

Capability: NFTDC-related molten-salt electrolysis and integrated magnet project

Prototype support: Candidate; confirm prototype engagement and engineering charge

Moq: Not published; quotation required

Price: No actuator-project quotation; request itemised price, tax and freight

Lead time: Not published; written delivery commitment required

Qualification gap: Verify commissioning and repeatable supplied samples; announced capacity not treated as available stock

Sources: [I36] [I37]

For the existing arm options, NMotion and Kikobot remain complete-joint qualification candidates; Mechtex is a motor/manufacturing development route; maxon India is a configured component and drive route. These roles are not drop-in equivalence claims. Imported parts are allowed for the Indian V0 design, with origin disclosure. [I01] [I03] [I05] [I06]

All supplier quality/capability statements are first-party claims or official disclosures, not independently audited performance.

All test prescriptions, selection candidates and qualification gaps are proposed engineering actions. Source IDs support the underlying capability/material context, not validation of the proposed actuator.

Prices, MOQ and lead times are deliberately unresolved except the stated distributor ordering policy. Obtain domestic tax, freight, duties, currency and origin breakdown in any later RFQ.

Innovation opportunities and priority experiments

Priorities below are engineering judgements based on benefit plausibility, evidence maturity, testability, development risk and fit with an Indian pilot supply chain. They are not numerical performance predictions. P1 means a strong first experiment; P2 needs additional integration work; P3 is a longer research bet. Compare at the same duty and include every auxiliary component.

Innovation assessment

Winding-to-housing thermal path

Limitation: Hot winding despite a modest case temperature.

Principle: Control impregnation, slot interface, stator fit and a repeatable conduction path to housing.

Evidence: Sandia demonstrates housing/heat-transfer improvements; maxon explains thermal torque limits.

Maturity: Established engineering; geometry-specific validation

Expected benefit: Lower hotspot temperature at a matched operating point, or a larger sustainable envelope.

Penalties: Potting complicates repair; interface tolerances and electrical insulation must be maintained.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Prototype machined housings and controlled impregnation before expensive topology changes.

Skills equipment: Thermal FEM; vacuum impregnation; thermocouples; resistance thermometry; dynamometer.

Experiment: A/B identical motor builds, same torque/speed/ambient/housing boundary; log input power and winding/housing temperatures.

Acceptance: Proposed gate, not a published product capability: Temperature reduction exceeds combined measurement uncertainty; equal or lower total mass; pass insulation and repeatability checks on at least three builds.

Priority: P1

Sources: [E01] [E15]

Structural heat spreading and controller separation

Limitation: Motor heats gearbox, encoder and inverter inside a small joint.

Principle: Use a deliberate conductive motor-to-link path while giving electronics a separate cooled mounting path.

Evidence: Kollmorgen identifies thermal coupling between motor, feedback, bearings and gearing.

Maturity: Established integration practice

Expected benefit: Protect the weakest component temperature limit and reduce controller-induced derating.

Penalties: More cable, housing area and connector volume; shared arm links can heat adjacent joints.

Indian supply-chain fit: Engineering assessment, supplier qualification required: CNC housing/link work is a practical localization entry point; qualify electronics separately.

Skills equipment: Thermal network modeling; PCB thermal design; environmental chamber; EMI tests.

Experiment: Compare co-located and separated power stages over the same multi-joint duty profile.

Acceptance: Proposed gate, not a published product capability: All monitored component limits met with declared margin; no increase in EMI faults or whole-arm mass beyond the frozen budget.

Priority: P1

Sources: [E02] [E11]

Active air or liquid cooling

Limitation: Passive rejection caps sustained output.

Principle: Transport heat to a larger exchanger with fan or pumped coolant.

Evidence: Sandia tested forced air and pumped water on a specific robotic-motor housing.

Maturity: Established cooling; robot-scale integration remains application-specific

Expected benefit: Potentially greater sustained torque; benefits must be measured at complete-system level.

Penalties: Pump/fan power, hoses, fluid, exchanger mass, leaks, vibration, noise and maintenance.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Begin with a removable external loop on a test stand; local fluid hardware alone does not qualify the actuator.

Skills equipment: Flow/pressure instrumentation; leak testing; thermal sensors; calorimetry; hose-flex tests.

Experiment: Compare passive, air and liquid cases at identical mechanical duty; include every cooling component and parasitic watt.

Acceptance: Proposed gate, not a published product capability: Improved sustainable torque per total installed mass or lower total energy for the mission, with no leak or cooling-fault damage.

Priority: P2

Sources: [E15]

Heat pipes and phase-change buffers

Limitation: Local hotspots or short transient peaks.

Principle: Move heat to a remote sink with a heat pipe, or temporarily absorb energy in phase-change material.

Evidence: Li et al. experimentally studied heat-pipe performance versus heat input, orientation, length and airflow, followed by a motor-cooling case study. Compact articulated-joint transfer is unvalidated; a phase-change buffer remains a separate proposed experiment.

Maturity: Research proposal for this joint

Expected benefit: Could move heat without a coolant pump or delay a peak-temperature rise.

Penalties: Orientation limits, contact resistance, added mass and finite storage; a phase-change buffer does not improve indefinite heat rejection by itself.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Prototype a removable thermal insert; imported heat pipes may be acceptable with declared origin.

Skills equipment: Thermal fixture; orientation jig; calorimetry; repeated melt/freeze or thermal-cycle tests.

Experiment: Hold heat input constant at all intended orientations; measure recharge/cooldown as well as operating time.

Acceptance: Proposed gate, not a published product capability: Improvement persists over repeated cycles and adverse orientations; thermal equilibrium separately demonstrated rather than replaced by longer warm-up.

Priority: P3

Sources: [E30] [E15]

Motor, winding and inverter co-design

Limitation: Copper/iron losses and bus limits conflict with torque and speed.

Principle: Choose winding turns, conductor geometry, switching frequency and power devices together for the duty envelope.

Evidence: maxon separates winding/iron losses; TI separates power-stage loss mechanisms.

Maturity: Established engineering

Expected benefit: Move loss away from the dominant operating region; reduce phase-current ripple or inverter heating.

Penalties: Lower resistance, higher inductance, faster switching and high speed are competing choices; EMI can worsen.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Local winding and PCB assembly are plausible; magnet wire, MOSFET and insulation origins need part-level disclosure.

Skills equipment: Electromagnetic FEA; winding trials; LCR meter; power analyzer; oscilloscope; EMI pre-compliance.

Experiment: Compare winding/inverter variants at the same shaft torque-speed points and bus limits.

Acceptance: Proposed gate, not a published product capability: Lower total electrical loss over the declared mission without losing peak torque, speed or insulation margin.

Priority: P1

Sources: [E01] [E11]

Low-loss magnetic circuit and segmented magnets

Limitation: Speed-dependent magnetic losses and rotor heating.

Principle: Evaluate thinner low-loss laminations, appropriate magnet segmentation and magnetic-circuit optimization.

Evidence: NRCan supports lamination loss control; DOE/ORNL evaluates PM eddy-current loss.

Maturity: Established principles; custom small-motor manufacturing risk

Expected benefit: Lower iron/rotor loss where those losses dominate.

Penalties: More tooling, burr/insulation control, magnet assembly and balance work; segmentation is not automatically beneficial at every speed.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Start with imported qualified lamination/magnet stock and local assembly; qualify stamping or laser edge damage.

Skills equipment: Electromagnetic/thermal FEA; core-loss measurement; precision stacking; magnet bonding and balancing.

Experiment: Measure no-load loss versus speed and loaded loss versus torque across matched designs.

Acceptance: Proposed gate, not a published product capability: Measured mission loss reduction beyond uncertainty, with no unacceptable ripple, demagnetization or assembly-yield penalty.

