KELLOGG'S RESEARCH LABS

NITINOL

ACTUATOR ENGINEERING LAB BOOK

14 labs in characterization, shape setting, design and control, on thirteen actuator forms

For upper-level mechanical engineering and materials science courses



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Welcome

Nitinol is a very sophisticated actuation technology. One piece of it can replace a motor, a gearbox and a spring, and it can make motions that no other actuator can. Engineers who can specify it, size it and control it are rare. This book is a semester of labs that trains them.

There are fourteen labs, one per week. Students start by measuring the four temperatures that define a nitinol actuator and finish by commanding a single part with three independent degrees of freedom. In between they set shapes in a furnace, train a two-way actuator, build a drive board, write a user interface that gives proportional control, and run a part to fatigue failure.

Every lab is built around an actuator form from KRL's Handbook of Nitinol Actuators. By the end of the semester a student has handled thirteen forms and can choose between them.

Who this book is for

- Upper-level mechanical engineering and materials science courses: smart materials, mechatronics, actuators, materials characterization or a capstone lab
- Students who have had mechanics of materials, heat transfer or thermodynamics, and circuits, and who can write a short program
- Instructors with no prior nitinol experience

How the book is organized

Part	Labs	What students do
Part 1: The Material	1–4	Measure transformation temperatures and stiffness. Set a shape. Train a two-way actuator.
Part 2: Drive and Control	5–8	Build the drive board. Balance the energy budget. Close a position loop with a sensor and with resistance. Write a user interface for proportional control. Manage heat for cycle speed.
Part 3: Design and Sizing	9–12	Size high-force, rotary, snap-acting and peristaltic actuators and test them against the design.
Part 4: Life and Systems	13–14	Run a fatigue test. Command a multi-degree-of-freedom actuator. Then an open design project.
Instructor Pages		Kits, equipment, instrument options, expected results, answer keys, code listings and troubleshooting.

Benchtop core, instrument options

Every lab runs on a bench with the KRL College Kit, a current-limited power supply, a multimeter, a thermocouple and a microcontroller. No lab depends on a large instrument.

Each lab also has an **instrument option** for departments that have a differential scanning calorimeter (DSC), a load frame, a furnace with a controller, a thermal camera or data acquisition. The option repeats the core measurement the way an industrial test lab would, usually to an ASTM standard, so students can compare a bench result with a reference result.

What every lab includes

- **Big idea:** one sentence on what the lab shows
- **Actuator:** the form used in the lab, with its two-letter KRL part code
- **Objectives, equipment and the instrument option**
- **Theory:** the equations needed to predict the result
- **Pre-lab:** short calculations, due before the session

- **Procedure, data and analysis:** including an uncertainty estimate
- **Report:** the deliverable, usually a one-page engineering memo
- **Go further:** an extension for fast teams, and an optional overdrive extension
- **Notes:** two grid pages for sketches, readings and questions

Student pages contain no answers. Expected results and answer keys are in the Instructor Pages at the back. They are part of the public book on purpose: in a lab, building and running the experiment matters more than arriving at a number.

Fixtures

The labs need a rigid frame to hang, clamp and load small parts. The test stand from the high school *Nitinol Robotics Lab Book*, built from LEGO® Technic™-compatible beams, works for most of them.

Aluminum extrusion is a stronger, low-cost option. A frame of 20 mm T-slot bars and corner brackets goes together with a hex key, takes the higher loads in Part 3 without flexing, and can be rebuilt for each lab. An optical breadboard or a set of 3D-printed brackets also works.

Print anything that touches a hot part in PETG or ASA, and isolate hot wire from plastic with silicone washers.

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Safety First

Safety messages in this book follow ANSI Z535.6, the US standard for safety information in product manuals. Each lab adds the messages specific to it.

Signal word	Meaning
⚠ DANGER	Will cause death or serious injury. No hazard in this book reaches this level.
⚠ WARNING	Could cause death or serious injury.
⚠ CAUTION	Could cause minor or moderate injury.
NOTICE	Could damage equipment or materials, but not people.

⚠ WARNING	**Burn hazard: hot parts, hot water and furnaces.** A powered nitinol part passes 100 °C in seconds, several labs use water up to 95 °C, and Lab 3 uses a furnace at 550 °C. Do not touch a part while it is powered or for 30 seconds after. Handle hot water and furnace loads with tongs and the gloves your lab requires.

⚠ WARNING	**Eye hazard: nitinol is powerful.** Pound for pound, nitinol is one of the strongest actuator materials made. A wire as thin as pencil lead lifts more than 3 kg, and the Belleville and snap-through parts in Part 3 release their force suddenly. A loaded part that is not properly constrained can slip and whip into an eye. Wear safety glasses whenever a part is loaded, powered, armed or being cut.

⚠ CAUTION	**Hot electronics.** The drive board switches several amps. A shorted wire, a MOSFET without a gate resistor or a clip lead that is too thin gets hot enough to burn. Set the supply's current limit before every session and keep the fuse in the circuit.

NOTICE	**Overheating destroys the memory.** A nitinol part held at full current keeps heating past its working range. Overheated under load it drifts and loses stroke. Above 350 °C treat the part as spent and replace it. Pulse the heating current, then drop to a holding current.

Nitinol in Brief

This chapter is a review. It sets the vocabulary and the numbers that every lab uses.

Two phases

Nitinol is close to half nickel and half titanium, atom for atom. It has two crystal structures.

- **Austenite** is the hot, stiff phase. It holds the part's **memory shape**, the shape set into it by heat treatment.
- **Martensite** is the cool, soft phase. It deforms at low stress by shifting between twin variants, with no slip, so the deformation is recoverable.

Transformation and reverse transformation

In this book, **transformation** means martensite to austenite on heating. That is when an actuator moves and does work. **Reverse transformation** means austenite to martensite on cooling, which resets the actuator. Research papers often use the words the other way around. Actuator buyers are not metallurgists, so KRL names the change by what the actuator does.

ASTM F2005 defines the four temperatures that mark the two changes.

Term	Meaning (ASTM F2005)
As	Austenite start: the transformation begins on heating
Af	Austenite finish: the transformation is complete on heating
Ms	Martensite start: the reverse transformation begins on cooling
Mf	Martensite finish: the reverse transformation is complete on cooling
Active Af	The Af of a finished part, measured after its final heat treatment

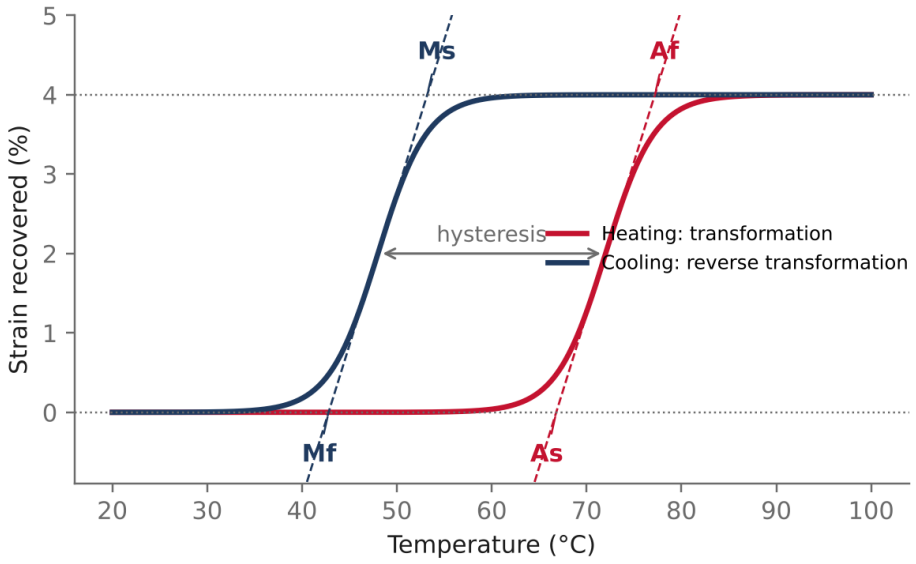


Figure 1. Strain recovered against temperature at constant load. Tangent lines at the steepest part of each branch mark the four temperatures. The gap between the branches is the hysteresis.

The gap between the two branches is the **hysteresis**, about 20 to 30 °C in ordinary nitinol. A part must cool below Mf, not just below As, to reset fully. If Af is above the ambient temperature, the part is a **shape memory** actuator. If Af is below ambient, the part is austenite at rest and is **superelastic**.

Three choices that do not interfere

- **The cross-section sets the force.** Force is stress times area. Length has nothing to do with it.
- **The length and the form set the motion.** Stroke is strain times length, multiplied or divided by the shape.
- **The transformation temperature sets when it happens.** Nothing else. Two parts of the same size and shape with different transformation temperatures give the same force and the same motion.

The shape is the gear ratio

A gram of nitinol worked to a given strain does the same work in any form. The form only decides how that work is split between force and stroke. A straight wire is the low gear: high force, short stroke. Wind the same wire into a spring and it becomes the high gear. This is why the Handbook of Nitinol Actuators is organized by shape, and why the labs here work through thirteen of them.

The four design levels

How hard nitinol is worked decides how long it lasts. KRL's handbook rates every part at four levels. Lab 13 tests them.

Level	Strain	Cycles before wear-out	Typical use
A	1%	1,000,000	Works continuously for the life of the machine
B	2.5%	100,000	Regular duty, many times a day for years
C	5%	10,000	The usual choice: frequent use over a normal service life
D	7%	100	Occasional or one-shot: deployment, release, set-and-forget

Numbers to know for 0.5 mm wire

Several labs use 0.5 mm actuator wire, the best all-round size for student work. These are typical values. Use the data card in your kit where its numbers differ.

Property	Typical value
Cross-sectional area	0.196 mm^2
Resistance	About 4 Ω per meter
Mass	About 1.3 g per meter (density 6.45 g/cm^3)
Usable contraction	3 to 5% of length (plan on 4%)
Long-life pull	About 33 N, which is 170 MPa
Heating current	2 A to start, 3 A maximum, in pulses of 5 seconds or less
Specific heat	About 0.47 J/(g·°C)
Latent heat of transformation	About 24 J/g
Stress rate of the transformation temperatures	5 to 8 MPa/°C
Transformation finishes (Af), actuator wire	About 70 °C (see your data card)

Overdriving an actuator

The force figures in KRL's handbook are conservative, and a part can be driven beyond them on purpose. There are two ways, and they add.

- **Heat it further.** The force does not stop climbing at Af. Keep heating and it keeps rising with temperature, at the stress rate measured in Lab 1.
- **Heat it faster.** A sharp pulse of current gives more force than a gentle ramp.

That gives a nitinol actuator a reserve most actuators lack: an **emergency mode** for the day something jams. Use it as a reserve, not as the rating.

- **The limit is Md,** the temperature above which stress can no longer form martensite. Up to Md, overdriving costs some fatigue life, and the extra heat can also clear out retained martensite and sharpen a tired part.
- **Above Md** the part degrades faster with every hot cycle. **Above 350 °C** it is spent.
- **It fails safe.** An overheated nitinol actuator loses its force and goes slack. The worst thing an overdriven nitinol actuator does is stop.

Every lab ends with an optional overdrive extension.

> Overdrive rules for this book: pulses of 2 seconds or less, never above 200 °C on the thermocouple, safety glasses on, and your instructor's approval before any firmware limit is raised. Mark every part you overdrive and keep it out of later measurements.

Four ways to heat an actuator

- **Joule heating:** current through the part itself. Used in Labs 5 to 8 and 12 to 14.
- **A heating element:** a separate heater fastened to the part. The usual choice for thick parts in a product.
- **Ambient heating:** the surroundings do the heating and the part acts as its own sensor. Used in Labs 1, 9, 10 and 11.
- **Process heat:** hot gas or fluid already in the machine, steered onto the part by a small valve.

The actuators, lab by lab

Lab	Actuator form (KRL code)	Motion	What the lab teaches
1	Round wire (RW)	Straight pull	Transformation temperatures under load
2	Flat wire (FL)	Straight pull, bending	Stiffness of the two phases
3	Helical spring (HS)	Long pull	Shape setting
4	Helical spring (HS), two-way	Extends cool, closes hot	Two-way training
5	Torsion spring (TR)	Rotation about the coil axis	Joule heating and the energy budget
6	Edge wound spring (EW)	Very long pull	Closed-loop control: sensor and self-sensing
7	Flat spring (SR)	In-plane push	A user interface for proportional control
8	Face wound spring (FW)	Strong pull	Thermal management and cycle speed
9	Belleville (BV)	Short, very strong push	High-force design and stacking
10	Rod (RB), in torsion	Rotation	Direct-drive rotary design
11	Snap-through (ST)	Sudden snap	Bistability and passive control
12	Peristaltic (PE)	Traveling squeeze	Peristaltic pumping with several actuators
13	Split ring or C-clip (CC)	Gap opens or closes	Fatigue and life
14	Multi-degree-of-freedom actuator	Several independent bends	Many motions from one part

PART 1

The Material

Labs 1 to 4 treat nitinol as a material. Students measure the temperatures and stiffnesses that every later design depends on, then change them with heat treatment and training.

LAB

1

Transformation Temperatures Under Load

Big idea: *Four temperatures define a nitinol actuator, and stress moves all four.*

Actuator: Round wire (RW) Time: One 3-hour session

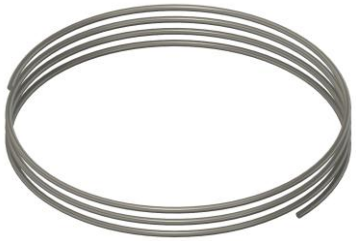


Figure 2. Round nitinol actuator wire, the simplest actuator form.

Objectives

- Measure As, Af, Ms and Mf by constant-force thermal cycling, the method of ASTM E3097
- Apply the tangent method and report the hysteresis width
- Find how fast the transformation temperatures rise with stress
- Compare with a stress-free bend and free recovery test, the method of ASTM F2082

Equipment (per team)

- 0.5 mm actuator wire, 30 cm, with a crimped loop at each end, and three loose 10 cm pieces
- Hooked steel masses, 0.5 kg and 2 kg
- Tall 2 L beaker, hot plate with stirrer, ring stand, ice
- Thermocouple and reader, 0.5 °C or better, with the junction taped beside the wire at mid-height
- Steel ruler or dial indicator, phone camera, 20 mm mandrel, 3D-printed recovery fixture with an angle scale
- Safety glasses

Instrument option

DSC, ASTM F2004. Cut a 25 to 45 mg sample, crimp it in an aluminum pan and cycle it between −20 and 120 °C at 10 °C/min. Read As, Af, Ms and Mf from the tangent intercepts of the two peaks, and the latent heat from the peak area. DSC measures a stress-free sample, so it gives the zero-stress end of this lab's data.

Theory

Hang a mass from the wire and cycle the temperature. The wire shortens as it transforms and lengthens as it reverses. Strain is the change in length over the gauge length:

$$\varepsilon = \Delta L / L_0$$

Plot strain against temperature and the two branches form a loop (see Nitinol in Brief). Draw a tangent through the steepest part of each branch. Where the heating tangent meets the lower baseline is As, and where it meets the upper baseline is Af. The cooling tangent gives Ms and Mf the same way.

The mass hangs under water, so buoyancy reduces its pull. For a steel mass in water:

$$F = m\,g\,(1 - \rho_{water} / \rho_{steel}) \approx 0.873\,m\,g \qquad \sigma = F / A$$

Stress favors martensite, so it raises all four temperatures. The Clausius-Clapeyron relation gives the rate, where ρ is density, ΔH the latent heat, T_0 the equilibrium temperature in kelvin and ε_t the transformation strain:

$$d\sigma/dT = \rho\,\Delta H / (T_0\,\varepsilon_t)$$

For nitinol the rate is 5 to 8 MPa/°C. A designer uses it in both directions: a loaded actuator needs more heat to move than its data card suggests, and it also resets at a higher temperature.

Pre-lab

P1 Find the stress in a 0.5 mm wire carrying a submerged 0.5 kg steel mass, and a submerged 2 kg steel mass.

P2 Using 6.5 MPa/°C, predict how far Af shifts between the two loads.

P3 Estimate the rate from the Clausius-Clapeyron relation with ρ = 6450 kg/m³, ΔH = 24 kJ/kg, T_0 = 340 K and ε_t = 0.06.

Procedure

⚠ WARNING	**Burn hazard.** The bath reaches 95 °C. Clamp the beaker, keep cords clear of the hot plate and lift the wire and masses out only with tongs.

1. Measure the gauge length L_0 between the crimps with the 0.5 kg mass hanging in room-temperature water.
2. Start the stirrer. Heat the bath at no more than 2 °C per minute. Record the length every 5 °C, and every 1 °C while the wire is moving. Continue to 95 °C.
3. Turn the heater off. Cool the bath with ice, a little at a time, and record the length on the way down to 30 °C at the same intervals.
4. Repeat steps 1 to 3 with the 2 kg mass.

