



ENGINEERING PROGRAMME

The Capability Ladder

Twenty engineering projects from first motor to witnessed tower intervention

Each project is a self-contained engineering exercise with a falsifiable completion criterion. A project is finished when the criterion is met and documented — not when it works once on a bench.

STEEPLEJACK ROBOTICS

ENGINEERING PROGRAMME V1

How to use this document

Each project is a self-contained engineering exercise with a falsifiable completion criterion. A project is finished when the criterion is met and documented — not when it works once on a bench.

The ladder is ordered by dependency, not difficulty. Some projects can run in parallel; the phase gates cannot be skipped. Where a project has a stated failure mode, that failure mode is the reason the project exists.

Three principles govern the whole programme:

BUILD THE MOCK STRUCTURE EARLY

A representative tower section at ground level — lattice members at correct spacing and section, a real antenna mount, real fasteners — is the single highest-leverage piece of equipment in the programme. Almost every project from Phase 2 onward is faster and safer with one. Build it before Project 5.

EVERY PROJECT LOGS EVIDENCE

From Project 1, every run records its inputs, outputs and measurements in a consistent format. The commercial product is verified work, and the logging discipline that produces it cannot be retrofitted at Project 19.

NOTHING MODIFIES THE STRUCTURE

No rails, no fitted tracks, no pre-installed fixtures. Any solution requiring the tower to be prepared first reintroduces the climb and destroys the value proposition.

Cross-cutting requirements

These apply to every project and are not projects in themselves. They should appear as constraints in each design review.



Weight and transport budget

Two people must be able to carry, rig and recover the machine. Set a target mass early and hold every subsystem against it. A machine needing a crane has replaced one logistics problem with a worse one.



Dropped object prevention

Every tool, fastener and removable component is tethered or captive. A dropped 10 mm spanner from 40 m is a fatality. This is not a Phase 6 concern.



RF exposure and EMC

Work occurs near live transmitting antennas. Electronics must tolerate the RF environment without malfunction, and any operating procedure must respect exposure limits and any required downtilt or power reduction. Characterise this before working on live sites.



Weather envelope

Wind, rain, temperature and ice are the field conditions. State the envelope in which the machine is rated to operate, and design the fault behaviour for conditions outside it.



Structure variation

Lattice, monopole and guyed masts have fundamentally different climbing geometry. Decide early which is the primary target — lattice is the most tractable and the most common in the markets where development access is likely — and treat the others as later generalisation.

PHASE 1 Actuation and safety foundations

PROJECTS 1-4

GATE *no climbing work begins until Project 4 is complete.*

1 Motor control and drive characterisation

OBJECTIVE

Drive a geared or brushless actuator under closed-loop current control and characterise its real torque, speed and thermal envelope.

WHY IT MATTERS

Tower work is intermittent high-torque, which is a thermal problem rather than a peak-torque problem. Everything downstream depends on knowing what the actuator can actually sustain.

DONE WHEN

Measured torque-speed curve produced from your own bench data, not the datasheet. Continuous duty cycle at which the motor reaches thermal limit documented. Current limiting demonstrated under stall.

FAILURE MODE

Sizing from datasheet peak torque, then discovering the continuous limit at height with a bolt half-turned.

2 Closed-loop position control under load

OBJECTIVE

Hold and track commanded position within a stated tolerance while an external disturbance is applied.

WHY IT MATTERS

The tool must stay engaged with a fastener while the platform moves in wind. Position control that only works unloaded is not position control.

DONE WHEN

Holds position within stated tolerance under a step disturbance of at least 50% of rated load. Settles without sustained oscillation. Tuning method and final gains documented and reproducible.

FAILURE MODE

Tuning on a rigid bench with no load and no compliance, then finding the system unstable once mounted on anything that flexes.

3 Force and torque sensing

OBJECTIVE

Measure applied force and torque with known accuracy, repeatability and drift.

WHY IT MATTERS

Torque applied to specification is the deliverable and the evidence. Unmeasured torque is commercially worthless.

