PARAXIAL · CASE STUDY · V6 · 2026-09-29 12:04 PDT

Designing a robot camera that stays accurate as it heats up

An agricultural weeding robot needs to know exactly where a small weed is, even while its camera warms up. An AI agent used Paraxial to design the camera's lens, its mount and its liquid cooling together, in one coupled simulation, and to compare that with the usual one-team-at-a-time approach.

5.6 µm
how far the starting design's image slides when the head runs warm (limit 5 µm)

1.4 µm
drift after co-designing lens, mount and cooling. Within limit in every case

0.668
worst-case sharpness (MTF at the 31 lp/mm task frequency), up from 0.596

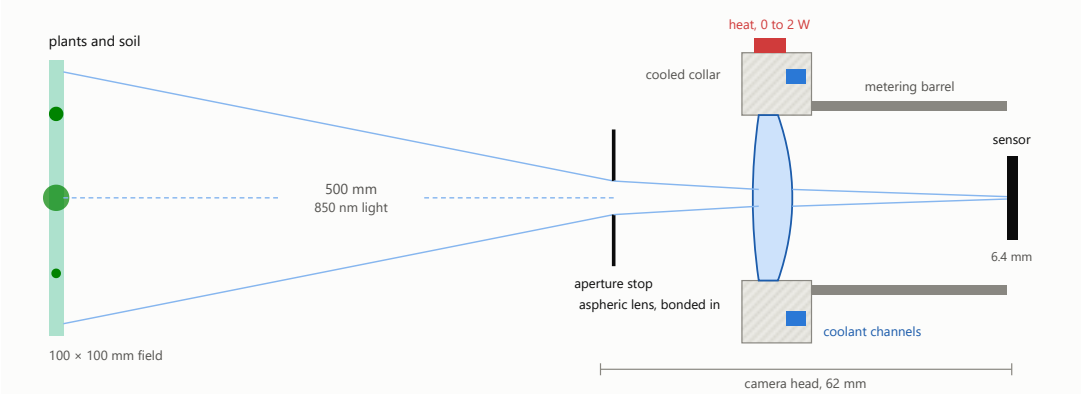
~15 s
to evaluate one complete design across all five operating conditions

> **Run end to end by an AI agent.** The whole study was carried out by an AI agent (Anthropic's Claude) working through Paraxial's API. The agent read the design brief, designed the lenses, set up and ran every simulation, checked its own results on finer meshes and unseen conditions, and produced the figures in this document. People wrote the brief, approved the agent's logins and reviewed the drafts.

The challenge

A camera-guided weeding robot has to put a tool on a weed that may be only 2–8 mm across, often right next to a crop. Its camera looks down from half a metre away. The electronics beside it warm the optical head, and warm parts move: the lens expands, shifts in its mount and changes how it bends light. The picture stays sharp, but it **slides across the sensor**. The software still recognises the weed, and then reports it in the wrong place.

At this camera's scale, 5 µm on the sensor is about 78 µm on the ground. Our target was to keep that drift under 5 µm in every operating condition, with the same software and no recalibration, while keeping the image sharp.

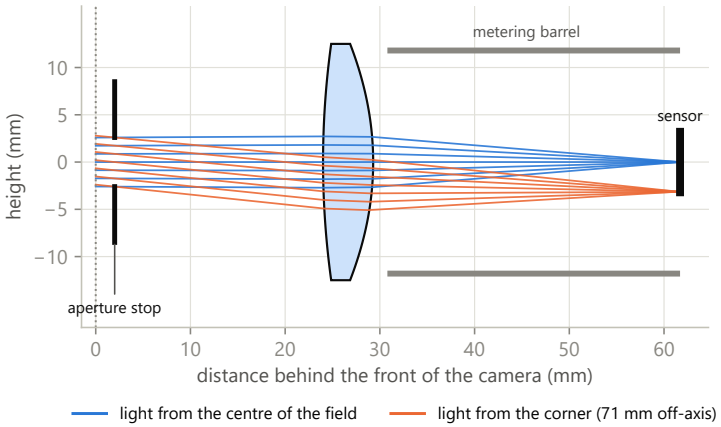


The modelled optical head: a single aspheric lens bonded into a liquid-cooled collar, a metering barrel to the sensor, and a heat load on one side of the collar. Inspired by commercial camera-guided weeding robots; an independent design exercise, not a model of any company's product.

The camera

The lens images a 100 × 100 mm patch of ground onto a 6.4 mm sensor under 850 nm illumination. We chose a **single aspheric element** so it could sit directly inside the cooled collar. Paraxial's optimizer shaped both of its surfaces to reach a worst-case sharpness of 0.610 across the whole field, against a requirement of 0.40.