Priority: P2

Sources: [E17] [E25]

Magnet-lean or rare-earth-free motors

Limitation: Supply dependence on high-performance permanent magnets.

Principle: Compare reduced-rare-earth PM, ferrite-assisted reluctance or switched-reluctance architectures.

Evidence: DOE describes alternative motor families and noise/control trade-offs in traction R&D.

Maturity: Emerging for compact precision robot modules; established in other applications

Expected benefit: Potential sourcing resilience; no assumption of matching current mass or sensitivity.

Penalties: Torque ripple, acoustics, current demand, control complexity and packaging can offset material savings.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Evaluate as a separate research track after V0 performance is measured; do not delay baseline on unproven parity.

Skills equipment: Electromagnetic optimization; custom drive/control; acoustic and torque-ripple rig; materials characterization.

Experiment: Build matched-envelope demonstrators and measure low-speed smoothness, total loss, mass and sustained output.

Acceptance: Proposed gate, not a published product capability: Meet a predeclared minimum arm-joint envelope without relaxing torque sensitivity; report any mass or energy penalty openly.

Priority: P3

Sources: [E16]

Transmission preload, surfaces and lubrication

Limitation: Friction, heat, backlash and wear compete.

Principle: Optimize tooth/contact geometry, finish, preload and lubricant together; measure cold/hot reversals.

Evidence: NSK demonstrates preload/friction trade-offs; SKF separates bearing-loss sources; strain-wave wear affects stiffness.

Maturity: Established engineering with demanding process control

Expected benefit: Reduce loss and drift while retaining useful stiffness.

Penalties: Insufficient preload raises lost motion; excessive preload raises heat; lubricant changes may affect seals and life.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Prioritize metrology and heat-treatment/finishing capability over nominal gearbox ratio replication.

Skills equipment: Gear metrology; roughness and hardness inspection; preload fixtures; torque transducer; wear analysis.

Experiment: Map friction/backlash before and after staged cycling, using identical bearings and loads.

Acceptance: Proposed gate, not a published product capability: Meets frozen lost-motion and life-stage drift limits with lower mission loss; no damaging wear or lubricant incompatibility.

Priority: P1

Sources: [E08] [E14] [E27]

Output encoder plus calibrated torque sensing

Limitation: Motor angle/current can miss transmission error and output load.

Principle: Add output-side angle measurement; for sensitive contact use a calibrated elastic strain element or load cell.

Evidence: Secondary-encoder research demonstrates improved joint tracking; SEA research measures force via elastic deflection.

Maturity: Established sensing; packaging and calibration are product work

Expected benefit: Better observability of output motion and applied load.

Penalties: Added mass, wiring, strain compliance, temperature drift and calibration cost.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Local mechanical sensing flexure and calibration are feasible candidates; encoder/ADC origins remain explicit.

Skills equipment: Precision encoder fixture; traceable torque reference; strain instrumentation; thermal chamber; control expertise.

Experiment: Compare motor-only estimation against output sensing in bidirectional low-torque contact and thermal soak.

Acceptance: Proposed gate, not a published product capability: Three-sigma noise plus drift fits the task torque budget; full-range hysteresis and overload recovery documented.

Priority: P1

Sources: [E18] [E04]

Friction/cogging compensation and adaptive thermal derating

Limitation: Low-speed disturbances and conservative or unsafe current limits.

Principle: Map angle/velocity/temperature disturbances; identify thermal model; constrain current using measured temperature and uncertainty.

Evidence: Kollmorgen discusses cogging compensation; Kawaharazuka et al. demonstrated online thermal-model learning and temperature management in a musculoskeletal humanoid.

Maturity: Established controls; model validity is application-dependent

Expected benefit: Smoother low-speed torque and better use of verified thermal capacity.

Penalties: Model error, aging and unobserved hotspots can make compensation or derating unreliable.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Strong firmware/calibration opportunity with modest first-build tooling cost.

Skills equipment: Real-time firmware; current calibration; thermal model identification; torque fixture; robust control testing.

Experiment: Train on one duty set, validate on unseen profiles, temperature changes and reversed loads.

Acceptance: Proposed gate, not a published product capability: Validation error stays within declared torque/temperature margin; sensor loss causes bounded derating; no claimed force sensing from current alone.

Priority: P1

Sources: [E26] [E29]

Selective holding brake, counterbalance or clutch

Limitation: Gravity holding creates heat without useful output motion.

Principle: Reduce motor holding demand using a properly sequenced brake or passive gravity compensation; clutch only with controlled engagement.

Evidence: Kollmorgen documents holding-brake and suspended-load sequencing; counterbalance/clutch extension is a proposed mechanical option.

Maturity: Established components; application-specific mechanism

Expected benefit: Lower energized holding burden where the task allows a locked or balanced joint.

Penalties: Added mass, backlash, wear, release delay and engagement shock; a holding brake is not automatically an emergency dynamic brake.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Start at shoulder/elbow, measuring the entire support assembly and fail behavior.

Skills equipment: Load-safe fixture; brake timing control; torque sensing; spring/counterbalance design; cycle rig.

Experiment: Run move-hold-release cycles at maximum proposed gravity load and test power interruption.

Acceptance: Proposed gate, not a published product capability: No uncontrolled drop; releases only with verified torque support; net mission energy benefit and acceptable sensitivity after release.

Priority: P1

Sources: [E19]

Remote actuation and purposeful compliance

Limitation: Distal mass amplifies proximal loading; rigid transmission may complicate contact.

Principle: Move motor mass proximally using tendons or introduce a designed series spring where its bandwidth trade-off is acceptable.

Evidence: DLR documents antagonistic tendon mechanisms; Pratt/Williamson establishes SEA control trade-offs.

Maturity: Established research architectures; productization requires wear/calibration work

Expected benefit: Potentially lighter wrist/hand or improved contact compliance.

Penalties: Cable friction/stretch, spring travel, resonance, routing and maintenance; proximal system mass still counts.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Useful second-stage hand/wrist experiment after baseline joint requirements are stable.

Skills equipment: Cable routing/termination tooling; tension sensors; spring characterization; frequency-response measurement.

Experiment: Compare joint-local and remote versions with equal end-effector task accuracy and contact loads.

Acceptance: Proposed gate, not a published product capability: Lower distal inertia with task bandwidth retained; tension/hysteresis drift stays within a declared service interval.

Priority: P2

Sources: [E10] [E04]

Regenerative power architecture

Limitation: Braking motion can overvoltage the bus or waste recoverable energy.

Principle: Provide rated energy sink, battery charge acceptance or bus sharing; size resistor/clamp for worst-case simultaneous deceleration.

Evidence: ODrive documents an actual regeneration clamp and thermal monitoring.

Maturity: Established power-system engineering

Expected benefit: Predictable braking behavior; possible energy reuse when a suitable sink exists.

Penalties: Extra electronics/resistor heat and mass; battery charge limits and shared-bus faults require control.

Indian supply-chain fit: Engineering assessment, supplier qualification required: Design local bus distribution and protection around qualified components; no inference that every PSU can absorb energy.

Skills equipment: Power analyzer; programmable source/sink; oscilloscope; fault-injection fixture.

Experiment: Simultaneously decelerate representative inertias and lower gravity loads with worst-case sink condition.

Acceptance: Proposed gate, not a published product capability: Bus remains within every component rating; resistor and wiring stay within thermal ratings; faults produce controlled stop behavior.

Priority: P1

Sources: [E12]

Serviceable modules and end-of-line calibration

Limitation: Variable assembly quality, hidden origin and expensive repairs.

Principle: Use replaceable bearings/electronics where feasible, datum-controlled assembly and serialized calibration records.

Evidence: Commercial manuals expose version-specific interfaces; strain-wave wear evidence motivates repeat measurements. The proposed production method is engineering judgment.