DONE WHEN

Calibrated against a certified reference. Error budget stated. Repeatability documented over at least fifty cycles. Temperature drift characterised across the intended operating range.

FAILURE MODE

Using motor current as a proxy for output torque. Gearbox friction and efficiency vary with load, temperature and wear, and the resulting error is large, non-linear and unacceptable as evidence.

4 Fail-safe grip

OBJECTIVE

A gripping mechanism that maintains hold on a structural member when power is removed, and that requires a positive command to release.

WHY IT MATTERS

This is the most important mechanism in the machine. Every other capability is negotiable; this one determines whether the safety case is possible at all.

DONE WHEN

Holds full machine mass plus a documented dynamic factor with power disconnected, demonstrated repeatedly. Release requires positive command and cannot occur through single-point failure. Mechanism principle documented — over-centre linkage, spring-applied power-released brake, irreversible worm drive, or equivalent.

FAILURE MODE

Any grip depending on continuous power or continuous control. If a software fault or a flat battery can drop the machine, no operator will permit it on their structure and no insurer will price it.

PHASE 2 Manipulation

PROJECTS 5–8

GATE *Build the mock structure before starting this phase.*

5 Force-controlled gripper

OBJECTIVE

Grasp and hold objects of varying geometry with controlled, measured grip force.

WHY IT MATTERS

Components handled on a tower — light units, brackets, radio units — are of differing size and fragility, and grip force must be sufficient without damage.

DONE WHEN

Grasps a defined set of test objects with grip force controlled to a stated tolerance. Detects and reports slip. Retains hold on power loss.

6 Multi-axis manipulator

OBJECTIVE

A manipulator with sufficient degrees of freedom to reach fastener and mount positions from a fixed platform attachment point.

WHY IT MATTERS

The reachable workspace determines how many times the platform must reposition, and repositioning is the slowest and highest-risk part of any operation.

DONE WHEN

Reachable workspace mapped and documented against the mock structure's fastener positions. Percentage of target positions reachable from a single platform attachment stated. Singularities identified and handled.

FAILURE MODE

Optimising for reach at the cost of stiffness. A long compliant arm cannot deliver accurate torque.

7 Calibrated torque tool

OBJECTIVE

Apply a commanded torque to a fastener to a stated accuracy, and record the value achieved.

WHY IT MATTERS

This is the core deliverable of the whole machine. Antenna mount fasteners have specified torques and the evidence of compliance is what the operator is buying.

DONE WHEN

Applies commanded torque within a stated percentage error, verified against a reference transducer, across the full intended range and across at least fifty repetitions. Records applied torque, angle and time-series for every operation.

8 Reaction force and base stability

OBJECTIVE

Characterise how manipulator forces transfer into the platform, and quantify the torque at which platform position exceeds tolerance.

WHY IT MATTERS

Applying 60 Nm to a bolt applies 60 Nm to the platform. Achievable torque accuracy is set by the grip and structural stiffness, not by the arm. This coupling is the hardest problem in the design and the most common integration failure in mobile manipulation.

DONE WHEN

Measured relationship between applied torque and base displacement documented. Maximum applicable torque within positional tolerance stated. A reaction compensation strategy — bracing, counter-torque, second attachment point — demonstrated to raise that limit.

FAILURE MODE

Developing arm and platform as independent subsystems and discovering the coupling at integration, by which point both architectures are fixed.

PHASE 3 Perception and measurement

PROJECTS 9–11

9 Structural member detection and pose estimation

OBJECTIVE

Detect tower structural members and estimate their position, orientation and section relative to the machine.

WHY IT MATTERS

The climbing system must know where the next attachment point is, at what angle, and whether it is within grip capability.

DONE WHEN

Detects and estimates pose of members on the mock structure and on photographs of real towers, within stated positional and angular error, under varying light. Reports confidence and fails safe when confidence is low.

10 Antenna and mount detection

OBJECTIVE

Detect antennas, identify mount type and locate the adjustment hardware.