Bend and free recovery.

5. Chill a 10 cm wire in ice water. Bend it 180° around the 20 mm mandrel, which strains the surface about 2.4%.
6. Lay it in the recovery fixture in a bath at 30 °C. Heat at 2 °C per minute and record the angle recovered every 2 °C until the wire is straight.
7. Repeat with two more wires.

Data

Bath temperature (°C)	Length, heating (mm)	Length, cooling (mm)	Strain, heating (%)	Strain, cooling (%)

Analysis

Q1 Plot strain against temperature for both loads. Use the tangent method to find As, Af, Ms and Mf at each stress.

Q2 Report the hysteresis width at each stress, measured between the midpoints of the two branches.

Q3 Find dσ/dT from the shift in Af and again from the shift in Ms. Estimate the uncertainty from your temperature and length resolution.

Q4 A design holds 100 MPa on the wire inside a 60 °C enclosure. Will the wire reset when the power is cut? Show the numbers.

Q5 Extrapolate your Af values to zero stress. Compare the result with Af from bend and free recovery, and with DSC if you ran it. Should the three agree?

Report

A one-page memo: the strain-temperature plot with tangents, a table of the four temperatures at both stresses, and the stress rate with its uncertainty.

Go further

Cycle the wire 50 times under the 2 kg mass and repeat the measurement. Which temperatures moved? Lab 13 returns to this drift.

Go further: overdrive

Clamp a 15 cm wire at fixed length between a rigid post and a spring scale, in air. Heat it with the bench supply in current limit and a thermocouple on the wire. Record the force at 10, 30 and 60 °C above Af. Stop at 50 N. Compare the rise in stress per degree with your answer to Q3. This is "heat it further," measured.

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LAB

2

Two Phases, Two Stiffnesses

Big idea: *Martensite and austenite are mechanically different materials. An actuator works by switching between them.*

Actuator: Flat wire (FL) Time: One 3-hour session

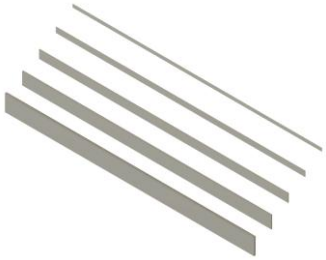


Figure 3. Flat wire in a range of widths.

Objectives

- Measure the elastic modulus of martensite and of austenite with a cantilever test
- Find the strain at which each phase stops behaving elastically
- Explain, from the two stress-strain curves, why a heated actuator overpowers its bias

Equipment (per team)

- Actuator flat wire, 80 mm: martensite at ambient temperature
- Superelastic flat wire, 80 mm, same section: austenite at ambient temperature
- Micrometer, steel ruler or height gauge, clamp block or small vise
- Small masses from 1 to 50 g (weighed washers work) and a thread hanger
- Mandrel set: 25, 15, 12 and 8 mm. Hot water at 90 °C, tongs, safety glasses

Instrument option

Load frame, ASTM F2516. Pull the superelastic strip to 6% strain, unload to 7 MPa, then pull to failure. Report the upper plateau strength at 3% strain, the lower plateau strength at 2.5%, the residual elongation and the tensile strength. Then pull an actuator strip to 6% and unload to see the detwinning plateau.

Theory

Clamp a strip of width b and thickness t as a cantilever of length L and hang a force F from the tip. While the deflection δ stays under about a tenth of L:

$$\delta = F L^3 / (3 E I) \qquad I = b t^3 / 12 \qquad so \qquad E = 4 F L^3 / (b t^3 \delta)$$

The largest strain is at the clamp, on the surface:

$$\varepsilon = 3 t \delta / (2 L^2)$$

Bent around a mandrel of diameter D, the surface strain is:

$$\varepsilon = t / (D + t)$$

The two phases respond differently to larger strain. Martensite yields at low stress by **detwinning**: its twin variants shift, the strip takes a set, and heating recovers it. Austenite above Af transforms to martensite under stress and transforms back when released, which is superelasticity.

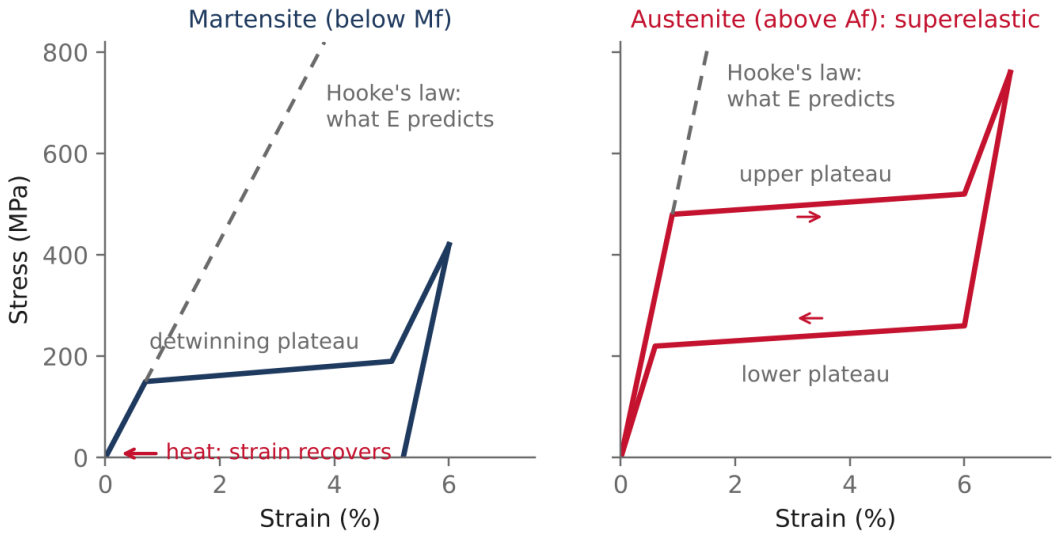


Figure 4. Stress against strain for the two phases. Martensite keeps a set that heating recovers. Austenite returns by itself along a lower plateau. The dashed lines show what Hooke's law predicts from the first slope.

"What is the Young's modulus of nitinol?"

Short answer: it usually does not matter. Here is why.

Young's modulus E belongs to Hooke's law: stress = E × strain. Steel and aluminum parts are designed to stay on that straight line. Nitinol parts are designed to leave it.

1. **Nitinol works past the line.** The straight start of each curve in Figure 4 ends below 1% strain. Actuators and superelastic parts work at 1% to 8% strain, on the plateaus. There the stress barely changes as the strain grows, and E does not describe it.
2. **E gives the wrong answer.** Take austenite at E = 75 GPa and stretch it 6%. Hooke's law predicts 75,000 MPa × 0.06 = 4,500 MPa. The real stress is about 500 MPa, the upper plateau. Hooke's law is nine times too high. The dashed lines in Figure 4 show the error.
3. **E is not one number.** Martensite measures 25 to 40 GPa and austenite 60 to 85 GPa. An actuator switches between the two on every cycle and passes through every mixture on the way. Both values also move with temperature, processing and load history.
4. **Design with these instead.** Transformation temperatures, plateau stresses, recoverable strain and the four design levels (see Nitinol in Brief). Force is stress times area. Stroke is strain times length. Neither calculation uses E.

When E does matter: small deflections that stay under about 1% strain. Examples are the rate of a spring (Lab 3, with the shear modulus G), vibration frequency and buckling. You measure E in this lab to prove that the two phases are different materials. You will not use it to size an actuator.

■ Pre-lab

P1 A strip 3.0 mm wide and 0.50 mm thick is clamped with L = 50 mm. Take E = 30 GPa. What tip force deflects it 5 mm?

P2 What is the surface strain at the clamp in that case? Is the test still elastic?

P3 What mandrel diameter strains the surface of a 0.50 mm strip by 4%?

Procedure

1. Measure the width and thickness of each strip at five places. Thickness enters cubed, so measure it carefully.
2. Clamp the actuator strip with 50 mm free. Add mass in six steps until the tip has dropped about 5 mm. Record the deflection at each step, then again as you remove the masses.
3. Repeat with the superelastic strip.

Larger strains.

4. Wrap the actuator strip halfway around the 25 mm mandrel, release it, and record the angle it keeps. Repeat on the 15, 12 and 8 mm mandrels.
5. Dip the strip in 90 °C water with tongs. Record what it does.
6. Repeat both steps with the superelastic strip.

Data

Mass (g)	Force (N)	Deflection, loading (mm)	Deflection, unloading (mm)

Analysis

Q1 Fit a line to force against deflection for each strip and find E. Carry the uncertainty in t through the calculation.

Q2 What is the ratio of the two moduli? What does it mean for an actuator and its bias spring?

Q3 At what strain did the actuator strip first keep a set? What happened in hot water, and why?

Q4 At what strain did the superelastic strip keep a set?

Q5 An actuator wire works against a steel bias spring. Using the stress-strain figure, explain why the wire stretches cold and contracts hot, and what limits the bias force on each side.

Report

A one-page memo with both force-deflection plots, the two moduli with uncertainty, and a short answer to Q5.

Go further

Load the superelastic cantilever until the tip drops 25 mm, then unload in the same steps. Plot both paths. The area between them is energy dissipated as heat, the basis of nitinol damping.

Go further: overdrive

Warm the superelastic cantilever to about 60 °C with a hair dryer and repeat the large-deflection test from Go further. Does the load at the plateau rise? The same stress rate that you measured in Lab 1 makes a hotter actuator push harder, up to the temperature Md where stress can no longer form martensite.

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LAB

3

Shape Setting a Spring

Big idea: *Heat treatment gives nitinol its memory shape and tunes its properties. Time and temperature are design variables.*

Actuator: Helical spring (HS) Time: One 3-hour session



Figure 5. A helical nitinol spring.

Objectives

- Shape-set three springs from straight wire at three furnace temperatures
- Measure springback, the transformation finish temperature and the spring rate in both phases
- Choose a heat treatment for an actuator and defend the choice

Equipment (per team)

- 0.5 mm actuator wire, three 45 cm pieces
- Three steel mandrels, 6 mm rod with a cross-drilled hole and a screw clamp at each end
- Furnace or kiln that holds 450 to 550 °C, with its own thermocouple. A hobby enamel kiln works.
- Long tongs, furnace gloves, metal bucket with a few liters of water for quenching
- Calipers, steel ruler, hooked masses from 10 to 100 g, 2 L beaker, hot plate, thermocouple

Instrument option

Programmable furnace and DSC. Run a full matrix of three temperatures and three times, and measure each sample by DSC (ASTM F2004). Plot Af against time at each temperature.

⚠ WARNING	**Burn hazard: furnace at 550 °C.** Load and unload the furnace only with tongs and furnace gloves. Parts look the same at 500 °C as at 20 °C. Cool every part in the water bucket before anyone touches it.

Theory

Nitinol takes a new memory shape when it is held in that shape at 450 to 550 °C for a few minutes and then quenched. The treatment relieves the stress of forming and resets the microstructure. Too little heat and the part springs back toward its old shape. Too much and it loses strength and stability. The treatment also moves the transformation temperatures, by an amount that depends on the alloy and its history, which is why every step from melt to finished part has to be controlled.

Quenching means cooling a hot part quickly by plunging it into a liquid. It stops the heat treatment at a known moment. A part left to cool in air keeps changing as it cools, at a rate that depends on the fixture, the bench and the draft in the room. Two teams with the same recipe then get different parts.

In this lab, quench in plain water at room temperature. Fill a metal bucket with a few liters and stand it within one step of the furnace. Carry the mandrel from the furnace to the water with tongs in one motion. Lower it in until it is fully under and stir it for 10 seconds. Expect a hiss and a puff of steam. The part is then safe to handle.

Quench	Use it for nitinol?	Why
Water at room temperature	Yes. The standard choice for wire, strip and small fixtures.	Fast, repeatable and safe. Nitinol does not crack in a water quench the way some steels do.
Still air or a fan	Not in this lab.	Slow and uneven, so the transformation temperatures drift. The fixture also stays hot enough to burn for many minutes.
Oil	No.	Oil quenching is for steels that crack in water. Here it only adds fire and fumes.
Ice water or brine	Not needed.	No benefit over plain water for parts this small.

A close-wound spring of wire diameter d, mean coil diameter D and n active coils has a rate:

$$k = G\,d^4 / (8\,D^3\,n)$$

where G is the shear modulus. Deflecting it by δ under a force F gives a shear strain and stress at the wire surface of:

$$\gamma = d\,\delta / (\pi\,D^2\,n) \qquad \tau = 8\,F\,D / (\pi\,d^3)$$

Pre-lab

P1 A spring has d = 0.5 mm, D = 6.5 mm and n = 20. How far does it travel for a shear strain of 2%?

P2 What force does it produce at a shear stress of 150 MPa?

P3 Predict its rate with G = 25 GPa (austenite) and with G = 8 GPa (martensite).

Procedure

1. Wind 20 close coils of wire onto each mandrel. Pass the ends through the cross holes and clamp them so the wire cannot unwind.
2. Heat-treat one mandrel at 450 °C, one at 500 °C and one at 550 °C, each for 10 minutes after the furnace recovers its temperature. Quench in water straight from the furnace.
3. Remove each spring. Measure its outside diameter and free length. Springback is the growth in coil diameter over the mandrel size.
4. Stretch each spring cold to three times its free length. Lower it into a 30 °C bath and heat at 2 °C per minute. Record the temperature at which it finishes closing. That is its Af.
5. Measure the cold spring rate with three small masses in room-temperature water. Keep the deflection small.
6. Measure the hot spring rate the same way in 90 °C water. Correct the masses for buoyancy.

Data

Treatment	Coil OD (mm)	Springback (%)	Af (°C)	k cold (N/mm)	k hot (N/mm)
450 °C, 10 min					
500 °C, 10 min					
550 °C, 10 min					

Analysis

Q1 Plot springback against furnace temperature. Which treatment set the shape best?

Q2 Did Af change with the treatment? By how much, and in which direction?

Q3 Find G for each phase from the measured rates. Compare with the pre-lab values.

Q4 Which treatment would you specify for an actuator spring, and what would you check before committing?

Q5 Why quench instead of letting the mandrel cool in air?

■ Report

A one-page process sheet for the spring you would build: mandrel, temperature, time, quench, and the measured Af, stroke and force with tolerances.

■ Go further

Set a fourth spring with a torch, pulling it out the moment the wire barely glows. Measure it the same way. How does its scatter compare with the furnace parts?

■ Go further: overdrive

Hold your best spring at a fixed extension against a spring scale, in air. Heat it with current and record the force just above Af and again 50 °C hotter. How much reserve does heating further give a spring?

NOTES

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LAB

4

Training a Two-Way Spring

Big idea: *Shape memory is one-way by default. Training adds a second shape.*

Actuator: Helical spring (HS) Time: One 3-hour session



Figure 6. A two-way helical spring. It closes when heated and extends by itself when it cools, with no bias spring.

Objectives

- Train a helical spring to extend by itself on cooling and close on heating
- Measure two-way stroke against the number of training cycles
- Decide when a two-way part is worth its cost

Equipment (per team)

- Three helical spring actuators from the kit: 0.5 mm wire, 10 coils, 6.5 mm mean coil diameter, memory shape closed
- Stretch gauge: two pins 110 mm apart on a board, and two wire hooks
- Hot water at 90 °C and ice water, in separate beakers. A shallow tray for the extension.
- Steel ruler, skewer, small washers, paper clips, tongs, safety glasses

Instrument option

Hot stage and camera. Record spring length against temperature through a full cycle to get the two-way hysteresis loop. Run DSC before and after training to see how training moves the transformation temperatures.

Theory

A one-way actuator remembers only its hot shape. Something else, a bias spring or the load, has to deform it again when it cools. A **two-way** actuator remembers a hot shape and a cool shape and moves between them with no bias.

Two-way memory is made by **training**. Repeated cycles leave a pattern of defects in the metal that favors particular martensite variants, so the part drifts toward the same deformed shape each time it cools. The two-way strain is a fraction of the one-way strain, and the force on cooling is small. KRL also makes parts that remember three or more shapes and is the only company in the world with that capability.

A helical spring makes the effect easy to measure: one number, its length. The two-way stroke is the difference between the free length cool and the free length hot. From Lab 3, the shear strain that goes with it is:

$$\delta_{tw} = L_{cool} - L_{hot} \qquad \gamma_{tw} = d\,\delta_{tw} / (\pi D^2 n)$$

Pre-lab

P1 How far must you stretch a spring with d = 0.5 mm, D = 6.5 mm and n = 10 to reach a shear strain of 4%?

P2 A trained spring is 5 mm long hot and 18 mm long cool. What is its two-way shear strain?