Maturity: Established manufacturing discipline

Expected benefit: Better repeatability, traceability and lower rework uncertainty.

Penalties: Connectors and separable joints add volume; extra calibration time and fixtures affect cost.

Indian supply-chain fit: Engineering assessment, supplier qualification required: High-priority domestic value creation: housings, assembly, test, firmware and repair independent of eventual component localization.

Skills equipment: CMM/runout fixtures; torque tools; balancing; insulation tester; calibration database; end-of-line dynamometer.

Experiment: Build a pilot batch, disassemble/reassemble a sample, then compare mass, friction, encoder zero, thermal path and torque gain.

Acceptance: Proposed gate, not a published product capability: Every shipped unit has component-origin and calibration record; repaired units meet the same acceptance gates as new units.

Priority: P1

Sources: [E20] [E21] [E22] [E27]

The portfolio should be conditional. If winding temperature is limiting, improve the heat path before enlarging the motor. If gearbox friction sets the force floor, extra encoder bits alone will not solve sensitivity. If the duty consists mainly of long static holds, a brake or counterbalance may reduce heat more effectively than a cooling fan, but its mass, engagement shock and safety behaviour must be included. [E01] [E13] [E19]

Emerging magnet-lean or rare-earth-free motors merit exploration where supply-chain resilience is valuable. They should not be presented as a proven compact wrist replacement. Prototype at equal installed output, envelope, cooling and acoustic limits; compare controller complexity, torque ripple and efficiency over the mission, not a single favourable operating point. [E16] [E25]

Manufacturing economics: what volume changes

Illustrative planning model in INR, dated 25 October 2026. Every monetary input, yield, warranty reserve and volume factor is an editable assumption. None is a supplier quotation. These scenarios are sensitivity examples for a medium rotary module; they are not predictions of Indian market prices.

The compared boundary is a motor, reduction, output support, driver, encoder, housing and harness assembled as one joint. Brake, external cooling and tool flange customisation are excluded and must be added if needed. Delivered-to-bench parts budgets include inbound logistics/import costs; the separate delivery allowance covers outbound finished-unit packing and freight. There is no separate blanket customs rate. GST, sales margin, finance, facilities overhead and upstream magnet/steel factories are excluded. The result is engineering batch cost, not a selling price.

Three routes illustrate different control over the supply chain. Domestic assembly minimises initial process development but retains component dependence. Progressive localisation introduces local winding, housings, shafts and selected machining. Deeper production develops the motor and precision transmission process; it does not imply every material or semiconductor is Indian, and does not include building a rare-earth refinery or magnet-sintering plant.

Route / scope	Parts / assembly per start	Engineering / tooling / test infrastructure
A - Domestic assembly Import qualified motor/transmission/sensing as needed; assemble, integrate and test in India.	INR 34,000 / 2,500	INR 1,200,000 / 400,000 / 800,000
B - Progressive localisation Local windings, housing, shaft and selected machining; imported critical gears, magnets or sensors until qualified.	INR 28,000 / 3,500	INR 2,400,000 / 1,200,000 / 1,200,000
C - Deeper joint production Develop motor and precision transmission production in India; advanced sensors/materials may remain imported. No magnet refinery or sintering plant in budget.	INR 22,000 / 5,000	INR 5,000,000 / 4,000,000 / 2,500,000

Route	Final test / outbound per good unit	Warranty reserve	Maintenance allowance per good unit
A - Domestic assembly	INR 1,800 / 1,200	3% of recurring manufacturing cost	INR 1,500
B - Progressive localisation	INR 2,200 / 1,000	4% of recurring manufacturing cost	INR 1,500

Route	Final test / outbound per good unit	Warranty reserve	Maintenance allowance per good unit
C - Deeper joint production	INR 3,000 / 1,000	5% of recurring manufacturing cost	INR 1,500

Parts-volume factors are assumed to be 1.00, 0.92 and 0.82 for 10, 100 and 1,000 good units respectively, for all three routes. Assembly labour is not discounted. Yield assumptions are shown with each batch result. These inputs are not negotiated discounts or measured factory yields.

```
Starts = ceiling(good units / yield). Recurring cost = [(parts x volume factor + assembly labour) x starts + (final test + delivery) x good units] / good units.

Fully allocated cost per good unit = recurring cost x (1 + warranty reserve fraction) + planned maintenance allowance + (engineering + tooling + test infrastructure) / good units.
```

Maintenance is a separate illustrative allowance of INR 1,500 per delivered joint for one planned service within an assumed first 1,000 operating hours, covering labour and consumables. This planning horizon is not a validated service interval or lifetime. Warranty reserve covers unscheduled defect support; it is not applied to the maintenance allowance. Replace both with actual service policy, failure data and labour/parts quotations. No end-user downtime cost is modelled.

Scrapped starts consume the full assumed parts and assembly budget; no salvage credit is included. Starts are a deterministic planning estimate, not a probability-based guarantee of batch yield. Final test and delivery are charged per good unit in this simplified model. It omits rework loops and test cost for failed units, so those should be added before investment decisions. Infrastructure is allocated fully to each isolated batch scenario; do not sum all three batch examples or interpret this as accounting depreciation.

Route / good units	Yield / starts	Recurring + warranty + maintenance per good unit	Fully allocated per good unit
A - Domestic assembly / 10	90% / 12	INR 49,704	INR 289,704
A - Domestic assembly / 100	94% / 107	INR 41,819	INR 65,819
A - Domestic assembly / 1000	96% / 1042	INR 37,196	INR 39,596
B - Progressive localisation / 10	82% / 13	INR 47,416	INR 527,416
B - Progressive localisation / 100	90% / 112	INR 38,910	INR 86,910
B - Progressive localisation / 1000	94% / 1064	INR 34,108	INR 38,908
C - Deeper joint production / 10	70% / 15	INR 48,225	INR 1,198,225

Route / good units	Yield / starts	Recurring + warranty + maintenance per good unit	Fully allocated per good unit
C - Deeper joint production / 100	82% / 122	INR 38,032	INR 153,032
C - Deeper joint production / 1000	91% / 1099	INR 32,287	INR 43,787

The workbook separates engineering, tooling and test infrastructure inputs and shows starts, yield, recurring cost, reserve and fully allocated cost. Volume factors apply only to parts. A larger batch does not automatically improve yield or produce a discount: both require evidence. The example deliberately shows how local parts savings can be outweighed by development cost and process loss at early volumes.

Replace assumptions with quotations for the same frozen drawing, tolerance, coating, inspection, delivery quantity and origin declaration. Ask for one-off fixture and tool costs separately. Record replacement parts, calibration time, field service and supplier change control. For maintenance, budget labour and downtime as well as wear parts; the illustrative warranty reserve is not a reliability calculation.

Qualification: from a promising joint to evidence

Every test begins with a calibrated measurement chain and a frozen hardware/firmware revision. Record uncertainty and synchronize torque, speed, position, current, bus voltage and temperatures. The acceptance criteria below are proposals; freeze them before testing and preserve failures as well as passes.

Test protocols and acceptance gates

Mass, envelope and support boundary

Setup: Weigh the exact joint with gearbox, encoder, driver, bearings, connectors and brake; separately weigh external supports/cooling.

Measurement: Mass, envelope, connector swept volume, centre of mass and mounting datums; preserve revision/serial/photo record.

Acceptance: Proposed: Comparable configuration list complete; measurement uncertainty recorded; no bare motor compared with complete joint.

Sources: [E06] [E12] [E24]

Torque-speed and electrical map

Setup: Calibrated dynamometer at each intended DC bus voltage, cold and hot; signed torque/speed in both directions.

Measurement: Output torque, speed, phase RMS/peak current, DC bus current, electrical input, mechanical output and temperature.