WHY IT MATTERS

Mounts vary widely across manufacturers, vintages and undocumented site modifications. The machine must recognise what it is looking at before it can act on it.

DONE WHEN

Classifies a documented set of common mount types from real site imagery. Locates fastener positions within stated error. Explicitly reports unrecognised configurations rather than guessing.

11 Azimuth and downtilt measurement

OBJECTIVE

Measure antenna azimuth and mechanical downtilt with a stated and defensible error budget.

WHY IT MATTERS

These are the measurements the operator is paying for, before and after intervention. The number is only worth what its stated accuracy is worth.

DONE WHEN

Measurements agree with a reference method within a documented tolerance. Full error budget published, including sensor error, mounting error and structural movement. **Required accuracy confirmed with at least two tower operators, not assumed** — this determines the entire sensing architecture and it is cheap to ask.

FAILURE MODE

Achieving impressive precision against a specification nobody asked for, or discovering late that the industry requires tighter tolerance than the sensor suite can deliver.

PHASE 4 Locomotion

PROJECTS 12–14

GATE *Project 4 must be complete. All work in this phase begins at low height over matting.*

12 Controlled ascent with secondary retention

OBJECTIVE

Ascend a structural member under control, maintaining at least two independent points of attachment at all times.

WHY IT MATTERS

Two-point attachment is the rule human climbers work to, and for the same reason. A machine that ever has a single point of failure between itself and the ground will not pass a safety case.

DONE WHEN

Ascends the mock structure at a documented rate with two independent attachments maintained continuously, verified by instrumentation rather than observation. Demonstrated across repeated cycles with no single-point-of-failure state.

13 Controlled descent and load holding

OBJECTIVE

Descend under control, and hold position indefinitely at any point without power.

WHY IT MATTERS

Descent is more dangerous than ascent, because gravity assists the failure mode. Most climbing mechanisms are easier to design going up.

DONE WHEN

Descends at a controlled rate with no uncommanded acceleration under any single fault injected. Holds indefinitely at arbitrary positions with power removed. Emergency stop leaves the machine in a stable held state.

14 Obstacle traversal and structure variation

OBJECTIVE

Traverse joints, bolted plates, cable trays, section changes and other real-world discontinuities. Handle variation in member size and geometry.

WHY IT MATTERS

Real towers are not clean prisms. They carry decades of undocumented additions, and every one of them is between the machine and the work.

DONE WHEN

Traverses a documented catalogue of obstacle types on the mock structure. Member size range handled is stated. Behaviour on encountering an untraversable obstacle is defined, safe and reported to the operator.

FAILURE MODE

Building a mock structure that is cleaner than reality. Photograph real towers and reproduce their mess deliberately.

PHASE 5 Remote operation and fault behaviour

PROJECTS 15–17

GATE *This phase is what makes the machine deployable. It is also what an operator's risk function will examine most closely.*

15 Teleoperation with latency and feedback

OBJECTIVE

Operate the full machine remotely with visual and force feedback sufficient to perform manipulation tasks.

WHY IT MATTERS

Teleoperation is the product. Autonomy is a later efficiency gain layered on top of a working service.

DONE WHEN

An operator who did not build the machine completes a manipulation task on the mock structure using only the remote interface. Performance characterised across a range of induced latency and bandwidth constraints representative of field connectivity. Camera selection and arbitration usable without training in the mechanism.

FAILURE MODE

An interface only its author can drive. Test with someone else, early.

16 Loss-of-link and fault-state behaviour

OBJECTIVE

Define, implement and prove deterministic behaviour under communications loss, power fault, sensor failure and command timeout.

WHY IT MATTERS

This is the first question any competent safety assessor asks. There must be a documented answer with evidence behind it, not an intention.

DONE WHEN

Behaviour on each fault class is specified in writing, implemented, and demonstrated by injecting each fault. The machine reaches a defined safe state — attached, held, not moving — within a stated time in every case. Recovery from safe state on link restoration is controlled and requires operator confirmation.

17 Recovery of a disabled machine from height

OBJECTIVE

A proven method of recovering the machine from the structure when it is unpowered or unresponsive.