P3 The same spring as a one-way actuator works at 2% shear strain. What fraction of that stroke does the two-way effect give?

Procedure

1. Measure each spring before training. Dip it in hot water and record its length. Move it to ice water with nothing touching it and record its length again.
2. **Spring A, training.** Cool the spring in ice water. Hook its ends, stretch it to the 110 mm gauge, and release it. Dip it in hot water until it closes. That is one cycle.
3. After cycles 1, 2, 5, 10, 20 and 30, move the spring from hot water to ice water with nothing touching it. Lay it beside the ruler and record its cool length, then its hot length.
4. **Spring B, control.** Give an untrained spring 30 hot and cold dips with no stretching. Measure its cool and hot lengths.
5. **Heating force.** Hang trained spring A in the hot water with paper clips on its free end. Add clips until it no longer closes.
6. **Cooling force.** Stand spring A, closed, over a skewer in an empty beaker. Thread washers onto the skewer on top of it and pour in ice water. Add washers until it no longer extends.

Data

Cycle	L cool (mm)	L hot (mm)	Two-way stroke (mm)	Two-way strain (%)
1				
5				
10				
30				

Analysis

Q1 Plot two-way stroke against cycles for spring A. Does it level off?

Q2 Compare spring A with the control. What does the training?

Q3 Did the hot length stay at the closed length? What does that tell you about the cost of training?

Q4 Compare the force on heating with the force on cooling.

Q5 Give one product where a two-way part is the right choice and one where a one-way part with a bias is better.

Report

A one-page memo with the training curve, the final two-way stroke and strain with uncertainty, and your answer to Q5.

Go further: forward and reverse training

There are two ways to train a two-way part. They are named for the temperature at which the part is deformed.

- **Reverse two-way training** deforms the part below Mf, while it is martensite. The procedure above is reverse training: you stretched spring A in ice water.

- **Forward two-way training** deforms the part above Af, while it is austenite. The stretch then forms martensite by stress instead of rearranging martensite that is already there.

Train the third spring forward. Fill a shallow tray with water at 90 °C. Hold the spring under the water with the two hooks, stretch it to the same 110 mm, hold it for 5 seconds and release it under the water. That is one cycle. The hot spring pulls back several times harder than the cold one, so grip the hooks firmly. Measure its cool and hot lengths after cycles 1, 2, 5, 10, 20 and 30, as you did for spring A.

Plot both training curves on one graph. Compare the two-way stroke at 30 cycles, the number of cycles each method needs to level off, and how much each one changes the hot length. Which would you choose for a production part, and why?

■ Go further

Run 200 unconstrained hot and cold cycles on spring A and measure again. Is the two-way stroke stable?

■ Go further: overdrive

Heat trained spring A to about 150 °C with hot air for one minute, let it cool, and measure its two-way stroke again. Extra heat drives out retained martensite. Did the overdrive erase some of the training?

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PART 2

Drive and Control

Labs 5 to 8 make the actuator move on command. Students build a drive board, follow the energy, close a position loop with a sensor and with the actuator's own resistance, and write a user interface for proportional control.

Build: The Drive Board

Labs 5 to 14 use the same drive board. Build one per team before Lab 5 and keep it for the rest of the semester.

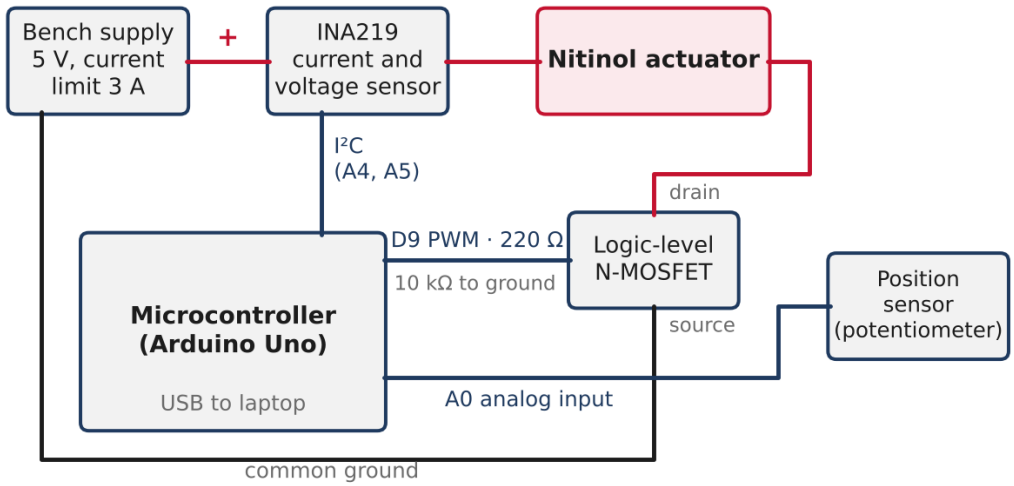


Figure 7. The drive board. A logic-level MOSFET switches the actuator current. The sensor reports current and voltage, and a potentiometer reports position.

Parts

Part	Qty	Notes
Microcontroller board (Arduino Uno or Nano)	1	Any board with four PWM pins and I²C
Logic-level N-channel MOSFET (IRLB8721 or similar)	4	One per channel. Labs 12 and 14 use all four.
220 Ω and 10 kΩ resistors	4 each	Gate series resistor and gate pull-down
INA219 current and voltage sensor breakout	1	0.1 Ω shunt, 3.2 A maximum
Potentiometer, 10 kΩ linear	1	Rotary or slide, as the position sensor
Bench power supply, 0 to 5 V, at least 5 A, with a current limit	1	
In-line fuse, 5 A, and 18 AWG hookup wire	1	Thin jumper wires overheat at these currents
Breadboard or screw terminals	1	Screw terminals for every actuator connection

Assembly

1. Wire the high-current path first: supply positive, fuse, sensor, actuator terminal, MOSFET drain. MOSFET source goes to supply negative.
2. Connect the gate to pin 9 through 220 Ω, and tie the gate to ground through 10 kΩ so the MOSFET stays off while the board resets.
3. Connect the sensor to 5 V, ground and the I²C pins. Connect the potentiometer ends to 5 V and ground and its wiper to A0.
4. Join the supply negative to the board ground. Without a common ground the MOSFET will not switch.

5. Add channels 1, 2 and 3 on pins 10, 5 and 6 the same way. They share the supply and the ground.
6. Install the firmware `krl_driver` from the lab pack (listed in the Instructor Pages). Open a serial monitor at 115200 baud and confirm that telemetry lines arrive 20 times a second.

■ Setting the supply

Set the supply voltage so that full duty gives the pulse current you want, then set the current limit about 10% above that as a safety net. For an actuator of resistance R:

$$V = I\,(R + 0.1\,\Omega + R_{leads}) \qquad P_{average} = D\,V^2 R \,/\, (R + 0.1\,\Omega + R_{leads})^2$$

where D is the duty cycle from 0 to 1. The PWM period is about 2 ms, far shorter than any thermal time constant in this book, so the actuator responds to the average power.

NOTICE	**Firmware limits.** The firmware caps channel 0 at 60% duty, trips at 3.2 A, and switches everything off if it hears nothing from the laptop for 3 seconds. Leave these in place.

LAB

5

Joule Heating and the Energy Budget

Big idea: *The actuator is its own heater. Where the energy goes sets how fast it moves and how efficient it is.*

Actuator: Torsion spring (TR) Time: One 3-hour session



Figure 8. A torsion spring. Heated, its legs swing about the coil axis.

Objectives

- Measure actuation time against electrical power and separate the energy to transform from the heat lost
- Find the holding power and estimate the convection coefficient
- Measure the efficiency of an actuator and explain what limits it

Equipment (per team)

- KRL torsion spring actuator of 0.5 mm wire, or wind one as in Lab 3: four wraps on a 6 mm mandrel with two 30 mm legs
- Pivot pin and frame, pointer, protractor, thread and small masses from 2 to 20 g
- Drive board and laptop, stopwatch or the telemetry log, safety glasses

Instrument option

Thermal camera or fine thermocouple with data acquisition. Record the spring temperature through the cycle and plot temperature against energy delivered. The flat section of the curve is the latent heat.

Theory

Heating a mass m of nitinol from ambient T_0 through its transformation takes sensible heat and latent heat:

$$E = m\,[\,c\,(T_f - T_0) + \Delta H\,]$$

At electrical power $P = I^2R$, with a loss to the air that is roughly constant near the transformation, the time to actuate is:

$$t = E\,/\,(P - P_{loss}) \qquad so \qquad P = E\,(1/t) + P_{loss}$$

A plot of P against 1/t is a straight line. Its slope is the energy to actuate and its intercept is the loss. The loss is also the power needed to hold the part hot, which gives the convection coefficient h over the wire surface A_s:

$$P_{hold} = h\,A_s\,(T_f - T_0) \qquad A_s = \pi\,d\,\ell$$

A torsion spring works its wire in bending. For a change in angle $\Delta\theta$ over n wraps of mean diameter D, the bending strain and the largest moment at a bending stress σ are:

$$\varepsilon = d\,\Delta\theta\,/\,(2\,\pi\,D\,n) \qquad M = \sigma\,\pi\,d^3\,/\,32$$

Efficiency is the mechanical work out over the electrical energy in. For a mass m_L lifted on an arm of radius r:

$$\eta = m_L \, g \, r \, \Delta\theta \, / \, (P \, t)$$

Pre-lab

P1 A torsion spring has four wraps of 0.5 mm wire at D = 6.5 mm and two 30 mm legs. Find the wire length, mass and resistance.

P2 Find the energy to heat it from 22 to 80 °C, including the latent heat. How long does that take at 2 A with no losses?

P3 Find the bending strain for a 90° swing, the moment at 170 MPa, and the mass that moment lifts on a 20 mm arm.

Procedure

1. Mount the spring on the pivot with one leg fixed. Hang a 5 g mass from the free leg on a 20 mm arm so that the mass re-opens the spring when it cools.
2. Measure the spring's resistance cold with the drive board: a 1-second pulse at 20% duty.
3. Set the supply for 1.0 A at full duty. Pulse the spring and record the time from power-on to full travel. Let it cool for 60 seconds. Repeat three times.
4. Repeat at 1.5, 2.0 and 2.5 A.
5. Hold the spring at full travel and lower the duty until the pointer just starts to fall. Record the current, voltage and duty. That is the holding power.
6. Raise the load in steps until the spring no longer completes its swing. Record the largest mass it lifts through the full angle.

Data

Current (A)	Voltage (V)	Power (W)	Time to full travel (s)	1/t (1/s)
1.0				
1.5				
2.0				
2.5				

Analysis

Q1 Plot power against 1/t and fit a line. Report the energy to actuate and the loss.

Q2 Compare the slope with your pre-lab energy. What could explain the difference?

Q3 Compare the holding power with the intercept. Estimate h.

Q4 Calculate the efficiency at 2 A with the largest load lifted. How could a designer raise it?

Q5 The handbook says never to hold a part at its one-second heating current. Use your data to explain why.

Report

A one-page energy budget for one cycle: electrical energy in, energy to transform, heat lost, and work out.

Go further

Repeat at one current with a small fan blowing across the spring. Which changes more, the slope or the intercept?

Go further: overdrive

Find the largest mass the spring lifts through its full swing with a gentle 1 A ramp, and again with a hard 3 A pulse of 1 second. This is "heat it faster." How much more does the pulse lift, and what did it cost in energy?

NOTES

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LAB

6

Closed-Loop Position Control

Big idea: *Feedback turns an on-off actuator into a proportional one. The position signal can come from a sensor or from the actuator's own resistance.*

Actuator: Edge wound spring (EW) Time: One 3-hour session



Figure 9. An edge wound spring: flat wire coiled on edge, for very long travel.

Objectives

- Build a proportional position loop with a position sensor and measure its steady error against gain
- Map resistance against position and find the resolution the drive board can reach
- Run the same loop on resistance feedback and compare the two signals

Equipment (per team)

- KRL edge wound spring actuator with crimped terminals
- Frame, bias masses of 20 and 50 g, steel ruler
- Slide potentiometer coupled to the moving end and wired to A0 on the drive board
- Drive board, laptop with Python 3, `krl_console.py` and `p_loop.py` from the lab pack, safety glasses

Instrument option

Four-wire measurement and a displacement sensor. Use a source-measure unit or data acquisition with separate sense leads at the crimps, and an LVDT or laser sensor for position. Compare the map with the two-wire result.

Theory

An actuator driven open loop is hard to place. Its position depends on its temperature, and its temperature depends on the load, the airflow and the last few seconds of history. A **closed loop** measures the position and corrects the heat until the position is right.

The simplest controller is **proportional**. The duty is the position error times a gain:

$$duty = K_p\,(target - position)$$

The duty cannot go below zero: the controller can add heat but cannot remove it. Holding a position also takes some heat, so a proportional controller settles a little short of its target. If holding takes a duty D_{hold}, the steady error is:

$$e = D_{hold} / K_p$$

More gain shrinks the error, until the loop overshoots and starts to hunt. Lab 7 adds an integral term that removes the error. In `p_loop.py` the whole controller is three lines:

```
error = TARGET - data['position']
duty = min(MAX_DUTY, max(0.0, KP * error))
link.write(('D0,%.1f\n' % duty).encode())
```

Two ways to measure position. The loop needs a position signal. This lab uses two.

- **A position sensor.** A slide potentiometer on the moving end reads position directly. The board reads it to 10 bits, about 0.1% of its travel, and the reading does not depend on load or temperature.
- **The actuator itself.** As nitinol transforms, its resistivity changes with the phase, and the part gets shorter and thicker. Its resistance falls by roughly 10 to 15% over the stroke, so resistance can stand in for position with no added sensor. This is self-sensing.

Self-sensing is elegant and demanding. The whole stroke is only about a tenth of the resistance, so the board has to resolve a small fraction of a percent of R to give useful position steps. Lead and contact resistance, load and ambient temperature all shift the map, and the resistance can be read only while current flows. Get the loop working on the sensor first. Then try resistance.

Resistance does have one advantage over heating power as a signal. Position plotted against power shows the full thermal hysteresis: 20 to 30 °C of dead band. Position plotted against resistance shows far less, since resistance follows the phase fraction directly.

The drive board measures the voltage and current of the whole loop, so its reading includes the leads and the MOSFET:

$$R_{actuator} = V / I - R_{leads}$$

■ Pre-lab

P1 An edge wound spring uses 0.15 × 0.41 mm strip. With a resistivity of 0.80 μΩ·m, find the resistance per 100 mm of strip.

P2 The current sensor resolves 4 mV. At 2.6 V and 1 A, what fraction of the resistance is one count? If resistance changes 12% over the full stroke, what position resolution does that give?

P3 The potentiometer has 60 mm of travel read to 10 bits, and the stroke is 30 mm. What is its position resolution as a percentage of stroke? Compare it with the resistance signal.

P4 Holding 50% takes a duty of 20%. What steady error does a proportional controller leave with $K_p = 2$? With $K_p = 8$?

■ Procedure

1. Hang the spring with the 20 g bias and couple the potentiometer slider to its moving end. Clip the leads together at the actuator end and measure the lead resistance with a short pulse.
2. **Calibrate the sensor.** Run `krl_console.py`. Send `L0,100` from the Command box. The position readout now shows the raw sensor count, 0 to 1023. Note the count with the spring fully extended. In open loop, raise the slider until the spring stops contracting and note the count again. Send both counts as `L<extended>,<contracted>`. The readout now runs from 0 to 100%. Check it against the ruler at mid-stroke.
3. **Open-loop map.** Start a log. Raise the duty from zero to full travel in 12 steps, waiting 20 seconds at each, then lower it in the same steps. Repeat for one more cycle, then once with the 50 g bias.
4. **Build the loop on the sensor.** Close the console. Open `p_loop.py` and read it until you can explain every line. Enter your two calibration counts, set `KP = 1` and `TARGET = 50`, and run it. Record the position it settles at and the duty it holds.
5. Repeat with `KP` set to 2, 4, 8 and 16. Note any overshoot, and the gain at which the position starts to hunt.
6. With your best gain, run targets of 25, 50 and 75%. Approach each from below. Then approach each from above: run a target of 90% first and restart at the lower target. Record each position from the ruler.
7. **The same loop on resistance.** From the heating branch of your 20 g map, read the resistance at 0% and 100% position. Enter them as `R_0` and `R_100`, set `SOURCE = 'resistance'`, and repeat step 6 at the same gain. The position column now comes from resistance, so read the true position from the ruler.

Data

Duty (%)	Current (A)	Voltage (V)	Resistance (Ω)	Position (%)

Signal	K_p	Target (%)	Approach	Settled position (%)	Holding duty (%)
Sensor					
Sensor					
Resistance					

Analysis

Q1 Plot position against average power, and position against resistance, for the same cycle. Report the hysteresis width of each as a percentage of the full span.