Acceptance: Proposed: Meet the frozen envelope; no peak claim without duration and recovery; identify calibration convention for torque constant and phase current.

Sources: [E01] [E11] [E21]

Zero-speed holding and thermal equilibrium

Setup: Locked-output reaction torque fixture; sweep rotor electrical angles; provisional ambient points 25 deg C and 35 deg C, plus eventual worst-case product ambient.

Measurement: Winding estimate/sensor, case, inverter, encoder and bearing temperatures; current and drift.

Acceptance: Proposed near-steady screen: less than 1 C total drift over the final 30 minutes at all monitored winding, housing and driver nodes. This does not prove equilibrium: fit a thermal model, allow sufficient settling and require predicted remaining rise below a declared margin, with hotspot and component-limit checks. Demonstrate 8-hour holding only at a stated torque if required; this is not service-life qualification.

Sources: [E01] [E02] [E28]

Dynamic duty and cooling interruption

Setup: Application trajectories including acceleration, contact and hold; coolants/fans logged; controlled cooling-fault experiment.

Measurement: RMS/peak torque, temperatures, average power, fan/pump power and thermal recovery.

Acceptance: Proposed: No temperature exceeds qualified limit minus uncertainty margin; derating preserves controllability; mission completes under stated duty.

Sources: [E15] [E01]

Precision, cogging, friction and torque sensitivity

Setup: Traceable output encoder and torque reference; low-speed reversals at multiple temperatures and load directions.

Measurement: Unpowered cogging; powered ripple; breakaway torque; lost motion; hysteresis; repeatability; minimum controllable torque including noise/drift.

Acceptance: Proposed: Meet task-specific error and sensitivity limits before setting vendor-equivalence claims; report encoder resolution separately from actual accuracy.

Sources: [E13] [E26] [E18]

Stiffness, bearings and shock

Setup: Supported reaction fixture with combined radial/axial/moment loads; instrumented controlled impact below established structural limits.

Measurement: Torque-angle slope, permanent set, runout, preload change, vibration and post-test precision.

Acceptance: Proposed: No permanent deformation or damage; bearing loads within exact assembly rating; retained performance checked after impact.

Sources: [E06] [E07] [E03]

Control dynamics and communication

Setup: Timestamped command/feedback; frequency sweep under representative inertia; contact fixture and injected packet delay/loss.

Measurement: Bandwidth, latency distribution, jitter, settling, overshoot, stability and watchdog response.

Acceptance: Proposed: Meet frozen task bandwidth and bounded fault response; SDK/ROS support alone does not pass real-time acceptance.

Sources: [E03] [E04] [E18]

Regeneration, brake and power-loss behavior

Setup: Worst-case gravity descent and simultaneous braking; test PSU/battery sink limits, brake timing and power cuts with restrained load.

Measurement: DC voltage transient, recovered/dissipated energy, resistor temperature, stopping distance and load drift.

Acceptance: Proposed: No bus overvoltage or uncontrolled load motion; holding and dynamic braking are separately qualified.

Sources: [E12] [E19]

Endurance and service interval

Setup: Multiple units running a declared load/speed/temperature spectrum; staged inspections and recorded lubrication/maintenance.

Measurement: Hours and cycles, failure modes, torque/stiffness/friction drift, seal and bearing condition, insulation and encoder health.

Acceptance: Proposed: Pass the declared demonstration duration and drift limits; publish sample count and censoring. Do not translate a short zero-failure test into a guaranteed service life.

Sources: [E27] [E14]

Production and repair repeatability

Setup: Pilot lot with serialized materials/process history; independent reassembly and replacement of wear/electronic parts.

Measurement: Dimensional yield, end-of-line torque calibration, winding resistance, insulation, thermal resistance proxy and rework hours.

Acceptance: Proposed: All units satisfy same frozen limits; repair restores calibration and documented origin; reject selection bias from reporting only best prototype.

Sources: [E20] [E21] [E22]

A useful development fixture needs a reaction torque reference, speed/position measurement, controllable load, safe load restraint, temperature instrumentation and power measurement on the DC side. Add phase-current measurement when diagnosing copper and inverter loss. Steady holding tests need a torque fixture that does not require movement. Use resistance thermometry or embedded winding sensing to supplement surface temperatures. [E01] [E03] [I24]

Calibration and data practice: retain raw time-series files, units, sensor ranges, calibration certificates, sample timing, ambient and mounting photos, script version and analysis notebook. Compare repeat builds and report spread. An uncontrolled fan, changed grease fill or different mounting plate invalidates a thermal A/B comparison unless it is explicitly the variable under test.

Endurance sequence: measure baseline friction/lost motion and thermal rise; run a stated load/temperature spectrum; periodically repeat baseline measurements; inspect wear and lubrication at planned intervals. Report censored tests and failures. Establishing life needs enough samples, a failure definition and a statistical model; 100 hours of prototype operation establishes only that test exposure, not a service-life guarantee. [E27] [E14]

A staged development and investment decision

Stage	Work package	Decision evidence
0 - Boundaries	Choose wrist and medium-joint envelope; create mass ledger, origin register and mission/load histogram.	Every comparison uses installed mass and the same thermal boundary; requirements remain traceable.
1 - Characterise	Instrument benchmark and candidate Indian joints; hold, torque-speed, friction, drift and bus tests.	Raw logs, calibration and uncertainty; no unresolved overheating or power-loss behaviour.
2 - V0 Indian joint	Develop housing, winding/assembly, sensing integration and firmware around qualified bought-in parts.	Matches declared mass/envelope and selected mission; documented imported components and repair process.
3 - Controlled improvements	A/B experiments on thermal path, sensing, transmission and counterbalance; one variable at a time.	Benefit measured including auxiliary mass, power, cost and reliability penalties.
4 - Pilot production	Freeze process drawings and inspection; build a serialised pilot lot with supplier traceability.	Yield, variation, rework and endurance evidence justify the next batch; service parts available.
5 - Arm integration	Validate links, bearings, cables, tool changer, force sensing and task software on the actual arm.	Payload/workspace/mission limits measured; specialist laboratory and soldering tasks individually validated.

A small parallel-gripper tool should precede a dexterous hand. The common interface needs a mechanically indexed datum, positive retention, defined electrical power and communications, tool identity and mass/centre-of-mass metadata. Repeatable attachment does not itself prove tool-position accuracy; check deflection and calibration after repeated changes. A wrist force/torque sensor, compliant fixture or remote-centre compliance may matter more for assembly than increasing peak motor torque.

For soldering, biological work and sensitive electronics, actuator development is only one layer. Task-specific fixturing, sensing, thermal isolation, contamination control, cable management and process verification need independent acceptance. Avoid converting a successful general pick-and-place demonstration into a claim of reliable biological or electrical work.

Recommended investment order: fund measurements and fixtures first; then one repairable V0 module and the most promising thermal-path change; then repeatability and endurance; finally production tooling. Defer expensive topology changes until measured loss and failure budgets show that conventional improvements cannot meet the target. The white paper supplies a decision framework, not a guarantee that a specific unbuilt actuator will succeed.

Sources and claim locators

Open the title or reference ID, then locate the section listed below. URLs are retained in the supporting workbook. A webpage without a publication date is not assigned an invented date.

E01 / Continuous operation range of BLDC (EC) Motors

maxon Support. Source date/revision: Updated 2024-08-29. Accessed 2026-10-25.

Locate: Technical Background & Solution; Border continuous operation range

Supports: Manufacturer explanation: winding Joule losses, speed-dependent iron losses and heat rejection constrain continuous torque; its example winding limit is not universal.

E02 / Demystifying the Use of Frameless Motors in Robotics

Kollmorgen. Source date/revision: 2019-02-14. Accessed 2026-10-25.