WHY IT MATTERS

Every operator will ask what happens when it dies at thirty metres. "It hasn't yet" is not an answer, and a machine that requires a rigger to climb up and free it has reintroduced the exact risk the product exists to remove.

DONE WHEN

At least one recovery method demonstrated on a fully unpowered machine at height — controlled descent on reserve power, mechanical release from ground via tether, or equivalent. Recovery procedure documented to the standard a method statement requires. Time to recover measured.

FAILURE MODE

Treating this as an afterthought. It constrains the mechanism, and discovering the constraint after the mechanism is fixed means redesigning it.

PHASE 6 Field tasks and evidence

PROJECTS 18–20

18 Fastener engagement under field conditions

OBJECTIVE

Locate, engage and turn fasteners that are corroded, painted, seized, non-standard, or out of nominal position.

WHY IT MATTERS

This is where laboratory manipulators fail. A clean hex head on a bench is a solved problem; a twenty-year-old galvanised bolt with paint over the flats and a mount that has shifted three millimetres is not.

DONE WHEN

Engages and turns fasteners from a deliberately degraded test set — rusted, painted, damaged, mispositioned — with a documented success rate. Detects failure to engage and reports rather than forcing. Breakaway torque limit defined so the machine does not shear a fastener it cannot see.

FAILURE MODE

Testing only on new hardware. Buy or make a degraded fastener set and use it from the beginning of this phase.

19 Complete work tasks with evidence capture

OBJECTIVE

Perform full maintenance operations end to end — azimuth adjustment, downtilt adjustment, bracket manipulation, component replacement — each producing an evidence package.

WHY IT MATTERS

The commercial product is not the motion; it is the verified completed work order. The evidence package is what the operator files and what their client accepts.

DONE WHEN

Each target task completes on the mock structure. Each produces an evidence package containing before and after measurements with stated accuracy, torque values applied against specification, timestamped visual record, full command and sensor log, and operator identity. **The package format has been shown to a tower operator and confirmed as sufficient for their compliance file.**

20 Witnessed intervention on a real tower

OBJECTIVE

Perform a complete teleoperated maintenance intervention on an actual telecommunications tower, witnessed by a tower operator, with no human on the structure.

WHY IT MATTERS

This is the artefact that converts a project into a company. Everything before it is preparation.

DONE WHEN

The intervention completes on real steel. A tower operator representative witnesses it and provides written feedback. The evidence package is delivered and assessed. Recorded in full for use in commercial conversations.

Sequencing notes

What can run in parallel.

Phase 3 perception work is largely independent of Phases 1, 2 and 4 and can proceed alongside them with a second person or in alternating blocks. Everything else is dependent.

What cannot be skipped.

Project 4 gates all climbing work. Projects 16 and 17 gate all work on live infrastructure. These are not sequencing preferences; they are the conditions under which anyone will let you on a tower.

On pace.

Mechanical iteration has physical cycle times. Parts arrive when they arrive; prints take as long as they take; a redesigned bracket costs a week regardless of hours worked. Effort compresses the software and the analysis. It does not compress the machining. Plan the mechanical path first and fill the waiting with software, perception and documentation.

On documentation.

Every project produces a written record: what was built, what was measured, what failed, what was changed. This is not administrative overhead — it is the raw material of a patent application, a safety case and a technical due diligence, all three of which arrive sooner than expected.

What runs alongside the ladder

The ladder is the engineering programme. It is necessary and not sufficient. Three things must progress in parallel, and they determine whether the engineering ever reaches a customer:

Site access.

Written permission to develop on a real tower. Without it the programme stops at Project 14. This is the first thing to secure and the hardest to substitute.

Safety competence.

A work-at-height and structural specialist engaged early, shaping the design rather than assessing it afterwards.

Operator conversations.

What tasks they would pay to have done remotely, what accuracy they require, what evidence they would accept, and what would have to be true for them to permit a machine on their structure.

The engineering answers whether the machine can work. These answer whether it matters.