

Serviceable modules and durable force sensing

Notes from a chat with Claude, October 3–4, 2026.

Question: Which "big, serviceable modules" should hold the complexity? And what does "sense force where hardware is durable" mean?

1. "Put complexity in big, serviceable modules": which ones

A serviceable module is big enough to be robust, standard enough to be cheap, reports its own faults, and swaps out in minutes. From the shoulder outward:

- **Arm joint actuators.** Each joint is one sealed unit: motor, gearbox, position sensor, driver electronics and a temperature sensor, with one bolt pattern and one connector. Humanoids like Unitree's G1 and cheap arms like OpenArm and reBot are built from such units, often bought off the shelf from makers like Damiao or Robstride. When one fails it reports an error code, and you unbolt it and fit a spare.
- **The gripper as one unit.** It has one motor, a lead screw or linkage, a standard mounting flange and one connector, so the whole gripper swaps in minutes. Only the fingertip pads wear, and they're separate consumables (Robotiq's 2F-85 gripper has replaceable pads).
- **Tool changers.** A quick-change plate at the wrist lets the robot put down one end effector and pick up another: gripper, suction cup or screwdriver. Factories get "dexterity" this way, from swappable tools rather than fingers.
- **Forearm motor packs,** if you do want a hand. All the hand's motors sit in the forearm, as in the Shadow Hand and NYU's RUKA, and the fingers become mostly passive structure plus replaceable tendons. The motors can then be bigger, cooled and swapped as one pack, and the weak points (tendons, pads) become consumables.
- **Wrist cameras, batteries and compute.** These plug in, and some humanoid batteries hot-swap.

Why this matters: reliability (how often things fail) isn't the whole story. Repair time counts just as much:

availability = time between failures ÷ (time between failures + repair time)

Take the earlier illustrative hand that fails every ~280 hours:

- With a 4-hour teardown per failure, availability is 98.6%, about an hour lost every 70.
- With a 10-minute module swap, it's 99.94%.

Failures still happen; they just cost minutes. The anti-pattern is complexity spread across tiny parts inside the fingers and palm. A frayed tendon or stripped micro-gear means taking the hand apart, finding the fault, then re-tensioning and recalibrating.

2. "Sense force where hardware is durable"

A robot needs to know contact forces: how hard it's gripping, whether it has touched something, whether an object is slipping. You can measure them at the contact surface with a tactile skin, but the skin is the part that wears out.

The key fact: force travels through the whole structure. When the gripper squeezes an object, the same force pushes back through the fingers, gears, motor, wrist and every arm joint (Newton's third law). So you can measure it

anywhere along that path. The design question is where the sensor will survive. Three places sit behind the contact:

1. Motor current. In an electric motor, torque is proportional to current. The motor driver already measures current to run the motor, so this sensor costs nothing and sits sealed inside.

- A gripper sets its grip force by capping the current.
- It knows it's holding something when the jaws stop at a nonzero width while current rises.
- It knows it dropped something when the width suddenly snaps shut.

There's a condition: the gearing must be mild and low-friction. Gears add friction and multiply the motor's own inertia by the gear ratio squared, so at 10:1 the motor's inertia feels 100× bigger and at 100:1 it feels 10,000× bigger. Contact forces then vanish into friction and inertia. That's why legged robots use lightly geared motors (MIT's Mini Cheetah uses 6:1), where current closely tracks joint torque. It's also why a finger geared 100:1 can't feel much through its motor.

2. Joint torque sensors. A strain gauge on a metal flex piece inside each joint measures torque directly; Franka and KUKA iiwa arms have one in every joint. From the pattern across joints, the controller can estimate where a collision happened and how hard. That's how collaborative arms stop when they bump a person.

3. Wrist force/torque sensor. A six-axis sensor between the arm and the gripper measures the total push and twist on the end effector, protected behind the gripper. It's the standard tool for insertion tasks: feel the peg touch the edge of the hole, then slide it in.

Vision fills a gap. A wrist camera can see an object shift in the jaws, which reveals slip that force readings might miss.

What you give up. These signals give the net force: a few numbers. They don't tell you where on the pad the contact is, the pressure pattern, the texture, or the first micro-slip before an object slides. Skin measures those. So the rule is to get force from durable places by default, and to add skin only where a task really needs that detail, as a cheap, replaceable consumable.

For your G1 plan: Unitree's SDK reports an estimated torque for every joint. Log it from day one alongside joint positions. That gives the policy a contact signal with no extra wearing part, and it still works if you swap the tactile Dex3-1 hands for grippers.