Locate: Thermal considerations and Applying and Validating Your Solution

Supports: Manufacturer engineering guidance on frameless installation, motor/gear/encoder thermal interactions and housing/cooling trade-offs.

E03 / Proprioceptive Actuator Design in the MIT Cheetah: Impact Mitigation and High-Bandwidth Physical Interaction for Dynamic Legged Robots

Wensing et al.; IEEE Transactions on Robotics; MIT author proof. Source date/revision: 2017; DOI 10.1109/TRO.2016.2640183. Accessed 2026-10-25.

Locate: Abstract, actuator-design analysis and experimental sections; 14-page author proof

Supports: Research evidence for low-ratio high-torque motors, reflected inertia, backdrivability and impact/force-control trade-offs. Findings concern the studied Cheetah, not every QDD joint.

E04 / Series Elastic Actuators

Pratt and Williamson; IROS 1995; author-paper copy hosted by CMU. Source date/revision: 1995; DOI 10.1109/IROS.1995.525827. Accessed 2026-10-25.

Locate: Architecture, control and experimental results; 8-page paper

Supports: Original research on intentional series elasticity for force/impedance control and the associated bandwidth/deflection trade-offs.

E05 / Harmonic Drive Strain Wave Gear Technology

Harmonic Drive LLC. Source date/revision: Undated live technical page. Accessed 2026-10-25.

Locate: Strain Wave Gear Principle; The Components

Supports: Manufacturer description of wave generator, flexspline and circular spline, compact high reduction and zero-backlash claim.

E06 / SHG-2UH-LW Gear Unit

Harmonic Drive LLC. Source date/revision: Undated live product table. Accessed 2026-10-25.

Locate: Compare Products columns: rated torque L10, repeated/momentary peak, backdriving torque, K1/K2/K3 stiffness

Supports: A practical example showing zero-backlash products still have finite stiffness, backdriving torque, separate load ratings and specified mass boundaries.

E07 / Cycloidal Gear Technology

Nabtesco Motion Control. Source date/revision: Undated live engineering page. Accessed 2026-10-25.

Locate: Nabtesco Cycloidal Gear Technology; Operating Principle; two-stage gearbox features

Supports: Manufacturer description of two-stage RV architecture, rolling contact, crank support and internal angular bearings; comparative shock and precision claims are vendor claims.

E08 / No.2613 MT-Frix Low-Friction Ball Screws for Machine Tools

NSK. Source date/revision: 2026. Accessed 2026-10-25.

Locate: Introduction and Features of MT-Frix

Supports: Manufacturer technical review: rotary-linear conversion; preload increases rigidity but also dynamic preload torque; friction design affects heat.

E09 / RV / HRV Planetary Roller Screws

Rollvis SA. Source date/revision: Undated live product page. Accessed 2026-10-25.

Locate: Description and Features

Supports: Manufacturer description of threaded orbiting rollers and precision-ground nut/roller/shaft construction. Relative performance claims are not independent benchmarking.

E10 / Mechatronics of David

German Aerospace Center (DLR). Source date/revision: Undated page; cited underlying work 2008-2011. Accessed 2026-10-25.

Locate: Mechanics; Variable Stiffness Actuators; Electronics

Supports: First-party platform disclosure: antagonistic tendon springs in the hand, distinct wrist/upper-arm mechanisms, spring deflection sensing and motor electronics.

E11 / Motor Driver Slew Rate Considerations for 48V Automotive Systems

Texas Instruments; Menon and Ferri. Source date/revision: SDAA218; date not established from extracted page. Accessed 2026-10-25.

Locate: Section 2: Power Loss and Thermals in Motor Driver Systems

Supports: Manufacturer application note on inverter conduction/switching loss and slew-rate considerations. Automotive numerical examples are not transferred to robot joints.

E12 / ODrive Regen Clamp Datasheet

ODrive Robotics. Source date/revision: Documentation 0.6.12; live revision. Accessed 2026-10-25.

Locate: Usage & Wiring; Overtemperature Protection; Brake Resistor Selection

Supports: Actual regenerative-energy management component: excess bus energy diverted to a resistor; resistor temperature monitoring; mass differs with terminals/heat spreader.

E13 / Meaning and impact of Cogging torque and Ripple torque

maxon Support. Source date/revision: Live support page; exact update date not captured. Accessed 2026-10-25.

Locate: Cogging and ripple explanations

Supports: Manufacturer distinction between position-dependent cogging and energized torque ripple; neither is an encoder-resolution metric.

E14 / Using a friction model as an engineering tool

SKF Evolution. Source date/revision: 2006. Accessed 2026-10-25.

Locate: SKF bearing-friction model

Supports: Manufacturer engineering model separates rolling, sliding, seal and lubricant-drag losses.

E15 / Improving robotic actuator torque density and efficiency through enhanced heat transfer

Sandia National Laboratories; ASME DSCC2016. Source date/revision: 2016; SAND2016-10189C; DOI 10.1115/DSCC2016-9738. Accessed 2026-10-25.

Locate: Abstract and Additional Metadata

Supports: Institutional research abstract reports a specific motor housing experiment with passive, forced-air and pumped-water cooling. Its percentages are deliberately not generalized here.

E16 / Electric Motors Research and Development

US Department of Energy. Source date/revision: Undated current page; historical traction-motor programme context. Accessed 2026-10-25.

Locate: Comparison of IPM, induction and switched-reluctance motors

Supports: Government R&D overview supports rare-earth-reduction motivation and reluctance noise/control trade-offs, not robotic torque-density parity.

E17 / Electric Motors: Energy Efficiency Reference Guide

Natural Resources Canada. Source date/revision: Live guide; exact edition date not established. Accessed 2026-10-25.

Locate: Loss mechanisms and energy-efficient motor design

Supports: Government engineering guide supports thinner laminations reducing eddy-current loss and separation of magnetic/electrical/mechanical losses.

E18 / Flatness Based Control of an Industrial Robot Joint Using Secondary Encoders

Weigand, Gafur and Ruskowski; Robotics and Computer-Integrated Manufacturing 68, 102039. Source date/revision: 2021-01-13 preprint; journal DOI 10.1016/j.rcim.2020.102039. Accessed 2026-10-25.

Locate: Abstract; model and experimental validation on KUKA Quantec KR300 Ultra SE

Supports: Experimental primary paper on secondary-encoder feedback and flexible-joint modeling; no universal accuracy multiplier inferred.

E19 / Holding Brake

Kollmorgen motor installation documentation. Source date/revision: Undated live documentation. Accessed 2026-10-25.

Locate: Holding brake operation and suspended-load warning

Supports: Manufacturer guidance separates holding-brake use, motor torque sequencing and gravity-load behavior.

E20 / Technical Support and Download

CubeMars. Source date/revision: Page firmware notice 2026-01-19; manuals separately versioned. Accessed 2026-10-25.

Locate: AK Module Product Manual v3.0.1; driver manual; CAN/UART demo; CAD/catalogue links

Supports: First-party evidence for commercial integrated-module documentation and firmware ecosystem; product and hardware revisions must be matched.

E21 / RobStride Product Information

RobStride official repository. Source date/revision: Live README identifies product specification 2026-07-13. Accessed 2026-10-25.

Locate: Product Selection; Common Specifications; User Manuals

Supports: First-party integrated QDD family and downloadable model manuals; rated torque requires specified aluminum heat sinks.

E22 / DM-J4310-2EC V1.2 Geared Motor User Manual V1.4

DAMIAO / dmBots official repository. Source date/revision: 2026-09-14; hardware V1.2; manual V1.4. Accessed 2026-10-25.

Locate: pp.7-10 specifications/protection/drawings; pp.11-17 control modes

Supports: Pinned first-party manual already captured in local benchmark manifest; reference for revision discipline and integrated geared motor, not a new independent endurance measurement.