Q2 Plot the steady error of the sensor loop against K_p. Does it follow $e = D_{hold} / K_p$? What happened at the highest gains?

Q3 Did the direction of approach change where the loop settled? Why?

Q4 Compare the sensor loop with the resistance loop at the same gain: error against the ruler, noise in the duty, and repeatability.

Q5 How did the larger bias change the resistance map? What does that mean for a product whose load varies?

Q6 List two advantages and two limits of self-sensing compared with a separate position sensor. When would you choose each?

Report

A calibration sheet for the actuator: the resistance map, its fit, its hysteresis and the conditions it is valid for. Add one paragraph recommending a position signal and a gain for this actuator.

Go further

Warm the actuator with a hair dryer while it holds 50% under resistance feedback. How far does the true position move?

Go further: overdrive

Keep heating for 2 seconds after the stroke is complete and watch the resistance. Once the transformation is finished, resistance stops falling and starts to climb with temperature. Use that turn as a signature: change the firmware to report “overdrive” when it sees it.

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LAB

7

A User Interface for Proportional Control

Big idea: *A tuned loop, a slider and a clear display turn a proportional actuator into something another person can use.*

Actuator: Flat spring (SR) Time: Two 3-hour sessions

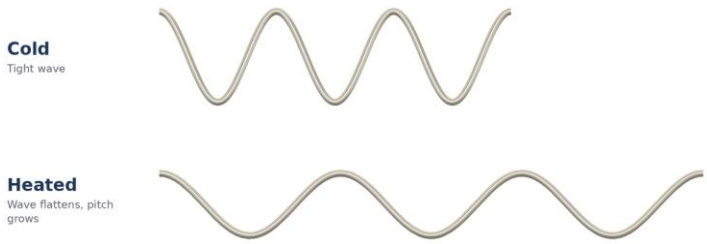


Figure 10. A flat spring. Heated, the wave flattens and the pitch grows.

Objectives

- Run and read the starter interface, first on a simulated actuator and then on hardware
- Add integral action to the proportional loop from Lab 6, tune it, and measure its step response
- Extend the interface with a feature of your own design and test it on another team

Equipment (per team)

- KRL flat spring actuator in a 3D-printed slotted track, with a light steel return spring
- Slide potentiometer coupled to the moving end
- Drive board, laptop with Python 3, the starter interface `krl_console.py` from the lab pack

Instrument option

Frequency response. Add a sine generator to the interface, sweep the target from 0.01 to 2 Hz, and plot gain and phase. Compare the bandwidth going up with the bandwidth going down.

Theory

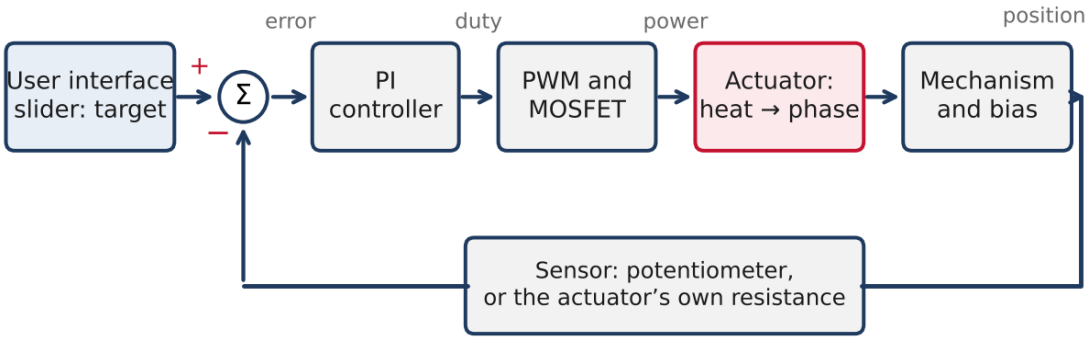


Figure 11. The position loop. The interface sets a target, the controller sets the duty, and the actuator converts heat into position.

The proportional loop in Lab 6 left a steady error. An integral term removes it. The firmware runs a proportional-integral (PI) controller 20 times a second on the position error e:

$$duty = K_p\, e + K_i \int e\, dt$$

Three features of nitinol shape the tuning.

- **One-sided actuation.** The controller can add heat but cannot remove it. The duty is clamped at zero, and the way down is set by cooling. Overshoot cannot be driven back, so tune for none.
- **Hysteresis.** After the target moves, the temperature must cross the dead band before the position follows. The integral term winds up while it waits. The firmware stops integrating whenever the duty is clamped.
- **A slow plant.** The thermal time constant is seconds. A 20 Hz loop and a 490 Hz PWM are both fast enough to treat as continuous.

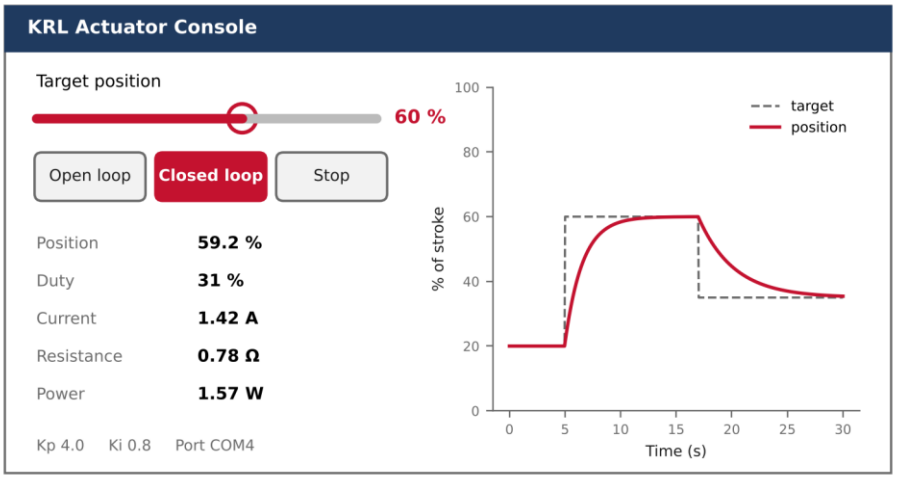


Figure 12. The starter interface: a target slider, mode buttons, live readouts and a strip chart.

Pre-lab

P1 An actuator has a thermal time constant of 5 s. What is its small-signal bandwidth?

P2 Read `krl_console.py`. What does the slider send in open loop, and what does it send in closed loop?

P3 Why does the interface resend the slider value once a second?

Procedure

1. **Simulation.** Run `python krl_console.py sim`. In open loop, raise the slider slowly and find the duty at which the simulated actuator starts to move and the duty at which it finishes. Lower it and find where it returns.
2. Select closed loop. Step the target from 20 to 60%, then to 35%. Try three sets of gains and note what each does.
3. **Hardware.** Connect the board. Calibrate the potentiometer from the Command box, as in Lab 6, so that the readout runs from 0 to 100% over the actuator's travel.
4. In open loop, map steady position against duty in ten steps up and ten down, waiting 20 seconds at each.
5. In closed loop, repeat the 20 to 60 to 35% steps with your best gains from step 2. Log each run. Adjust the gains until there is no overshoot going up.
6. Hold 50% for two minutes. Record the average power.

Your feature.

7. Add one feature to the interface. Choose from: a motion profile played from a file, a second actuator on channel 1 with its own slider, a soft start that limits the rate of change of the target, or a power and energy display with a limit. Agree the choice with your instructor.
8. Hand your laptop to a student from another team with no instructions. Ask them to move the actuator to 40%, hold it, and stop it. Note everything they get wrong.

Data

K_p	K_i	Step	Rise time (s)	Overshoot (%)	Steady error (%)
		20 → 60			
		60 → 35			
		20 → 60			

Analysis

Q1 Plot the open-loop map. How wide is the dead band, as a percentage of the duty range?

Q2 Report rise time, overshoot and steady error for each gain set. Which would you ship?

Q3 Compare the 20 to 60 step with the 60 to 35 step. Why are they different, and what would make them alike?

Q4 How much power did holding 50% take? Compare it with the holding power in Lab 5.

Q5 What did the outside operator get wrong, and what did you change?

Report

A short design note: the step-response plots, your gains, a screenshot of your interface, the code for your feature, and the usability findings.

Go further

Switch to mode 3 and close the loop on resistance instead of the potentiometer, using your Lab 6 method. Compare the step responses.

Go further: overdrive

Add an emergency mode to your interface: one button that sends a single hard pulse above the normal duty limit, with a lockout until the actuator has cooled and a counter that records every use. Raise the firmware limit only with your instructor's approval. Why does the counter matter?

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LAB

8

Thermal Management and Cycle Speed

Big idea: *Heating can be bought with power. Cooling has to be designed in.*

Actuator: Face wound spring (FW) Time: One 3-hour session



Figure 13. A face wound spring: flat wire coiled with its broad face against the mandrel.

Objectives

- Measure the cooling time constant in still air, in moving air and in water
- Predict and measure the fastest cycle rate in each case
- Compare flat strip with round wire, and choose a cooling strategy for a specified cycle rate

Equipment (per team)

- KRL face wound spring actuator with crimped terminals, and a steel bias spring or a hanging mass
- Your helical spring from Lab 3, for comparison
- Fine thermocouple held against a coil with polyimide tape, position potentiometer
- Small fan, 1 L beaker of distilled water at room temperature, drip tray
- Drive board and laptop, safety glasses

Instrument option

Thermal camera. Record the temperature along the spring during cooling. Check whether the end coils, clamped to cold terminals, cool first.

⚠ CAUTION	**Water near electronics.** Keep the beaker and drip tray below and away from the drive board. Keep the supply at 5 V or less, and dry the terminals after the water test.

Theory

A thin part cools as a lumped mass when its Biot number is small:

$$Bi = h\,L_c / k < 0.1 \qquad L_c = V / A_s$$

Its temperature then decays exponentially toward ambient with a time constant τ:

$$T(t) = T_\infty + (T_{hot} - T_\infty)\, e^{(-t/\tau)} \qquad \tau = \rho\, c\, L_c / h$$

For a round wire of diameter d, L_c is d/4. For a flat strip much wider than its thickness t, L_c is close to t/2. A strip has more surface for its section than a wire, so it cools faster. The actuator has reset when it reaches Mf, so the cooling time is:

$$t_{cool} = \tau \ ln\left[(T_{hot} - T_{\infty}) / (M_f - T_{\infty}) \right]$$

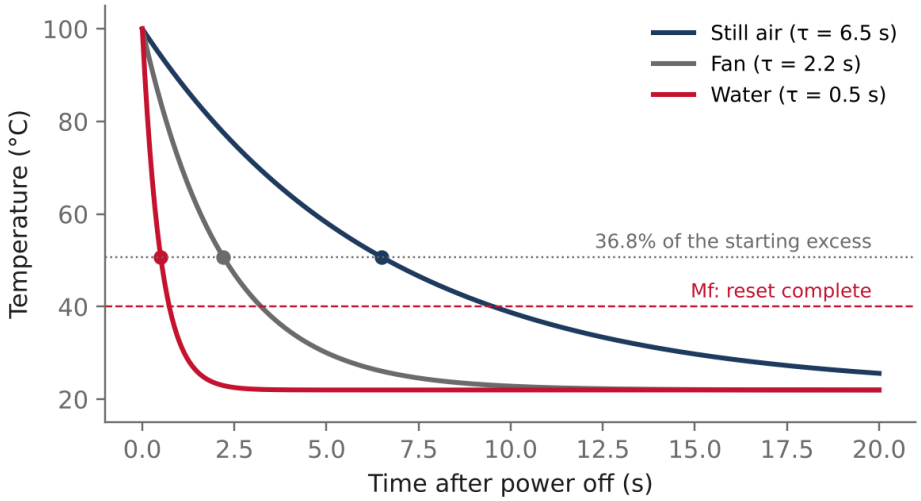


Figure 14. Cooling after power-off for three ways of removing heat. The dot on each curve marks one time constant.

Two levers follow. A larger h or a thinner section shortens τ. A higher transformation temperature raises Mf further above ambient, which shortens the wait.

■ Pre-lab

P1 Find τ for a 0.5 mm round wire with h = 60 W/(m²·°C), ρ = 6450 kg/m³ and c = 470 J/(kg·°C).

P2 That wire is at 90 °C, ambient is 22 °C and Mf is 45 °C. How long until it resets? Repeat for a grade 30 °C higher, starting at 120 °C with Mf at 75 °C.

P3 Find τ for a strip 0.15 mm thick at the same h. Check its Biot number with k = 10 W/(m·°C).

■ Procedure

1. Mount the face wound spring with its bias and calibrate the position readout.
2. Heat to full stroke, then cut the power. Log temperature and position until the spring has fully reset. Repeat three times in still air.
3. Repeat with the fan blowing across the spring.
4. Repeat with the spring submerged in the water. Note the power needed to reach full stroke under water.
5. For each case, run the actuator on a square-wave target and raise the frequency until the stroke falls to 70% of its full value. Record that frequency.
6. Repeat the still-air test with your round-wire helical spring from Lab 3.

■ Data

Actuator and cooling	τ (s)	Time to reset (s)	Fastest rate at 70% stroke (Hz)	Power to actuate (W)
Face wound, still air				
Face wound, fan				
Face wound, water				
Helical, still air				

■ Analysis

Q1 Fit an exponential to each cooling curve. Report τ and the h it implies.

Q2 Compare the measured fastest rates with $1/(t_{heat} + t_{cool})$.

Q3 How much more power did the spring need under water? What control strategy avoids that cost?

Q4 Compare τ for the flat-strip spring and the round-wire spring. Does the ratio follow L_c?

Q5 A product needs 2 Hz. List three ways to get there and the price of each.

■ Report

A one-page thermal design note for a 2 Hz version of this actuator, with the predicted cycle time.

■ Go further

Point the fan along the coil axis instead of across it. Does the direction matter?

■ Go further: overdrive

Overdrive the spring to 60 °C above Af, cut the power and time the reset. Compare with the reset after a normal stroke, and with the prediction from the cooling-time equation. Emergency mode has a price in cycle time.

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PART 3

Design and Sizing

Labs 9 to 12 are design labs. Each starts from a requirement, sizes an actuator form the students have not used before, and tests the result against the prediction.

LAB

9

High Force From a Small Stack

Big idea: *A Belleville actuator trades almost all of its stroke for force, and stacking trades it back.*

Actuator: Belleville (BV) Time: One 3-hour session



Figure 15. A Belleville washer, and three stacked in series.

Objectives

- Measure the force and stroke of a single Belleville actuator by constant-load recovery
- Test the series and parallel stacking rules
- Size a stack for a specified force and stroke

Equipment (per team)

- Four KRL Belleville actuators of one size, with a guide pin that fits the bore
- Lever press with a 10:1 ratio (see Instructor Pages), dial indicator reading 0.01 mm
- Hooked masses to 3 kg, small aluminum cup that holds the stack under water
- Kettle, water at 95 °C and at room temperature, thermocouple, turkey baster or syringe, safety glasses

Instrument option

Load frame with a heated platen or chamber. Record the full force-deflection curve cold and hot, single and stacked, and overlay them.

⚠ WARNING	**Pinch and eye hazard.** The stack pushes with hundreds of newtons. Keep fingers out of the lever press, guide the stack on its pin and wear safety glasses.

Theory

A Belleville actuator is a conical disc. Cold, a load flattens it. Hot, it recovers its cone and pushes back. The stroke is a fraction of a millimeter and the force is very high for the size. A disc 9 mm across with a 5 mm bore, 1 mm thick, delivers roughly 300 N over about 0.3 mm.

Stacking changes the gear ratio. For N discs:

Series (cones alternating): stroke × N, force unchanged *Parallel (cones nested): force × N, stroke unchanged*

An actuator's output falls from its **blocked force** at zero travel to zero force at its **free stroke**. If the fall is close to linear, the most work comes from the middle of the line:

$$W_{max} \approx F_{blocked}\,\delta_{free} / 4$$

A thick disc has too little electrical resistance to heat with current, so this lab heats with hot water. In a product the heat would come from a heating element or from the surroundings.

Pre-lab

P1 A 2 kg mass hangs at the end of a 10:1 lever. What force acts on the stack? If the stack lifts 0.3 mm, how far does the mass rise?

P2 Estimate the mass of the 9 mm disc and its largest work per gram, using the linear model. Compare with a wire at 170 MPa and 4%.

P3 Which stack gives 600 N over 0.6 mm from these discs?

Procedure

1. Zero the dial indicator on the lever with the cup and one cold disc in place and no load.
2. Hang 0.5 kg. Wait for the disc to settle and record the indicator. Fill the cup with 95 °C water and record the rise. Draw the hot water off, refill with room-temperature water, and let the disc reset.
3. Repeat with 1, 1.5, 2, 2.5 and 3 kg, or until the hot disc no longer lifts the load.
4. Repeat the series with two discs in series, then with two in parallel.
5. Build the stack from your pre-lab and test it at three loads.