E23 / Integrated Smart Actuator

Moog. Source date/revision: Undated brochure; retrieved live. Accessed 2026-10-25.

Locate: Overview and integrated components

Supports: First-party hydraulic robotic actuator integrates servo valve, control, sensing and fieldbus; comparison must include hydraulic supply infrastructure.

E24 / GPX 16 Planetary Gearhead

maxon. Source date/revision: Catalogue page 381; exact edition not stated. Accessed 2026-10-25.

Locate: Technical data, stage count, efficiency, output bearing and drawings

Supports: Manufacturer stage-specific gearbox data; illustrates efficiency and packaging dependence on configuration, not a complete-joint specification.

E25 / Non-Heavy Rare-Earth High-Speed Motors

ORNL / US DOE Annual Merit Review. Source date/revision: 2020. Accessed 2026-10-25.

Locate: PM Eddy Current Loss Calculation and project approach

Supports: Primary R&D presentation examining PM eddy-current loss and reduced-heavy-rare-earth designs; traction application, not proof of a small robot actuator.

E26 / Cogging and Torque Ripple Questions

Kollmorgen. Source date/revision: 2013; live article. Accessed 2026-10-25.

Locate: Mapping cogging and compensating rotor-position-dependent forces

Supports: Manufacturer engineering guidance supporting measured compensation maps; not elimination of every low-speed disturbance.

E27 / A Preliminary Experimental Study on the Effects of Wear on the Torsional Stiffness of Strain Wave Gears

Actuators 11(11), 305; primary experimental research. Source date/revision: 2022. Accessed 2026-10-25.

Locate: Experimental method and torsional stiffness/hysteresis results

Supports: Experimental study connects wear and measured strain-wave stiffness; specific specimens do not establish general lifetime hours.

E28 / Thermal resistance

Nidec Corporation. Source date/revision: Undated live technical glossary. Accessed 2026-10-25.

Locate: Thermal equilibrium equations winding-housing and housing-ambient

Supports: Primary manufacturer explanation of thermal resistance and steady-state temperature rise.

E29 / Estimation and Control of Motor Core Temperature with Online Learning of Thermal Model Parameters: Application to Musculoskeletal Humanoids

Kawaharazuka et al.; IEEE Robotics and Automation Letters. Source date/revision: arXiv upload 2024-07-10; underlying journal DOI 10.1109/LRA.2020.2990889. Accessed 2026-10-25.

Locate: Abstract, thermal-model adaptation and humanoid experiment

Supports: Research demonstrates online thermal parameter estimation and temperature management on a musculoskeletal humanoid; upload date is not assumed to be original publication date.

E30 / Experimental study on heat pipe performance and a case study on electric motor cooling

Li et al.; Case Studies in Thermal Engineering 72, 106419. Source date/revision: 2025-08; DOI 10.1016/j.csite.2025.106419. Accessed 2026-10-25.

Locate: Abstract: heating power, inclination, length and airflow study

Supports: Primary experimental paper supports heat-pipe sensitivity to orientation and boundary conditions; not a small-joint product qualification.

R01 / Unitree H1 official introduction

Unitree. Source date/revision: 2023 model introduction; webpage undated. Accessed 2026-10-25.

Locate: Specifications items 4-9

Supports: Original H1 joint peak/limit torques: knee 360, hip 220, ankle 45, arm 75 Nm; not continuous ratings.

R02 / Unitree H1 / H1-2 technical parameters

Unitree. Source date/revision: Undated live product page. Accessed 2026-10-25.

Locate: H1-2 highlights; H1/H1-2 parameter table; M107 joint motor

Supports: H1-2 arm peak 120 Nm and leg peak 360 Nm; seven arm axes; six leg axes; cross-roller output bearings; M107 shown without full joint SKU mapping.

R03 / Unitree G1 official introduction

Unitree. Source date/revision: Model launched 2024-05-13; page undated. Accessed 2026-10-25.

Locate: Specifications items 5 and 10-13

Supports: Knee maximum 120 Nm; dual encoders, hollow joint routing and local air cooling. Exact joint variants not specified.

R04 / Unitree Go2 official product comparison

Unitree. Source date/revision: Undated live product page. Accessed 2026-10-25.

Locate: Motor performance enhanced; Knee Joint Parameters; footnote 1

Supports: Selected Go2 configurations publish approximate 45 Nm maximum joint torque and joint heat-pipe cooling; not a continuous rating.

R05 / An Electric New Era for Atlas

Boston Dynamics. Source date/revision: 2024 electric Atlas announcement. Accessed 2026-10-25.

Locate: Opening paragraphs

Supports: Hydraulic predecessor retired; new Atlas fully electric. No joint motor or reducer supplier disclosed here.

R06 / Atlas industrial product specifications

Boston Dynamics. Source date/revision: 2026 product version; page undated. Accessed 2026-10-25.

Locate: We're engineering a better robot; Your Journey to Atlas

Supports: 56 DoF,90 kg,50 kg instantaneous versus 30 kg sustained payload; IP67 and -20-40 deg C are whole-robot claims; Hyundai field testing described.

R07 / Spot SDK 5.2 About Spot

Boston Dynamics. Source date/revision: SDK5.2.0; page undated. Accessed 2026-10-25.

Locate: Hips and joints

Supports: Two hip actuators and one knee actuator per leg;12 leg DoF. No actuator mass, lifetime or SKU disclosed.

R08 / Spot SDK 5.2 joint transmission supplemental data

Boston Dynamics. Source date/revision: SDK5.2.0; page undated. Accessed 2026-10-25.

Locate: Joint Transmission Details / Knee Joints / Coupled SH1/EL0 Joints

Supports: Manufacturer prose identifies ball-screw/push-rod knee and coupled shoulder/elbow drives. Simulation-oriented torque table excluded from datasheet ratings.

R09 / Spot SDK 5.2 arm and gripper specifications

Boston Dynamics. Source date/revision: SDK5.2.0; page undated. Accessed 2026-10-25.

Locate: Arm specifications; asterisk at 22 deg C

Supports: Arm mass 8 kg including gripper; continuous 5 kg lift at 0.5 m at 22 deg C; six axes plus gripper. These are assembly-level specifications.

R10 / Tesla Robotics Mechanical Engineer, Actuator Integration, Optimus

Tesla. Source date/revision: Undated current recruitment disclosure. Accessed 2026-10-25.

Locate: What to Expect; What You'll Do

Supports: Tesla states in-house rotary and linear electromechanical actuator development. Recruitment evidence does not identify installed hardware on a particular revision.

R11 / Introducing Figure 03

Figure. Source date/revision: 2025-10-09. Accessed 2026-10-25.

Locate: Designed for Helix; mass manufacturing discussion

Supports: Figure 03 actuators designed in-house; tactile hand and sensory redesign; no joint SKU, reduction ratio or continuous thermal envelope.

R12 / Figure 02 production at BMW

Figure. Source date/revision: 2025-11-19. Accessed 2026-10-25.

Locate: BMW Deployment Highlights; Hardware Reliability and Learnings

Supports: Manufacturer reports 1250+operational hours; forearm packaging/thermal constraints and electronics were failure lessons; Figure 03 removes distribution board/dynamic cabling.

R13 / Ramping Figure 03 Production

Figure. Source date/revision: 2026-04-29. Accessed 2026-10-25.

Locate: Ramping Robot Production

Supports: Manufacturer reports 9000+actuators across more than 10 SKUs and robot end-of-line first-pass yield over 80%; not independent audit or lifetime certification.

R14 / Apptronik collaborates with NVIDIA

Apptronik. Source date/revision: 2024 announcement; exact date not retrieved. Accessed 2026-10-25.

Locate: Apollo design scalability bullets

Supports: Apollo launchedAugust 2023; linear actuation and force-control architecture described. Does not disclose all joints or mechanism dimensions.