Data

Load on stack (N)	Cold height change (mm)	Hot lift (mm)	Work (mJ)

Analysis

Q1 Plot hot lift against load for the single disc. Extrapolate to find the blocked force and the free stroke.

Q2 Do the series and parallel stacks follow the rules? Where do they fall short?

Q3 At what load is the work per cycle greatest? Compare the work per gram with your pre-lab estimate.

Q4 Did your pre-lab stack meet 600 N over 0.6 mm? What would you change?

Q5 The disc heated in seconds in water. How would you heat it in a dry product, and what sets the cycle time?

Report

A one-page sizing sheet: the single-disc line, the stacking factors you measured, and a stack design for 1 kN over 1 mm.

Go further

Put a steel Belleville washer of the same size in the press. Compare its behavior between cold and hot water.

Go further: overdrive

Find the largest load one disc lifts in 95 °C water. Then heat the dry disc with a hot air gun to 150 °C on a thermocouple and find the largest load again. Express the gain as a percentage of the rated force.

NOTES

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LAB

10

Direct-Drive Rotation

Big idea: *A rod twisted cold untwists when heated: a rotary actuator with no bearing, gear or lever. Its radius sets the angle and its section sets the torque.*

Actuator: Rod (RB), in torsion Time: One 3-hour session



Figure 16. Nitinol rod and bar in a range of sizes.

Objectives

- Measure recovered angle against torque for a nitinol rod in torsion
- Test the relations between angle, length and radius, and between torque and section
- Size a rotary actuator for a specified joint

Equipment (per team)

- KRL 2 mm nitinol rod, 100 mm long, with flatted ends
- Fixed clamp, bearing block and a 100 mm arm
- Hooked masses from 20 to 300 g, protractor or rotary potentiometer
- Hot air gun and a thermocouple taped to the rod
- Calipers, gloves, safety glasses

Instrument option

Torsion tester with a furnace. Record torque against twist cold and hot, and the recovery under constant torque as the rod is heated.

⚠ WARNING	**Burn hazard.** The hot air gun and the rod exceed 100 °C. Let the rod cool below 40 °C on the thermocouple before touching it.

Theory

Twisting a rod strains it in shear, most at the outer surface. For a rod of length L and radius r twisted through an angle θ:

$$\gamma = \theta\, r / L \qquad so \qquad \theta = \gamma\, L / r$$

A longer or thinner rod swings further. The torque at a surface shear stress τ is:

$$T = \tau\, J / r \qquad J = \pi\, r^4 / 2$$

Metal near the axis is barely strained and adds little torque. KRL's production torque actuators are tubes for that reason: the bore removes metal that does little work. A tube of outer radius r_o and bore radius r_i has:

$$J = \pi\,(r_o^{\,4} - r_i^{\,4}) / 2$$

A rod is used here since it costs far less in small quantities. Like the Belleville, it is too thick to heat with current, so this lab heats it with hot air.

Pre-lab

P1 A rod has r = 1.0 mm and L = 60 mm between the clamp and the arm. What angle corresponds to a shear strain of 3%?

P2 Find J, the torque at 100 MPa, and the mass that torque lifts on a 100 mm arm.

P3 A tube of the same outer radius has a bore 60% of its diameter. How much torque does it give up, and how much mass does it save?

Procedure

1. Measure the rod's diameter and its free length between the clamp and the arm.
2. With the rod cold, hang 20 g on the arm and note the angle. Add mass until the arm has turned through the angle for 3% strain from your pre-lab calculation. Do not exceed it.
3. Keep that mass on the arm and heat the rod evenly to 20 °C above its Af. Record the angle recovered.
4. Let it cool under load and record the angle it returns to. This is one biased cycle.
5. Repeat steps 3 and 4 at four more masses, up to the one the hot rod cannot lift.
6. Record how long heating and cooling take.

Data

Torque (N·mm)	Cold angle (°)	Hot angle (°)	Angle recovered (°)	Work (mJ)

Analysis

Q1 Plot the angle recovered against torque. Estimate the blocked torque and the free angle.

Q2 From the free angle, find the shear strain actually recovered.

Q3 Compare the torque per gram of your rod with the tube in the pre-lab.

Q4 Size a solid rod for a joint that needs 2 N·m through 90°. Use 100 MPa and 3% strain.

Q5 How long did a cycle take? What would you change for a joint that must cycle every 10 seconds?

Report

A one-page design sheet for the 2 N·m joint in Q4, with the rod size, the heating method and the expected cycle time.

Go further

Mount two rods end to end, twisted in opposite directions, with the arm between them. Heat one, then the other. You have built an opposing pair that is powered both ways.

Go further: overdrive

Find the largest torque the rod lifts at 20 °C above Af, then at 80 °C above Af. Plot blocked torque against temperature and compare the slope with the stress rate from Lab 1.

NOTES

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LAB

11

Bistability and Passive Control

Big idea: *A snap-through actuator collects heat slowly and releases its stroke all at once, with no controller.*

Actuator: Snap-through (ST) Time: One 3-hour session



Figure 17. A snap-through actuator in cutaway: a nitinol dome, armed (pressed inside out) and tripped (snapped back on heating).

Objectives

- Measure the trip temperature of a snap-through dome and its repeatability
- Measure the energy and the duration of the snap
- Design a passive thermal safety device around it

Equipment (per team)

- Three KRL snap-through domes of one size, with a seat ring that lets the rim turn
- Arming tool with a rounded tip, 6 mm steel ball, vertical clear tube with a millimeter scale
- 2 L beaker, hot plate with stirrer, thermocouple, tongs
- Small resistor or cartridge heater, phone camera with slow motion, spring-loaded pin with a known rate
- Safety glasses

Instrument option

High-speed camera and force sensor. Film the snap at 5,000 frames per second or more, and record the impulse with a piezoelectric force sensor on an oscilloscope.

⚠ WARNING	**Eye hazard: sudden release.** An armed dome trips without warning as it warms, even in a hand. Wear safety glasses, and keep armed domes in ice water until they are seated.

Theory

The dome is shape-set as a shallow spherical cap. Pressed inside out while cold, it stays inverted with no power. As it warms, recovery stress builds while the inverted shape still holds. At the trip temperature the inverted shape becomes unstable and the dome snaps back. Heating can take seconds or minutes. The snap does not.

That separates two things every other actuator ties together: the power of the heat source and the speed of the stroke. A weak source, or the surroundings alone, can trigger a fast, strong motion.

A ball of mass m resting on the dome and launched to a height h gives a lower bound on the energy released:

$$E \geq m\,g\,h$$

Stress moves the trip temperature, as in Lab 1. A preload that resists the snap raises it.

Pre-lab

P1 A 6 mm steel ball weighs 0.88 g. It is launched 150 mm. What energy did it receive?

P2 The dome took 30 s to warm at 0.5 W and delivered that energy in 4 ms. Compare the mechanical power during the snap with the average over the warm-up.

P3 A device must not trip in a 60 °C car interior and must trip by 90 °C. What trip temperature and tolerance would you specify?

Procedure

1. **Trip temperature.** Arm a cold dome and seat it in its ring. Lower it into the bath at 30 °C and heat at 1 °C per minute. Record the temperature at the snap.
2. Cool, re-arm and repeat five times. Then test the other two domes three times each.
3. **Energy.** Seat an armed dome under the clear tube with the ball resting on its center. Warm it with the heater. Film the launch in slow motion and read the peak height. Repeat five times.
4. Count the video frames in which the dome is moving, and note the frame rate.
5. **Preload.** Press the spring-loaded pin on the center of an armed dome with a force of 1 N, and repeat the trip temperature test. Repeat at 2 N and 4 N.

Data

Trial	Dome	Preload (N)	Trip temperature (°C)	Launch height (mm)

Analysis

Q1 Report the mean and standard deviation of the trip temperature for one dome, and across the three domes.

Q2 Report the launch energy and its scatter. How long did the snap last?

Q3 How did preload change the trip temperature? Relate the slope to Lab 1.

Q4 Compare the dome with a bimetal snap disc, a fusible link and a pyrotechnic release. Consider trigger, force, reuse and testability.

Q5 Sketch a battery disconnect that opens when a cell overheats. State the trip temperature and how you would test each unit.

Report

A one-page specification for the device in Q5: trip temperature and tolerance, force, reset method and test method.

Go further

Stack two domes in series and repeat the launch test. Does the energy double?

Go further: overdrive

Trip a dome with a slow ramp, then with the heater at full power pressed against it. Compare the launch heights. Does heating faster change the energy of the snap, or only the wait?

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LAB

12

A Peristaltic Pump With No Motor

Big idea: *Several simple actuators fired in the right order do a job none of them can do alone.*

Actuator: Peristaltic actuator (PE) Time: One 3-hour session

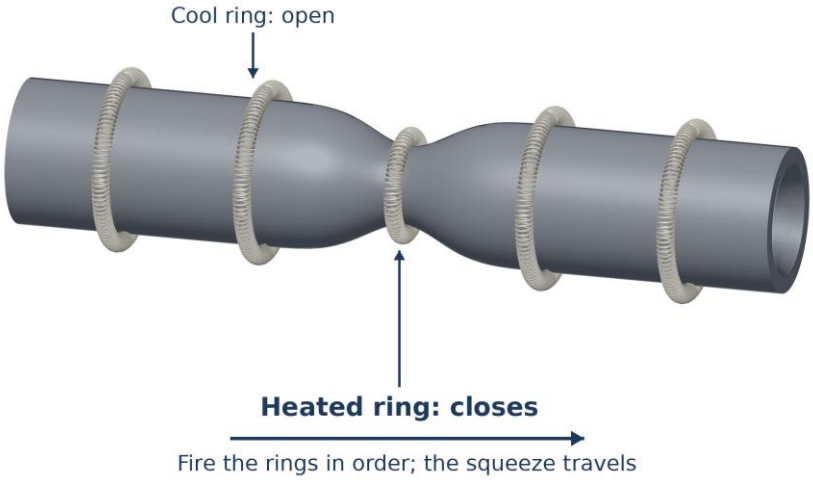


Figure 18. A peristaltic actuator: a soft tube ringed with spring actuators. A heated ring closes. Fired in order, the rings push the squeeze along.

Objectives

- Extend the interface to sequence four channels
- Measure pumped volume per cycle against timing, overlap and back pressure
- Find the fastest useful cycle and explain what limits it

Equipment (per team)

- KRL peristaltic actuator: a soft silicone tube with four spring-actuator rings
- Drive board with all four channels, laptop with your interface from Lab 7
- Two reservoirs, 10 mL graduated cylinder, ruler, stopwatch, water with a drop of food coloring, drip tray

Instrument option

Flow and pressure sensors. Log flow and outlet pressure through each cycle and plot the pressure-flow curve of the pump.

⚠ CAUTION	**Water near electronics.** Keep the reservoirs and tubing below the drive board and dry the ring terminals before applying power.

Theory

A ring of straight wire closes a tube by only a few percent of its diameter. A ring wound from a spring closes it by a third or more, enough to pinch it shut. Fire the rings in order and the pinch travels down the tube, pushing fluid ahead of it, the way a throat swallows.

If each ring displaces the volume under it, a tube of inside radius r_i and a ring of width w give, per cycle and per second:

$$V_{cycle} \approx \pi r_i^{\,2} w \qquad Q = V_{cycle} f$$

A single ring pushes fluid both ways. Keeping two rings closed at once blocks the way back, so the pump is its own check valve. That is the **overlap**. Cycle speed is set by how fast the rings cool, and the fluid itself cools them.

The pinch pressure of a ring with tension F on a tube of radius r over a width w is about F/(r w). The pump cannot deliver against a higher pressure than that.

Pre-lab

P1 The tube bore is 4 mm and each ring closes 12 mm of it fully. Find the volume per cycle and the flow at 0.2 Hz.

P2 Each ring has a resistance of 1.3 Ω and takes 1.5 A. With two rings on at once, what current does the supply deliver? Is the sensor within its range?

P3 Draw a timing diagram for four rings with 50% overlap between neighbors.

Procedure

1. Add a sequencer to your interface: a period, an on-time per ring and a delay between rings, sent as duty commands on channels 0 to 3.
2. Fill the tube and both reservoirs with no air. Set the outlet level with the inlet. Fire one ring alone ten times and record the net volume moved.
3. Run the four-ring sequence with no overlap at a 20 s period for 20 cycles. Record the volume delivered.
4. Repeat with 50% overlap.
5. With overlap, shorten the period in steps until the delivered volume per cycle falls to half.
6. At the best period, raise the outlet 100 mm, then 200 mm, and repeat. Then reverse the firing order.

Data

Sequence	Period (s)	Outlet head (mm)	Volume in 20 cycles (mL)	Volume per cycle (mL)
One ring		0		
No overlap	20	0		
50% overlap	20	0		

Analysis

Q1 Compare the volume per cycle with the prediction. What is the volumetric efficiency?

Q2 What did overlap change, and why?

Q3 Plot flow against frequency. Where is the peak and what limits it?

Q4 What was the highest head the pump held? Compare it with the pinch pressure estimate.

Q5 Name one application where this pump beats a motor-driven one, and one where it does not.

Report

A one-page data sheet for your pump: flow against frequency, flow against head, power, and the timing you recommend.

Go further

Empty the tube and drop in a soft foam pellet. Can the same sequence swallow it and pass it along?

Go further: overdrive

Raise the outlet until the pump stalls. Then drive each ring with a short pulse at 1.5 times its normal current, staying within the sensor limit. How much more head does the pump hold? A pump that can clear its own blockage is an emergency mode.

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PART 4

Life and Systems

Labs 13 and 14 look at the whole product: how long an actuator lasts, and how one part can do the work of a mechanism. An open design project follows.

LAB

13

Fatigue and Life

Big idea: *How hard nitinol is worked decides how long it lasts. Strain is the design variable.*

Actuator: Split ring or C-clip (CC) Time: One 3-hour session, plus a run that continues overnight

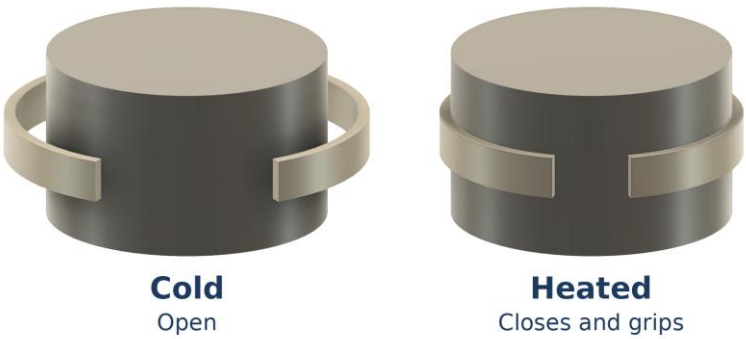


Figure 19. A C-clip, open when cold, closes onto the shaft when heated.

Objectives

- Cycle C-clip actuators at three strain levels with an automatic test
- Separate functional fatigue (loss of stroke) from structural fatigue (cracking)
- Compare the measured lives with the handbook design levels and apply a damage rule to a duty cycle

Equipment (per team)

- Six KRL C-clip actuators of one size, with crimped leads
- Fatigue fixture: a fixed post, and a sprung jaw that re-opens the cold clip to a set gap (see Instructor Pages)
- Three gap stops, for 2.5, 5 and 7% strain
- Drive board, position potentiometer on the jaw, small fan, clear polycarbonate shield, laptop

Instrument option

Scanning electron microscope and DSC. Image a fracture surface and find where the crack started. Run DSC on a cycled clip and a new one to see how cycling moved the transformation temperatures.

NOTICE	**Unattended running.** Leave a test running overnight only inside the shield, with the supply's current limit set, the firmware limits in place and your instructor's approval.

Theory

A nitinol actuator wears out in two ways. **Functional fatigue** is a slow loss of function: the stroke shrinks, the cold rest position creeps and the transformation temperatures shift, with nothing cracked. **Structural fatigue** is the growth of a crack, usually from the surface or an attachment, until the part breaks.

Both are driven by strain. The handbook's four design levels pair a strain with a life (see Nitinol in Brief). A C-clip of thickness t that moves between a closed radius R_c and an open radius R_o sees a surface strain of:

$$\varepsilon = (t / 2)\,(1/R_c - 1/R_o)$$

When the duty cycle mixes strain levels, Miner's rule adds the damage. With n_i cycles at a level whose life is N_i, failure is expected when:

$$\Sigma\,(n_i / N_i) = 1$$

Pre-lab

P1 A clip has t = 1.0 mm and a memory radius of 6 mm. What open radius gives 5% strain? What about 2.5% and 7%?