R15 / Apollo 2 official platform

Apptronik. Source date/revision: Undated live Apollo2 page. Accessed 2026-10-25.

Locate: Engineered for Real-World Strength; Built for More Uptime

Supports: Proprietary actuator platform;90%+efficiency and 7 x 22 operation are design claims without duty-specific actuator test data.

R16 / Jonathan Hurst answers questions about Digit 5

Agility Robotics. Source date/revision: 2026-10-22 Q&A; published approximately2026-10-23. Accessed 2026-10-25.

Locate: Actuator/QDD answer; Digit 3 versus 4 leaf-spring answer; Digit 4 versus 5 changes

Supports: Digit 5 planned proprietary cycloidal reductions and current-based torque control; small ankle to larger knee staged impact handling; Digit 3 springs versus Digit 4 rigid-link change described.

R17 / Agility prepares Digit 5 for commercial scale

Agility Robotics. Source date/revision: 2026-10-22. Accessed 2026-10-25.

Locate: Final early-access paragraph

Supports: Digit 5 early access expectedH1 2027. Therefore 2026 engineering statements are announced development, not demonstrated deployment specifications.

R18 / Fourier GR-2 product page

Fourier. Source date/revision: Undated GR-2 webpage. Accessed 2026-10-25.

Locate: Powering Dynamic Mobility; FSA 2.0 Actuator

Supports: Seven FSA variants;53 joints; dual encoder claim and >380 Nm family maximum. No complete per-joint SKU map.

R19 / Fourier GR-2 English single-page brochure

Fourier. Source date/revision: 2025-05-15 file path; document revision unspecified. Accessed 2026-10-25.

Locate: FSA 2.0 Actuator callout

Supports: This brochure instead claims >436 Nm; must not silently reconcile with >380 Nm webpage or assign either value to all joints.

R20 / Introducing NEO Gamma

1X Technologies. Source date/revision: 2025-02-21. Accessed 2026-10-25.

Locate: Design / Soft Covers; Hardware

Supports: NEO Gamma tendon-drive joint actuation. Hardware reliability improvement is relative claim, without absolute lifetime.

R21 / NEO's Hands: An API to the Physical World

1X Technologies. Source date/revision: 2026-07-09. Accessed 2026-10-25.

Locate: The joints are sensors; Fast enough to catch it; The hardware behind the instrument

Supports: Forearm motors with low-ratio tendon transmission;22 finger/palmDoF plus 3 wristDoF; approximately 5:1-15:1; wrist testing beyond 2 million high-load cycles claimed without full profile.

R22 / ANYbotics/maxon strategic partnership

ANYbotics. Source date/revision: 2020-09-15. Accessed 2026-10-25.

Locate: Opening and partnership description

Supports: maxon to handle future development and production of ANYmal actuators. Does not identify exact motor SKU for any current generation.

R23 / ANYdrive in ANYmal industrial-inspection overview

HazardEx / OEM-hosted partner article. Source date/revision: 2018-12 issue, regardless of later upload date. Accessed 2026-10-25.

Locate: ANYdrive: A powerful, torque-controllable robot joint

Supports: ANYbotics-hosted article describes compact sealed series-elastic ANYdrive; three units per leg with joint torque, position and impedance regulation.

R24 / ANYmal C: The Next Step in Robotic Industrial Inspection

ANYbotics. Source date/revision: 2019-08-20. Accessed 2026-10-25.

Locate: ANYmal C: The Next Step

Supports: New torque-controlled actuators intended for over 1 million cycles; load profile not published;2 h battery runtime and IP67 relate to robot.

R25 / Design of a high torque density modular actuator for dynamic robots

MIT DSpace / thesis author. Source date/revision: 2020-05 thesis. Accessed 2026-10-25.

Locate: Abstract; MIT thesis handle 1721.1/127165

Supports: MIT Mini Cheetah uses same replaceable modular actuators at all joints: hobby BLDC motor, internal planetary gearbox, controller and position sensor; thesis distinguishes next-generation redesign.

R26 / OpenArm 2.0 Motor

enactic / OpenArm. Source date/revision: Version2.0; page undated. Accessed 2026-10-25.

Locate: Motor Location paragraph and annotated diagram

Supports: DAMIAO 8009 P and 43 series; cross-roller motors at one-sided supports;4340 series explicitly not QDD. Diagram labels 8009 P,4340 P,4340,4310.

R27 / Spot installed product and service context

Boston Dynamics. Source date/revision: Undated current product page. Accessed 2026-10-25.

Locate: Reliable; Spot Specifications

Supports: Manufacturer reports >1500 robots with customers; this supports deployed-system maturity, not a specific actuator lifetime guarantee.

I01 / Smart Actuators

NMotion. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Smart Actuators overview and feature list; Request for Quotation

Supports: Integrated BLDC, harmonic transmission, controller, dual encoders and CAN; SDK and quotation route.

I02 / Get in Touch

NMotion. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Get in Touch: address and Nawe Robotics footer

Supports: Nawe Robotics sub-brand; NIT Calicut Technology Business Incubator address in Kozhikode.

I03 / KH Series

Kikobot. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: KH Series: Made in India; specifications; footer address

Supports: Made in India claim; integrated harmonic joints, brake options; Pune address.

I04 / Support and Delivery

Kikobot. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: From order to operation; Maintenance & Repairs; Spare Parts

Supports: Delivery timeline confirmed at order; India support, diagnostics, repairs and spares.

I05 / Manufacturing Facilities

Mechtex. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Our Manufacturing Facilities: CNC/VMC, winding and test-equipment descriptions

Supports: Navi Mumbai motor manufacturing; CNC/VMC, winding, lamination and assembly, torque and dimensional testing.

I06 / Shopping made easier

maxon. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Shopping made easier: Combination; Configuring drives; Contact

Supports: Bengaluru India office; modular motor, gearhead, encoder and controller combinations. No India manufacture statement.

I07 / Motors

Hical Technologies. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Motors: design/manufacture paragraph; Motor Design and Development Facilities

Supports: Motor design/development/manufacturing for high-reliability applications; Bangalore test ecosystem.

I08 / Rourkela Steel Plant

SAIL. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Electrical Steel Plant under facilities/product portfolio

Supports: Silicon Steel Mill produces cold-rolled non-oriented electrical coils at Rourkela.

I09 / Precision Electrical Steel Laminations

Tempel. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Precision Stamped Laminations; Value Added Capabilities; Chennai manufacturing-location entry

Supports: Precision lamination stamping, prototyping, assembly and material sourcing; Chennai manufacturing location. Global thin-gauge claim is not a Chennai-specific qualification.

I10 / Winding Wire and Manufacturing Facility

RR Shramik / Ram Ratna Wires. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Manufacturing Facility; winding-wire product list

Supports: Silvassa manufacturing; round/rectangular copper and aluminium winding wires; fine wire and insulation options.

I11 / Facilities

Shanthi Gears. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Facilities: in-house capabilities list

Supports: In-house forging, CNC machining, hobbing, gear grinding, heat treatment and metrology.

I12 / Aerospace Infrastructure

Sansera Engineering. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Precision aerospace machining capability; not evidence of qualified robotic reducers.

I13 / Gleason Works India

Gleason. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Bangalore local production and service; distributes globally manufactured gear machines, tools and software.

I14 / Parliament Question: Rare Earth Minerals

DAE / PIB. Source date/revision: 2026-01-29. Accessed 2026-10-25.

Locate: Paragraphs on IREL oxides, strategic Vizag plant and Bhopal mini-plants/recycling

Supports: IREL oxide production; operational strategic SmCo plant; Bhopal metal mini-plants and recycling. Scheme target is not available supply.