P2 One cycle takes 2 s of heating and 4 s of cooling under the fan. How long do 10,000 cycles take?

P3 A latch cycles 200 times a day at 2.5% and is forced 5 times a day at 7%. Use the design levels and Miner's rule to estimate its life.

Procedure

1. Fit the 7% stop. Mount a clip, set the fan, and find the shortest heating and cooling times that give full stroke. Use those times for every test.
2. Start the automatic test with the C command. Log the stroke every cycle. Run to fracture or to 500 cycles.
3. Fit the 5% stop and a new clip. Run 2,000 cycles during the session, and to 10,000 overnight if approved.
4. Fit the 2.5% stop and a new clip. Run 2,000 cycles.
5. For each clip, record the stroke and the cold rest position at cycles 1, 10, 100, 1,000 and at the end.
6. Examine each broken clip with a magnifier. Sketch where it cracked.

Data

Strain (%)	Cycles run	Stroke at cycle 1 (mm)	Stroke at end (mm)	Cycles to fracture
7				
5				
2.5				

Analysis

Q1 Plot stroke against cycles on a log axis for each strain. How much stroke was lost in the first 100 cycles, and after that?

Q2 Compare the cycles to fracture with the handbook design levels. Are the levels conservative?

Q3 Pool the class data and fit N = C ε^(−b). What exponent do you get?

Q4 Where did the clips crack, and why there?

Q5 A customer wants 100,000 cycles and the stroke of level C. Offer two ways to give them both.

Report

A one-page life estimate for a product of your choice: the duty cycle, the strain at each condition, the damage sum and the predicted life with a stated margin.

Go further

Leave the 2.5% test running for the rest of the semester and report its life in your project presentation.

Go further: overdrive

Cycle two clips at 5% strain: one normally, and one with every heating pulse twice as long. Compare the loss of stroke over 1,000 cycles. Then give the normal clip a single overdriven cycle and check whether any stroke comes back. Overdriving costs life, and an occasional hot cycle can also restore a tired part.

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LAB

14

Many Degrees of Freedom in One Part

Big idea: *A conventional actuator has one degree of freedom. One piece of nitinol can have many.*

Actuator: Multi-degree-of-freedom actuator Time: Two 3-hour sessions

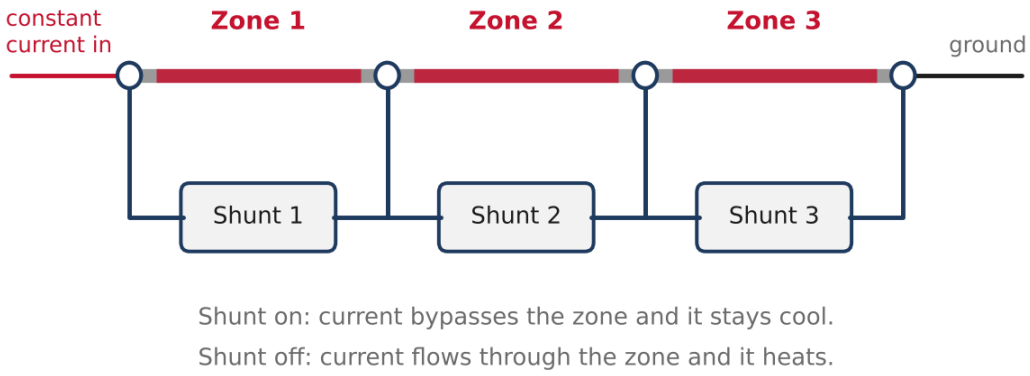


Figure 20. A multi-degree-of-freedom actuator: one part with three curl zones in series. A shunt MOSFET across each zone decides whether that zone heats.

Objectives

- Wire and command three independent bending zones in a single nitinol part
- Calibrate each zone, measure the crosstalk between zones, and predict the tip position
- Compare the part count with a motor-driven mechanism that does the same job

Equipment (per team)

- KRL three-zone curl actuator with four taps, on a superelastic backbone that straightens it when cool
- Drive board: channel 0 in series with the actuator as the master, channels 1 to 3 as shunts across the zones
- Bench supply with its current limit set to 2.0 A
- Laptop with your interface, phone camera on a stand, 10 mm grid as a background

Instrument option

Motion capture or a thermal camera. Track markers on each zone for the pose, or image the temperature along the part to see heat leak from one zone into the next.

Theory

A degree of freedom is one independent way to move. A conventional design needs an actuator for each one, plus the linkages, bearings and fasteners between them. Nitinol has no such limit. Zones of one part can be set to bend, twist or curl, and each zone can be heated separately. KRL has built a single part with 79 degrees of freedom.

This lab heats zones by **shunting**. A constant current runs through the whole actuator. A MOSFET across each zone carries the current around that zone when it is on, so the zone stays cool. Switch the shunt off and the zone heats. Pulse the shunt and the zone gets a share of the power:

$$P_{zone} \approx (1 - D_{shunt})\, I^2 R_{zone}$$

Treat each zone as a hinge at its center joining links of length L. With zone angles θ_1, θ_2 and θ_3, the tip is at:

$$x = L\,[\cos\theta_1 + \cos(\theta_1+\theta_2) + \cos(\theta_1+\theta_2+\theta_3)] \qquad y = L\,[\sin\theta_1 + \sin(\theta_1+\theta_2) + \sin(\theta_1+\theta_2+\theta_3)]$$

Heat conducts along the part, so a hot zone warms its neighbors. That **crosstalk** is the main limit on how closely zones can be packed.

Pre-lab

P1 Each zone is 40 mm of 0.5 mm wire. Find its resistance, and its voltage and power at 2 A.

P2 A shunt MOSFET has an on-resistance of 20 mΩ. What share of the current still flows through a shunted zone, and what share of full power does it get?

P3 With L = 40 mm, find the tip position for zone angles of 30°, −30° and 45°.

Procedure

1. Wire the shunts as in the figure. Each shunt's gate is driven from its channel pin through 220 Ω.
2. Turn all three shunts fully on, then bring the master to 60%. Confirm that no zone moves.
3. Add three sliders to your interface, one per zone, that set each shunt's duty. Label them by zone power, which is 100% minus the shunt duty.
4. **Calibration.** For zone 1 alone, step the zone power from 0 to 100% in six steps. Photograph the part against the grid at each step and measure the zone angle. Repeat for zones 2 and 3.
5. **Crosstalk.** Hold zone 2 at 100% for 60 seconds with the others at 0%. Measure the angles of zones 1 and 3.
6. **Poses.** Choose five poses. For each, predict the tip position, command it, photograph it and measure the tip.
7. Step zone 1 from 0 to 100% and time the motion. Then time the return.

Data

Pose	Zone powers (%)	Zone angles (°)	Tip predicted (mm)	Tip measured (mm)
1				
2				
3				

Analysis

Q1 Plot angle against zone power for each zone. Are the three alike? Is the relation proportional?

Q2 Express the crosstalk as the neighbor's motion over the driven zone's motion. How would you reduce it?

Q3 What was the tip error across your five poses? What dominates it?

Q4 List the parts of a motor-driven mechanism with the same three degrees of freedom. Compare the count with this actuator.

Q5 How do the wire count and the driver count grow with the number of zones? What would you change at 20 zones?

Report

A short technical note: the calibration curves, the crosstalk, the pose errors, and a paragraph on what a 10-zone version would need.

Go further

Close the loop on one zone with a camera or with its resistance, measured across its two taps, and repeat the pose test.

■ Go further: overdrive

Block the tip against a small scale. Shunt two zones, and give the third a single hard pulse with the master at full duty for 1 second. How much more tip force does the pulse give than normal drive, and how much did the neighboring zones move?

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Design Project

The semester ends with an open project. Each team designs, builds and tests a nitinol actuator system to a specification of its own, using any form in KRL's Handbook of Nitinol Actuators.

The brief

- Write a one-page specification: the motion, force and stroke at the output, the cycle rate, the life, the ambient temperature range and the power available.
- Choose the form by the motion, the design level by the life, and the transformation temperature by the ambient range.
- Size the actuator for force and stroke, then the bias, the drive and the cooling.
- Build it, with a user interface that gives proportional control or a clear reason why the design does not need one.
- Test it against every line of the specification.

Deliverables

- Design report of no more than eight pages, with the calculations in an appendix
- A working demonstration and a five-minute presentation
- A test report: each requirement, the measured result, and pass or fail

Scoring

Criterion	Points	What earns full marks
Specification	10	Complete, measurable and testable
Form selection and sizing	25	Choices follow from the requirements, with correct stress, strain and thermal calculations
Drive, control and interface	20	Safe, stable, and usable by someone outside the team
Build quality	15	Terminations, strain relief and heat isolation done properly
Testing	20	Every requirement tested, with uncertainty, and failures reported honestly
Communication	10	Clear, short, and readable by a manager who is not a specialist

> Tight tolerances are expensive. A specification that asks for more precision, life or speed than the product needs will cost more to meet. Ask for what the product needs.

Instructor Pages

Kits and equipment, fixtures, a semester plan, expected results and answer keys, code listings and troubleshooting.

Equipment and Kits

KRL College Kit (per team)

Item	Quantity	Labs
0.5 mm nitinol actuator wire, Af near 70 °C	5 m	1, 3, 5
Helical spring actuators, 0.5 mm wire, 10 coils, memory shape closed	4	4
Actuator flat wire and superelastic flat wire, same section	2 × 80 mm each	2
Torsion spring actuator	2	5
Edge wound spring actuator with terminals	2	6
Flat spring actuator	2	7
Face wound spring actuator with terminals	2	8
Belleville actuators with guide pin	4	9
2 mm nitinol rod, 100 mm, with flatted ends	1	10
Snap-through domes with seat ring	3	11
Peristaltic actuator, four rings on a silicone tube	1	12
C-clip actuators with leads, and three gap stops	6	13
Three-zone curl actuator with four taps and backbone	1	14
Crimp sleeves and M3 ring terminals	40	All
Data cards for every part	1 set	All

Lab-supplied equipment (per team)

- Drive board parts (see Build: The Drive Board), bench supply 0 to 5 V and 5 A with current limit, digital multimeter
- Laptop with Python 3, pyserial and the Arduino IDE
- Type K thermocouple and reader, hot plate with stirrer, 2 L beaker, kettle, ice, tongs
- Hooked masses from 1 g to 3 kg, steel ruler, calipers, micrometer, dial indicator reading 0.01 mm, protractor
- Rigid frame or test stand (aluminum T-slot extrusion is a strong, low-cost choice), clamps, 3D-printed fixtures in PETG or ASA, silicone washers
- Crimp tool, flush cutters, pliers, small fan, syringes and tubing, phone camera
- Safety glasses for every student

Shared equipment

- Furnace or kiln to 550 °C with a thermocouple, long tongs, furnace gloves, metal quench bucket (Lab 3)
- 3D printer, and a hot air gun (Lab 10)
- Clear polycarbonate shields for unattended fatigue tests (Lab 13)

Instrument options

Lab	Instrument	What it adds
1, 3, 4, 13	Differential scanning calorimeter	Stress-free transformation temperatures and latent heat, ASTM F2004
2, 9	Load frame, with a heated platen or chamber for Lab 9	Tensile properties to ASTM F2516 and full force-deflection curves

Lab	Instrument	What it adds
3	Programmable furnace	A full time and temperature matrix
5, 8, 14	Thermal camera or data acquisition	Temperature through the cycle and along the part
6, 7	Source-measure unit, displacement sensor	Four-wire resistance and reference position
10	Torsion tester	Torque against twist, cold and hot
11	High-speed camera, force sensor	Snap duration and impulse
12	Flow and pressure sensors	Pump curve
13	Scanning electron microscope	Fracture origin

Fixtures to build

Lever press, Lab 9. A stiff steel or aluminum bar pivots on a pin at one end. The stack sits on a flat anvil 30 mm from the pivot, under a hardened pad on the bar. Masses hang 300 mm from the pivot, and the dial indicator reads the bar at the same point. Weigh the bar and add its moment to every load.

Fatigue fixture, Lab 13. One end of the clip seats on a fixed post. The other seats on a jaw that slides on a rail and is pulled outward by a steel extension spring. Interchangeable stops limit the jaw's outward travel, which sets the open radius and so the strain. A slide potentiometer on the jaw reports the stroke.

A semester plan

Week	Activity
1	Safety, Nitinol in Brief, kit check
2 to 5	Labs 1 to 4
6	Build the drive board, Lab 5
7	Lab 6
8 and 9	Lab 7 (two sessions)
10	Lab 8
11 and 12	Labs 9 to 12, two labs per week in rotating stations, or choose two of the four
13	Lab 13, with the overnight run
14	Lab 14
15	Design project presentations

A 10-week quarter can drop Labs 4, 10 and 12 without breaking the sequence.

Expected Results and Answer Keys

Numbers are typical for the parts in the KRL College Kit. Use the data cards where they differ. P marks a pre-lab question and Q an analysis question.

Lab 1: Transformation Temperatures Under Load

P1 0.5 kg: $F = 0.5 \times 9.81 \times 0.873 = 4.28$ N, $\sigma = 4.28 / 0.196 = 21.8$ MPa. 2 kg: $F = 17.1$ N, $\sigma = 87.4$ MPa.

P2 $(87.4 - 21.8) / 6.5 = 10.1$ °C.

P3 $6450 \times 24{,}000 / (340 \times 0.06) = 7.6$ MPa/K, inside the 5 to 8 MPa/°C range.

Q1 For wire with an Af near 70 °C, expect roughly As 60 to 68, Af 70 to 78, Ms 50 to 58 and Mf 40 to 48 °C at 22 MPa. All four sit 8 to 13 °C higher at 87 MPa. Recovered strain is 3 to 5%.

Q2 20 to 30 °C. It changes little with stress.

Q3 5 to 8 MPa/°C. With 1 °C temperature resolution on a 10 °C shift, the uncertainty is about ±15%.

Q4 Mf under 100 MPa is about the stress-free Mf plus 100 / 6.5 = 15 °C, so about 55 to 63 °C. That is at or below the 60 °C ambient, so the wire will not reset reliably. Use a higher transformation temperature, a cooler location or a lower stress.

Q5 The zero-stress intercept and the bend and free recovery Af usually agree within a few degrees. DSC often differs by several degrees, since it senses heat flow in a stress-free sample and the other two sense motion. A specification must name the test method along with the temperature.

Lab 2: Two Phases, Two Stiffnesses

P1 $F = E\, b\, t^3\, \delta / (4\, L^3) = 30{,}000 \times 3.0 \times 0.125 \times 5 / (4 \times 125{,}000) = 0.113$ N, about 11.5 g.

P2 $\varepsilon = 3 \times 0.5 \times 5 / (2 \times 2500) = 0.0015$, or 0.15%. Yes, well inside the elastic range of both phases.

P3 $D = t\,(1/\varepsilon - 1) = 0.5 \times 24 = 12$ mm.

Q1 Martensite 25 to 40 GPa, austenite 60 to 85 GPa. A 2% error in thickness becomes a 6% error in E.

Q2 Austenite is 2 to 3 times stiffer. The same part is a stiff spring hot and a soft one cold, which is half of why the hot actuator wins against the bias.

Q3 A set appears near 1% strain, where detwinning begins. Heating transforms the martensite to austenite, which has only one variant, so the strip returns to its memory shape.

Q4 None up to the 8 mm mandrel (about 6%). Superelastic nitinol recovers 6 to 8%.

Q5 Cold, the bias must exceed the detwinning plateau (roughly 100 to 200 MPa in the wire) to stretch it. Hot, the recovery stress of austenite is several hundred MPa, so the wire overpowers the bias. The bias must sit between the two: strong enough to reset the cold wire, weak enough not to stall the hot one.

Lab 3: Shape Setting a Spring

P1 $\delta = \pi\, D^2\, n\, \gamma / d = \pi \times 42.25 \times 20 \times 0.02 / 0.5 = 106$ mm, about ten times its solid length of 10 mm.

P2 $F = \pi\, d^3\, \tau / (8\, D) = \pi \times 0.125 \times 150 / 52 = 1.13$ N.

P3 $D^3 = 274.6$ mm^3. Austenite: $25{,}000 \times 0.0625 / (8 \times 274.6 \times 20) = 0.036$ N/mm. Martensite: 0.011 N/mm.

Q1 Springback falls as temperature rises: several percent at 450 °C and near zero at 550 °C.

Q2 Expect a shift of several degrees across the three treatments. The direction depends on the alloy and its cold work, so report what was measured.

Q3 Austenite 20 to 28 GPa, martensite 7 to 10 GPa: a ratio of 2 to 3, as in Lab 2.

Q4 Usually near 500 °C: the shape is set, and the wire keeps its strength. Before committing, check Af, the recovered stroke and how both hold up over a few hundred cycles.