I15 / Ferrite Manufacturing Process

Delta Manufacturing. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Integrated hard ferrite manufacturing process; does not establish Indian sintered NdFeB production.

I16 / Company History

Permanent Magnets Ltd. Source date/revision: 2026 timeline; page undated. Accessed 2026-10-25.

Locate: History timeline, 2026 entry: NdFeB production via Quantum Magnetics

Supports: Alnico and magnetic assemblies; 2026 timeline claims NdFeB magnet production through Quantum Magnetics subsidiary. No batch-level origin/capacity qualification.

I17 / About SKF India

SKF. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Indian manufacturing footprint and domestic distribution; bearings, seals and lubrication. Specific bearing SKU origin not established.

I18 / Manufacturing Footprint

Schaeffler India. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Indian plants and bearing product ranges; no blanket evidence that every robotic bearing SKU is Indian-made.

I19 / Timken in India

Timken. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Jamshedpur and Bharuch manufacturing; bearing and friction-management products.

I20 / India Manufacturing

Trelleborg Sealing Solutions. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Trelleborg India Bengaluru Manufacturing Unit; Jigani unit paragraph

Supports: Bengaluru PTFE/PEEK/elastomer seals and Jigani precision metal seal parts.

I21 / India Plant Expansion

Klüber Lubrication. Source date/revision: 2024-05-24. Accessed 2026-10-25.

Locate: Opening existing-Mysore-plant paragraph; India company description

Supports: Existing Mysuru specialty-lubricant plant, R&D and tribology; expansion planned, not counted as operating capacity.

I22 / Kurkumbh manufacturing expansion

Henkel India. Source date/revision: 2024-07-17. Accessed 2026-10-25.

Locate: Opening paragraph: Phase III completion and Loctite plant

Supports: Completed manufacturing expansion for adhesives/sealants/surface treatment near Pune; SKU origins still require confirmation.

I23 / Encoder Channel Partner

Renishaw India. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Encoder applications and Indian offices/technology centres; no specific India-made encoder claim.

I24 / Contact HBM India

HBK. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Indian contact route for measurement products including torque sensors; country of manufacture not established.

I25 / Mayr opens plant in India

Mayr. Source date/revision: 2025-03-03. Accessed 2026-10-25.

Locate: Opening paragraphs: Halol plant opened toward end of 2024

Supports: Halol near Vadodara production plant opened late 2024 for safety brakes and clutches. Model-level domestic content remains unconfirmed.

I26 / Kaynes Technology capabilities

Kaynes Technology. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Our Services: Product Design; PCBA & Box Build; Cable Harness; Test Equipment

Supports: India ESDM, prototyping, PCBA/box build, harnesses and functional test fixtures; flexible volumes, no published actuator project MOQ.

I27 / Overview and Capabilities

Centum Electronics. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Bangalore electronics manufacturing and in-circuit/boundary-scan/JTAG testing.

I28 / New Customers

Mouser Electronics. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: No Minimum Order; Customer Service Office

Supports: Authorised component distributor, Bangalore office; no minimum order value for normally stocked items subject to factory restrictions. India office does not establish Indian stock.

I29 / SASMOS capabilities

SASMOS. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Bengaluru EWIS engineering and wire-bundle/subassembly manufacturing; aerospace experience is not robot flex-life validation.

I30 / Precision Metrology and Calibration

CMTI. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Precision Metrology & Calibration service list

Supports: Dimensional/gear measurement and equipment calibration services; project-specific accredited scope must be checked.

I31 / Motor Test Laboratory

CPRI. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Opening laboratory scope; Major tests; Range of test ratings; contact division

Supports: Published facility targets 415 V three-phase induction motors up to 55 kW; resistance, thermal-rise, locked-rotor and load tests. Suitability for low-voltage robot BLDC requires agreement.

I32 / ELANTAS Beck India at a glance

ELANTAS. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Pune and Ankleshwar facility descriptions

Supports: Pune and Ankleshwar manufacturing of enamels, resins, varnishes and compounds; pilot/application testing.

I33 / Aluminium Extrusions

Hindalco. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Main page / named sections

Supports: Indian extrusion and finishing capability, including Kuppam; high-conductivity extrusion products.

I34 / OEM Products

Sushma Industries. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: OEM business description and in-house force/torque/pressure-sensor description

Supports: In-house strain-gauge force/torque/pressure sensors; custom design, prototyping, validation, production, calibration and motor test systems.

I35 / ARCI NdFeB pilot plant

DST / PIB. Source date/revision: 2026-03-20. Accessed 2026-10-25.

Locate: Opening paragraphs: pilot inauguration; strip-cast alloy to finished sintered magnets

Supports: Hyderabad pilot established from strip-cast alloy through finished sintered magnets; pilot collaboration does not prove commercial stock.

I36 / Midwest Advanced Materials funding

DST / PIB. Source date/revision: 2024-05-30. Accessed 2026-10-25.

Locate: Opening funding/project paragraphs; oxide feedstock and molten-salt electrolysis description

Supports: Hyderabad funded project targets oxide-to-magnet chain using NFTDC molten-salt electrolysis technology; funding is not shipment proof.

I37 / REPM scheme bids received

MHI / PIB. Source date/revision: 2026-08-13. Accessed 2026-10-25.

Locate: Bidder list; final scheme paragraphs on target and gestation period

Supports: 20 bids received; 6,000 t/year target, five beneficiaries envisaged, two-year gestation. Midwest JV named bidder; no commissioning proof.

I38 / Rare Earth capacity statement

DAE / PIB. Source date/revision: 2026-03-25. Accessed 2026-10-25.

Locate: Third narrative paragraph beginning The Minister informed; 500 tonnes per year

Supports: Claims Vizag SmCo initial capacity 500 t/year; conflicts with April parliamentary release stating 3 t/year.

I39 / Rare Earth Reserves and Magnet Manufacturing

Ministry of Earth Sciences / PIB. Source date/revision: 2026-04-02. Accessed 2026-10-25.

Locate: Initiatives bullet beginning DAE has established: 3 tons SmCo annually

Supports: States Vizag SmCo 3 t/year and limited midstream industries; conflicts with March capacity claim.

I40 / Magnet Manufacturing Process

Arnold Magnetic Technologies. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: How SmCo and Neo Magnets Are Made; Finishing; Magnetizing

Supports: Alloying, powder production, alignment/pressing, sintering, machining, coating and magnetisation are distinct processes.

I41 / Neodymium Magnets

Arnold Magnetic Technologies. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: NdFeB grade-selection discussion and linked grade data sheets

Supports: Grade selection trades energy product against intrinsic coercivity; grade-specific data sheets and coatings available.

I42 / Product Catalogue

Ovako. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Product catalogue tables: 16MnCr5 and 42CrMo4 entries

Supports: 16MnCr5 case-hardening and 42CrMo4 quench/temper steel families; global material reference, not an India supplier verification.

I43 / Industrial Aluminium Extrusions

Hindalco. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Industrial extrusion alloy table: A6061 and A6082

Supports: 6061 and 6082 extrusion alloy/temper options.

I44 / Sushma Contact

Sushma Industries. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Contact Us: Peenya Bengaluru address

Supports: Peenya Bengaluru address.

I45 / Delta contact

Delta Manufacturing. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: About Delta Manufacturing: Nashik manufacturing facility

Supports: Company manufacturing facility in Nashik, India.

I46 / Factories

Shanthi Gears. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Factories: Coimbatore site addresses

Supports: Coimbatore factory addresses.

I47 / Contact Us

Permanent Magnets Ltd. Source date/revision: Not stated. Accessed 2026-10-25.

Locate: Corporate Office; Rare Earth Magnets, NdFeB Magnets - QTM

Supports: Mira Road Thane corporate office; NdFeB/Quantum Magnetics department and lamination/annealing contacts.