Q5 Slow cooling holds the part at intermediate temperatures for an uncontrolled time, where the microstructure and Af keep changing. Quenching makes the treatment repeatable.

Lab 4: Training a Two-Way Spring

P1 $\delta = \pi\, D^2\, n\, \gamma / d = \pi \times 42.25 \times 10 \times 0.04 / 0.5 = 106$ mm. With a closed length near 5 mm, that is about 110 mm between the pins.

P2 $\delta_{tw} = 13$ mm. $\gamma_{tw} = 0.5 \times 13 / (\pi \times 42.25 \times 10) = 0.49\%$.

P3 At 2% the stroke is 53 mm. 13 / 53 is about 25%.

Q1 It rises quickly over the first 10 to 20 cycles and then levels off. Expect a two-way shear strain from a few tenths of a percent to about 1%, which is 5 to 25 mm on this spring.

Q2 The control shows little or no two-way stroke. Temperature cycling alone does not train the spring. The repeated deformation does.

Q3 The hot length grows a little with cycles. Training spends some of the one-way memory to buy the second shape.

Q4 The spring lifts many times more on heating. Cooling force is small, so a two-way part cannot do much work on its return stroke.

Q5 Two-way suits tiny mechanisms with no room for a bias, such as a one-piece tweezer or a micro gripper. One-way with a bias is better wherever force, stroke or life matters on both strokes.

■ Lab 5: Joule Heating and the Energy Budget

P1 $\ell = \pi \times 6.5 \times 4 + 60 = 142$ mm. Mass = 1.27 g/m × 0.142 = 0.18 g. R = 4 Ω/m × 0.142 = 0.57 Ω.

P2 E = 0.18 × (0.47 × 58 + 24) = 9.2 J. P = 4 × 0.57 = 2.3 W, so t = 4.1 s.

P3 $\varepsilon = 0.5 \times 1.571 / (2\pi \times 6.5 \times 4) = 0.48\%$. M = 170 × π × 0.125 / 32 = 2.1 N·mm. Force at 20 mm = 0.10 N, about 10.6 g.

Q1 Slope 8 to 12 J and intercept 0.3 to 0.6 W for the spring in the pre-lab.

Q2 Agreement within about 25% is typical. The legs and clips are heated too, the final temperature overshoots Af, and the latent heat on the data card may differ.

Q3 They should agree within the scatter. With $A_s = \pi \times 0.5 \times 142 = 223$ mm² and a 50 °C rise, 0.5 W gives h = 45 W/(m²·°C), reasonable for a thin wire in still air.

Q4 Well under 1%: for 10 g lifted through 90° on a 20 mm arm, work is 3 mJ against about 10 J in. Efficiency rises when the metal is worked harder (more stress and strain per cycle) and when the pulse is short, so less heat escapes. Nitinol actuators convert a few percent at best.

Q5 At the pulse current the power is several times the loss, so the temperature keeps climbing after the transformation is complete. The part overheats, drifts and can lose its memory shape. Drop to the holding power.

■ Lab 6: Closed-Loop Position Control

P1 A = 0.0615 mm². $R = 0.80 \times 10^{-6} \times 0.1 / (0.0615 \times 10^{-6}) = 1.3$ Ω per 100 mm.

P2 4 mV / 2.6 V = 0.15% of R. Position resolution = 0.15 / 12 = 1.3% of stroke.

P3 60 / 1024 = 0.059 mm, which is 0.2% of stroke. That is about seven times finer than resistance, before noise.

P4 $e = D_{hold} / K_p$ = 10% of stroke at $K_p = 2$, and 2.5% at $K_p = 8$.

Q1 Against power, 25 to 50% of the span. Against resistance, a few percent to about 10%.

Q2 The error falls roughly as $1 / K_p$ at low gain. At higher gain the position overshoots, and the controller cannot drive it back, so it sits high until the part cools. Higher still, the duty chatters between zero and its limit and the position hunts.

Q3 Yes. From above, the controller can only switch off and wait. The part then holds on its cooling branch, which takes less heat than the heating branch, so the same gain leaves a different error.

Q4 The sensor loop repeats within 1 to 2% of stroke on top of its proportional error. Resistance feedback is typically 3 to 8% of stroke off, noisier, and worse when approached from above.

Q5 More load shifts the map, since stress changes both the geometry and the phase fraction at a given resistance. A product with a varying load needs a calibration per load, or a second signal.

Q6 Advantages: no extra part, wiring or space, and the signal comes from the actuator itself. Limits: it depends on load and ambient temperature, it needs a sensitive measurement, and it can be read only while current flows. Choose the sensor where accuracy matters and there is room for it. Choose self-sensing where there is no room for a sensor and a coarse position or an end-of-stroke signal is enough.

■ Lab 7: A User Interface for Proportional Control

P1 $f = 1 / (2\pi\tau) = 0.032$ Hz.

P2 Open loop: `D0,<percent>`, a duty. Closed loop: `S<percent>`, a target position.

P3 It is a keep-alive. The firmware switches the output off if it hears nothing for 3 seconds, so a crashed or disconnected laptop cannot leave the actuator powered.

Q1 Typically 25 to 50% of the duty range between the rising and falling branches.

Q2 Higher K_p shortens the rise and starts to overshoot. K_i removes the steady error and, set too high, overshoots after the dead band. The right choice has no overshoot going up and a steady error under 2%.

Q3 Going up is driven by power and takes 1 to 3 seconds. Going down waits for cooling and takes several times longer. Forced cooling or a thinner section speeds the way down (Lab 8). An opposing actuator makes both directions powered.

Q4 A fraction of a watt to a few watts depending on the actuator. It matches the convective loss at the holding temperature, as in Lab 5.

Q5 Open-ended. Common findings: unclear which mode is active, no obvious stop, and no sign that the actuator is still hot after stopping.

■ Lab 8: Thermal Management and Cycle Speed

P1 $\tau = \rho\, c\, d\, /\, (4h) = 6450 \times 470 \times 0.0005 / 240 = 6.3$ s.

P2 $t = 6.3 \times \ln(68/23) = 6.8$ s. Higher grade: $6.3 \times \ln(98/53) = 3.9$ s.

P3 $L_c = 0.075$ mm, so $\tau = 6450 \times 470 \times 0.000075 / 60 = 3.8$ s, 40% less than the wire. $Bi = 60 \times 0.000075 / 10 = 0.00045$, far below 0.1. The lumped model holds.

Q1 Still air 3 to 10 s, fan 1 to 3 s, water well under 1 s. The implied h runs from tens of W/(m²·°C) in still air to thousands in water. Coils shield each other, so a spring cools more slowly than a straight strip.

Q2 Agreement within about 30%. The measured rate is usually lower, since the end coils and the middle cool differently.

Q3 Several times more, and it may not reach full stroke at all. Cool only during reset: a fan, a valve or a pump switched on by the controller after the stroke is complete.

Q4 The strip spring is faster, roughly in proportion to L_c (t/2 against d/4), though coil spacing also matters. Fast actuators are thin: fine wire or flat strip, used in parallel if more force is needed.

Q5 Thinner sections in parallel (more parts and connections). Liquid or forced-air cooling (a pump or fan, and more heating power). A higher transformation temperature (more energy per cycle). Partial-stroke cycling near the middle of the hysteresis loop (less stroke).

■ Lab 9: High Force From a Small Stack

P1 Force = 10 × 2 × 9.81 = 196 N, plus the lever's own weight. The mass rises 3 mm.

P2 Volume = $\pi/4 \times (9^2 - 5^2) \times 1 = 44$ mm³, mass 0.28 g. $W = 300 \times 0.3 / 4 = 22$ mJ, or 0.08 J/g. A wire stores 170 MPa × 0.04 / 6450 kg/m³ = 1.05 J/g on a rectangular cycle. The disc works in bending, so much of its metal is lightly strained.

P3 Two in parallel, and two of those pairs in series: four discs.

Q1 For the 9 mm disc, about 300 N and 0.3 mm. Other sizes follow the kit data card.

Q2 Within 10 to 20%. Friction between nested discs takes some force from a parallel stack, and seating between discs takes some stroke from a series stack.

Q3 Near half the blocked force. Measured work per gram is of the order of 0.1 J/g, well under a wire.

Q4 Usually a little short on both. Add a disc in series for stroke, and derate the parallel force for friction.

Q5 A heating element clamped to the stack, or the surroundings if the product is a thermal safety device. Cycle time is set by conduction into and out of a thick part, so it is far slower than a wire.

■ Lab 10: Direct-Drive Rotation

P1 $\theta = 0.03 \times 60 / 1.0 = 1.8$ rad, or 103°.

P2 $J = \pi / 2 = 1.57$ mm⁴. $T = 100 \times 1.57 / 1.0 = 157$ N·mm. Force = 1.57 N, about 160 g.

P3 J falls by $0.6^4 = 13\%$, so the torque falls 13%. The area falls by $0.6^2 = 36\%$, so the mass falls 36%.

Q1 For the pre-lab rod, a free angle near 100° for 3% strain and a blocked torque of a few hundred N·mm.

Q2 $\gamma = \theta\, r / L$. Expect 2 to 3%: a little under the strain applied, since some is elastic and some is not recovered.

Q3 The tube gives 87% of the torque for 64% of the mass, so about 36% more torque per gram.

Q4 $J/r = \pi\, r^3 / 2 = 2000 / 100 = 20$ mm³, so r = 2.34 mm: a 4.7 mm rod. $L = \theta\, r / \gamma = 1.571 \times 2.34 / 0.03 = 122$ mm.

Q5 A minute or more in still air. Options: several thinner rods in parallel, a liquid to heat and cool the rod, or a tube with coolant through the bore.

Lab 11: Bistability and Passive Control

P1 $E = 0.00088 \times 9.81 \times 0.15 = 1.3$ mJ.

P2 During the snap: 1.3 mJ / 4 ms = 0.32 W. Averaged over 30 s: 0.043 mW. The snap concentrates the output about 7,500 times.

P3 About 75 °C ± 7 °C, which leaves 8 °C of margin at each end. The measured unit-to-unit scatter must fit inside the tolerance.

Q1 For one dome the standard deviation is typically 1 to 2 °C. Across domes it is a few degrees.

Q2 Of the order of a millijoule for a 25 mm dome, repeatable within about 15%. The motion fits inside one or two frames at 240 frames per second, so it lasts a few milliseconds at most.

Q3 Preload against the snap raises the trip temperature by a few degrees per newton. The mechanism is the same as in Lab 1: stress raises the transformation temperatures.

Q4 Bimetal disc: snaps on heat and resets, but low force. Fusible link: heat only, single use, cannot be tested. Pyrotechnic: high force, needs a current pulse, single use, lot-tested only. The dome combines a sudden release, high force for its size, a heat or low-current trigger, and a part that can be tripped, reset and tested.

Q5 Open-ended. A good answer seats the dome against the cell, has it throw a contact open, sets the trip temperature above the hottest normal cell temperature with margin, and adds a small heater so each unit can be tripped and reset in production test.

Lab 12: A Peristaltic Pump With No Motor

P1 $V = \pi \times 2^2 \times 12 = 151$ mm³ = 0.15 mL. $Q = 0.15 \times 0.2 \times 60 = 1.8$ mL/min.

P2 3.0 A, just inside the sensor's 3.2 A limit. Three rings at once would exceed it.

P3 Each ring is on for two time slots and each starts one slot after the one before: ring 1 in slots 1 and 2, ring 2 in 2 and 3, ring 3 in 3 and 4, ring 4 in 4 and 1.

Q1 Typically 40 to 80% of $\pi r^2 w$. The tube does not close to zero volume, and some fluid slips back as each ring opens.

Q2 A single ring moves almost nothing net, and a sequence without overlap loses a large share to backflow. Overlap keeps the tube closed behind the fluid, so delivery rises and holds up against head.

Q3 Flow rises with frequency, peaks, and then falls. Past the peak the rings have not cooled and reopened before they are fired again, so the stroke shrinks.

Q4 Typically a few hundred millimeters of water, the same order as F/(r w) less the pressure the tube wall takes.

Q5 It wins where the pump must be tiny, silent, sealed and free of rotating parts: dosing, sampling, sterile or corrosive fluid paths. It loses wherever flow rate or efficiency matters.

Lab 13: Fatigue and Life

P1 $1/R_o = 1/6 - 2\varepsilon/t$. At 5%: 0.0667 per mm, $R_o = 15$ mm. At 2.5%: $R_o = 8.6$ mm. At 7%: $R_o = 37.5$ mm.

P2 60,000 s, or 16.7 hours.

P3 Damage per day = 200/100,000 + 5/100 = 0.052. Life = 19 days. The five hard cycles do 96% of the damage.

Q1 Most of the loss comes early: several percent in the first 100 cycles at 5 to 7%, then a slow decline. At 2.5% the loss is small throughout.

Q2 Level D (7%) is rated at 100 cycles and level C (5%) at 10,000. Parts usually exceed the rating, since the handbook figures are conservative, but scatter of a factor of two or three is normal in fatigue.

Q3 Between 2.5 and 5% the design levels imply b near 3. Class data will scatter around that. The life falls much faster between 5 and 7%.

Q4 At the middle of the arc, opposite the gap, where the bending moment and strain are greatest, or at a crimp or a surface mark that concentrates strain.

Q5 Use level B strain in a form that multiplies motion, such as a longer or larger part, a lever or a spring form. Or ask about training, which stabilizes the stroke and extends life. Meeting both in a small part is possible but expensive.

Lab 14: Many Degrees of Freedom in One Part

P1 $R = 0.16\ \Omega$, $V = 0.32$ V, $P = 0.64$ W.

P2 Current share = 0.02 / (0.16 + 0.02) = 11%. Power share = $0.11^2 = 1.2\%$. The zone stays cool.

P3 Cumulative angles are 30°, 0° and 45°. $x = 40 \times (0.866 + 1 + 0.707) = 103$ mm. $y = 40 \times (0.5 + 0 + 0.707) = 48$ mm.

Q1 Similar in shape with different end angles. The curve has a dead band and a steep middle, as in Lab 7, so open-loop power gives coarse proportional control.

Q2 Typically 5 to 20% after a minute. Reduce it with space or heat sinks at the taps, short heating pulses, or a controller that subtracts the expected leak.

Q3 Typically 5 to 15 mm on a 120 mm part. The hinge model, hysteresis and crosstalk all contribute. Closing the loop on each zone’s resistance would cut it.

Q4 Three motors, three gearboxes, three position sensors, three joints with bearings, links, fasteners and a cable harness: 30 to 50 parts. The nitinol version is one actuator, one backbone and four taps.

Q5 N zones need N + 1 taps and N shunts. At 20 zones, mount the switches along the part and address them over a two-wire bus, so the harness does not become stiffer than the actuator.

Code Listings

All three files are in the lab pack. They are starting points: students are expected to read them, question them and extend them.

Drive board firmware: krl_driver.ino

```
// KRL drive board firmware for the Nitinol Actuator Engineering Lab Book
// Board: Arduino Uno or Nano.  Library: Adafruit INA219.
// Channel 0 (pin 9) has closed-loop control. Channels 1 to 3 are open loop.
//
// Commands, one per line at 115200 baud:
//   D<ch>,<pct>   open-loop duty for a channel, 0 to 100 percent
//   S<pct>        target position, 0 to 100 percent (closed loop on channel 0)
//   M<n>          mode: 0 off, 1 open loop, 2 closed loop on A0, 3 closed loop on resistance
//   K<kp>,<ki>    controller gains
//   L<lo>,<hi>    sensor reading at 0 and 100 percent position (A0 counts, or milliohms in mode 3)
//   C<n>,<on_ms>,<off_ms>   run n heat-cool cycles on channel 0 at the open-loop duty
//   X             stop everything
// Telemetry, 20 lines per second:
//   ms,mode,target,position,duty,mA,mV,mOhm,cycles

#include <Wire.h>
#include <Adafruit_INA219.h>

const byte PIN[4] = {9, 10, 5, 6};
// Duty limits in percent. Channel 0 is capped; raise it only with your instructor's approval.
const float MAX_DUTY[4] = {60, 100, 100, 100};
const float MAX_MA = 3200.0;        // over-current trip
const unsigned long WATCHDOG_MS = 3000;

Adafruit_INA219 ina;
float duty[4] = {0, 0, 0, 0};
float target = 0, kp = 4.0, ki = 0.8, integ = 0, lo = 100, hi = 900;
byte mode = 0;
long cyclesLeft = 0, cyclesDone = 0;
unsigned long onMs = 2000, offMs = 8000, phaseStart = 0, lastCmd = 0, lastTick = 0;
bool heating = false;
float mA = 0, mV = 0, mOhm = 0, pos = 0;
String line;

void allOff() {
  for (byte i = 0; i < 4; i++) { duty[i] = 0; analogWrite(PIN[i], 0); }
  mode = 0; integ = 0; cyclesLeft = 0;
}

void setup() {
  for (byte i = 0; i < 4; i++) { pinMode(PIN[i], OUTPUT); analogWrite(PIN[i], 0); }
  Serial.begin(115200);
  ina.begin();
}

void command(String s) {
  char c = s.charAt(0);
  float a = s.substring(1).toFloat();
  int comma = s.indexOf(',');
  float b = comma > 0 ? s.substring(comma + 1).toFloat() : 0;
  lastCmd = millis();
  if (c == 'X') allOff();
  else if (c == 'M') { mode = (byte)a; integ = 0; if (mode == 0) allOff(); }
  else if (c == 'S') target = constrain(a, 0, 100);
  else if (c == 'K') { kp = a; ki = b; integ = 0; }
  else if (c == 'L') { lo = a; hi = b; }
  else if (c == 'D') { byte ch = (byte)a; if (ch < 4) duty[ch] = constrain(b, 0, MAX_DUTY[ch]); }
  else if (c == 'C') {
    cyclesLeft = (long)a; cyclesDone = 0;
    int c2 = s.indexOf(',', comma + 1);
    onMs = (unsigned long)b;
    offMs = c2 > 0 ? (unsigned long)s.substring(c2 + 1).toFloat() : 8000;
    heating = true; phaseStart = millis(); mode = 1;
  }
}

void measure() {
  // Read current and voltage with channel 0 fully on for 1 ms, so the reading does not alias with the PWM.
  if (duty[0] <= 0 && mode != 3) { mA = ina.getCurrent_mA(); mV = ina.getBusVoltage_V() * 1000.0; return; }
  digitalWrite(PIN[0], HIGH);
  delay(1);
  mA = ina.getCurrent_mA();
```

```
  mV = ina.getBusVoltage_V() * 1000.0;
  analogWrite(PIN[0], (int)(duty[0] * 2.55));
  if (mA > 50) mOhm = 1000.0 * mV / mA;
}

void loop() {
  while (Serial.available()) {
    char ch = Serial.read();
    if (ch == '\n') { line.trim(); if (line.length()) command(line); line = ""; }
    else line += ch;
  }
  unsigned long now = millis();
  if (now - lastTick < 50) return;            // 20 Hz control and telemetry
  float dt = (now - lastTick) / 1000.0;
  lastTick = now;

  measure();
  float raw = (mode == 3) ? mOhm : analogRead(A0);
  pos = 100.0 * (raw - lo) / (hi - lo);

  if (mA > MAX_MA || (mode != 0 && cyclesLeft == 0 && now - lastCmd > WATCHDOG_MS)) allOff();

  if (mode >= 2) {                            // PI position control with anti-windup
    float err = target - pos;
    float u = kp * err + ki * integ;
    if (u > 0 && u < MAX_DUTY[0]) integ += err * dt;
    duty[0] = constrain(u, 0, MAX_DUTY[0]);
  }
  if (cyclesLeft > 0) {                       // automatic cycling for life tests
    if (heating && now - phaseStart >= onMs) { heating = false; phaseStart = now; }
    else if (!heating && now - phaseStart >= offMs) {
      heating = true; phaseStart = now; cyclesDone++; cyclesLeft--;
      if (cyclesLeft == 0) allOff();
    }
  }
  for (byte i = 0; i < 4; i++) {
    float d = (i == 0 && cyclesLeft > 0 && !heating) ? 0 : duty[i];
    analogWrite(PIN[i], (int)(d * 2.55));
  }
  Serial.print(now); Serial.print(','); Serial.print(mode); Serial.print(',');
  Serial.print(target, 1); Serial.print(','); Serial.print(pos, 1); Serial.print(',');
  Serial.print(duty[0], 1); Serial.print(','); Serial.print(mA, 0); Serial.print(',');
  Serial.print(mV, 0); Serial.print(','); Serial.print(mOhm, 0); Serial.print(',');
  Serial.println(cyclesDone);
}
```

■ Proportional loop for Lab 6: p_loop.py

```
"""A proportional position loop for a nitinol actuator.

Nitinol Actuator Engineering Lab Book, Lab 6. Works with the krl_driver firmware.
Run:  python p_loop.py COM5        (your board's port, or "sim" to run with no hardware)
Stop: Ctrl+C. Output is time, target, position and duty, ready to paste into a spreadsheet.
"""
import sys
import time
from krl_console import open_link, parse

KP = 4.0                    # gain: percent duty per percent of position error
TARGET = 50.0               # percent of stroke
SOURCE = 'sensor'           # 'sensor' or 'resistance'
A0_0, A0_100 = 100, 900     # sensor counts at 0 and 100 percent position
R_0, R_100 = 800, 700       # milliohms at 0 and 100 percent position
MAX_DUTY = 60.0             # percent

link = open_link(sys.argv[1] if len(sys.argv) > 1 else 'sim')
time.sleep(2)               # the board restarts when the port opens
if SOURCE == 'sensor':      # this script closes the loop: it reads the position and sets the duty
    link.write(('L%d,%d\nM1\n' % (A0_0, A0_100)).encode())
else:                       # the board closes the loop: it pulses the wire to read its resistance
    link.write(('L%d,%d\nK%.2f,0\nM3\n' % (R_0, R_100, KP)).encode())
buffer = b''
try:
    while True:
        buffer += link.readline()
        if not buffer.endswith(b'\n'):
            time.sleep(0.01)
            continue
        data, buffer = parse(buffer.decode(errors='ignore')), b''
        if data is None:
            continue
        if SOURCE == 'sensor':
            error = TARGET - data['position']
            duty = min(MAX_DUTY, max(0.0, KP * error))
```

```
            link.write(('D0,%.1f\n' % duty).encode())
        else:
            duty = data['duty']
            link.write(('S%.1f\n' % TARGET).encode())
        print('%.2f,%.1f,%.1f,%.1f' % (data['ms'] / 1000, TARGET, data['position'], duty))
finally:
    link.write(b'X\n')      # always leave the actuator off
```

■ Starter interface: krl_console.py

```
"""KRL Actuator Console: a starter user interface for proportional control of nitinol actuators.

Nitinol Actuator Engineering Lab Book, Labs 6 and 7. Works with the krl_driver firmware.
The Command box sends any firmware command, such as L210,655 to calibrate the position sensor.
Run:  python krl_console.py            (asks for a serial port; type "sim" to run with no hardware)
Needs: Python 3.8+, tkinter (included with most Python installs), pyserial (pip install pyserial).
"""
import csv
import math
import sys
import time

FIELDS = ['ms', 'mode', 'target', 'position', 'duty', 'mA', 'mV', 'mOhm', 'cycles']


def parse(line):
    """Turn one telemetry line into a dict of floats. Returns None for anything malformed."""
    parts = line.strip().split(',')
    if len(parts) != len(FIELDS):
        return None
    try:
        return dict(zip(FIELDS, (float(p) for p in parts)))
    except ValueError:
        return None


class Sim:
    """A stand-in for the drive board, so the interface can be built and tested with no hardware.

    Model: one thermal time constant, plus a phase fraction that follows separate heating and
    cooling curves (hysteresis). It speaks the same serial protocol as the firmware.
    """
    AMBIENT, TAU, K = 22.0, 4.0, 2.4          # deg C, seconds, deg C of steady rise per percent duty
    AS, AF, MS, MF = 62.0, 76.0, 54.0, 40.0   # transformation temperatures under load, deg C

    def __init__(self):
        self.t0 = time.time()
        self.last = self.t0
        self.temp = self.AMBIENT
        self.xi = 0.0                         # fraction transformed to austenite, 0 to 1
        self.mode, self.target, self.duty = 0, 0.0, 0.0
        self.kp, self.ki, self.integ = 4.0, 0.8, 0.0
        self.out = []

    def write(self, data):
        for cmd in data.decode().split('\n'):
            cmd = cmd.strip()
            if not cmd:
                continue
            c, rest = cmd[0], cmd[1:].split(',')
            if c == 'X':
                self.mode, self.duty, self.integ = 0, 0.0, 0.0
            elif c == 'M':
                self.mode, self.integ = int(float(rest[0])), 0.0
                if self.mode == 0:
                    self.duty = 0.0
            elif c == 'S':
                self.target = min(100.0, max(0.0, float(rest[0])))
            elif c == 'K':
                self.kp, self.ki, self.integ = float(rest[0]), float(rest[1]), 0.0
            elif c == 'D' and int(float(rest[0])) == 0:
                self.duty = min(60.0, max(0.0, float(rest[1])))

    def step(self, dt):
        pos = 100.0 * self.xi
        if self.mode >= 2:
            err = self.target - pos
            u = self.kp * err + self.ki * self.integ
            if 0 < u < 60:
                self.integ += err * dt
            self.duty = min(60.0, max(0.0, u))
        self.temp += (self.AMBIENT + self.K * self.duty - self.temp) * dt / self.TAU
        heat = min(1.0, max(0.0, (self.temp - self.AS) / (self.AF - self.AS)))
```

```
        cool = min(1.0, max(0.0, (self.temp - self.MF) / (self.MS - self.MF)))
        self.xi = min(cool, max(heat, self.xi))   # move only when a curve pushes the fraction
        ohm = 0.80 - 0.10 * self.xi
        ma = 0 if self.duty <= 0 else 2000
        return pos, ma, ma * ohm, 1000 * ohm

    def readline(self):
        now = time.time()
        if now - self.last < 0.05:
            return b''
        pos, ma, mv, mohm = self.step(now - self.last)
        self.last = now
        return ('%d,%d,%.1f,%.1f,%.1f,%.0f,%.0f,%.0f,0\n' % (
            1000 * (now - self.t0), self.mode, self.target, pos, self.duty, ma, mv, mohm)).encode()


def open_link(port):
    if port.lower() == 'sim':
        return Sim()
    import serial
    return serial.Serial(port, 115200, timeout=0)


def main(port):
    import tkinter as tk
    link = open_link(port)
    root = tk.Tk()
    root.title('KRL Actuator Console')
    state = {'rows': [], 'log': None, 'buf': b'', 'last_send': 0.0}

    def send(cmd):
        link.write((cmd + '\n').encode())
        state['last_send'] = time.time()

    def set_mode(m):
        send('M%d' % m)
        if m == 1:
            send('D0,%.1f' % target.get())
        elif m >= 2:
            send('K%s,%s' % (kp.get(), ki.get()))
            send('S%.1f' % target.get())

    def slider_moved(_=None):
        # In open loop the slider is the duty. In closed loop it is the target position.
        send(('D0,%.1f' if mode.get() == 1 else 'S%.1f') % target.get())

    def toggle_log():
        if state['log']:
            state['log'].close()
            state['log'] = None
            log_btn.config(text='Start log')
        else:
            state['log'] = open(time.strftime('run_%Y%m%d_%H%M%S.csv'), 'w', newline='')
            csv.writer(state['log']).writerow(FIELDS)
            log_btn.config(text='Stop log')

    left = tk.Frame(root, padx=10, pady=10)
    left.pack(side='left', fill='y')
    tk.Label(left, text='Target (percent)').pack(anchor='w')
    target = tk.Scale(left, from_=0, to=100, orient='horizontal', length=260, command=slider_moved)
    target.pack()
    mode = tk.IntVar(value=0)
    for text, m in (('Off', 0), ('Open loop: slider sets duty', 1),
                    ('Closed loop: slider sets position', 2), ('Closed loop on resistance', 3)):
        tk.Radiobutton(left, text=text, variable=mode, value=m, command=lambda m=m: set_mode(m)).pack(anchor='w')
    gains = tk.Frame(left)
    gains.pack(anchor='w', pady=6)
    kp, ki = tk.StringVar(value='4.0'), tk.StringVar(value='0.8')
    tk.Label(gains, text='Kp').pack(side='left')
    tk.Entry(gains, textvariable=kp, width=6).pack(side='left')
    tk.Label(gains, text='  Ki').pack(side='left')
    tk.Entry(gains, textvariable=ki, width=6).pack(side='left')
    tk.Button(gains, text='Apply', command=lambda: send('K%s,%s' % (kp.get(), ki.get()))).pack(side='left', padx=6)
    box = tk.Frame(left)
    box.pack(anchor='w', pady=2)
    cmd = tk.StringVar()
    tk.Label(box, text='Command').pack(side='left')
    tk.Entry(box, textvariable=cmd, width=12).pack(side='left', padx=4)
    tk.Button(box, text='Send', command=lambda: cmd.get().strip() and send(cmd.get().strip())).pack(side='left')
    readout = tk.Label(left, justify='left', font=('Consolas', 10))
    readout.pack(anchor='w', pady=6)
    tk.Button(left, text='STOP', bg='#C4122F', fg='white', width=12,
              command=lambda: (mode.set(0), send('X'))).pack(anchor='w')
    log_btn = tk.Button(left, text='Start log', width=12, command=toggle_log)
    log_btn.pack(anchor='w', pady=4)
```

```
    chart = tk.Canvas(root, width=520, height=320, bg='white', highlightthickness=1)
    chart.pack(side='left', padx=10, pady=10)

    def draw():
        chart.delete('all')
        rows = state['rows'][-400:]                # the last 20 seconds
        for pct in (0, 25, 50, 75, 100):
            y = 300 - 2.8 * pct
            chart.create_line(40, y, 510, y, fill='#DDDDDD')
            chart.create_text(20, y, text=str(pct), fill='#6B6B6B')
        for key, color in (('target', '#6B6B6B'), ('duty', '#1F3A5F'), ('position', '#C4122F')):
            pts = []
            for i, r in enumerate(rows):
                pts += [40 + 470 * i / 400.0, 300 - 2.8 * min(100.0, max(0.0, r[key]))]
            if len(pts) >= 4:
                chart.create_line(*pts, fill=color, width=2)
        chart.create_text(275, 12, text='gray: target   blue: duty   red: position', fill='#6B6B6B')

    def poll():
        chunk = link.readline()
        while chunk:
            state['buf'] += chunk
            chunk = link.readline() if state['buf'].endswith(b'\n') else b''
        *lines, state['buf'] = state['buf'].split(b'\n')
        for raw in lines:
            row = parse(raw.decode(errors='ignore'))
            if row:
                state['rows'].append(row)
                if state['log']:
                    csv.writer(state['log']).writerow([row[f] for f in FIELDS])
        if state['rows']:
            r = state['rows'][-1]
            watts = r['mA'] * r['mV'] / 1e6 * r['duty'] / 100.0
            readout.config(text='Position   %6.1f %%\nDuty       %6.1f %%\nCurrent    %6.2f A\n'
                                'Resistance %6.3f ohm\nPower      %6.2f W\nCycles     %6d' % (
                                    r['position'], r['duty'], r['mA'] / 1000, r['mOhm'] / 1000, watts, r['cycles']))
            draw()
        if mode.get() and time.time() - state['last_send'] > 1.0:
            slider_moved()                         # keep-alive, so the firmware watchdog stays quiet
        root.after(50, poll)

    def close():
        send('X')
        root.destroy()

    root.protocol('WM_DELETE_WINDOW', close)
    poll()
    root.mainloop()


if __name__ == '__main__':
    main(sys.argv[1] if len(sys.argv) > 1 else input('Serial port (or "sim"): '))
```

Troubleshooting

Symptom	Likely cause	Fix
Actuator does not move	Current too low, a loose crimp, or the supply in current limit	Check the current on the readout. Re-crimp. Raise the voltage, not the current limit.
Moves once, then gets weaker	Overheated, or strained beyond its design level	Shorten the pulse and drop to a holding current. Check the strain calculation.
Does not reset	Ambient above Mf under load, or the bias is too weak	Cool the part, reduce the stress, or strengthen the bias (Labs 1 and 2).
MOSFET gets hot	Not a logic-level part, or the gate is floating	Use a logic-level MOSFET with the 220 Ω and 10 kΩ gate resistors.
Telemetry stops	Watchdog tripped, or over-current	Send a command at least every 3 seconds. Check for a short.
Resistance reading is noisy	A loose clip lead, or the reading taken at very low current	Use screw terminals. Read resistance only above about 0.3 A.
Position loop oscillates	Gains too high, or a sticky mechanism	Halve K_p and K_i. Free the mechanism before tuning.
Position loop sits below target	Duty capped, or the supply voltage too low	Check the duty readout. Raise the supply voltage within the pulse current.
Spring will not hold its set shape	Furnace too cool, or too little time at temperature	Check the furnace with a second thermocouple. Time from when it recovers its setpoint.
Dome will not stay armed	Too warm when armed, or the rim is clamped	Arm it in ice water. Seat it so the rim can turn.
Pump moves fluid back and forth	No overlap, or air in the tube	Keep two rings closed at once. Bleed the air.

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