The lens: rays traced from the plant plane 500 mm away

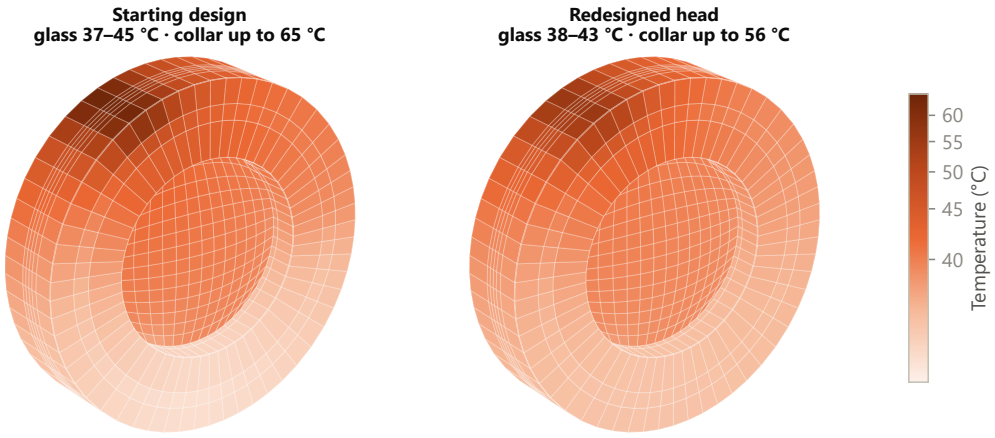


Ray trace of the final lens: light from the centre and the far corner of the 100 mm field, focused onto the sensor 62 mm behind the front of the camera.

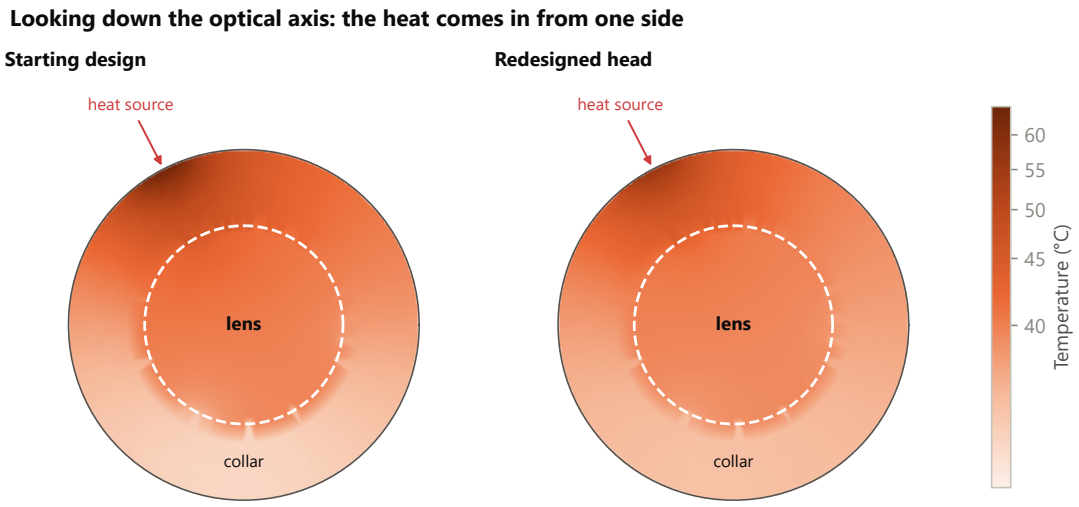
What heat does inside the head

For every design we solved the coolant flow, the heat conduction through metal and glass, and the resulting deformation, all together. Below is the hottest condition (2 W heat load, 35 °C coolant). The heat enters on one side, so one side of the lens runs warmer than the other.

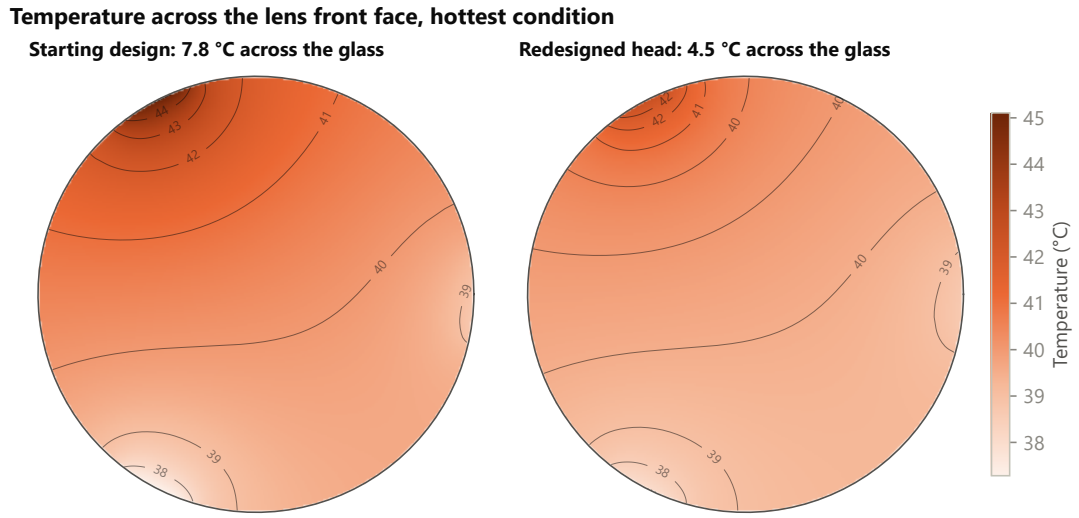
Solved temperature of the lens in its cooled collar, hottest condition



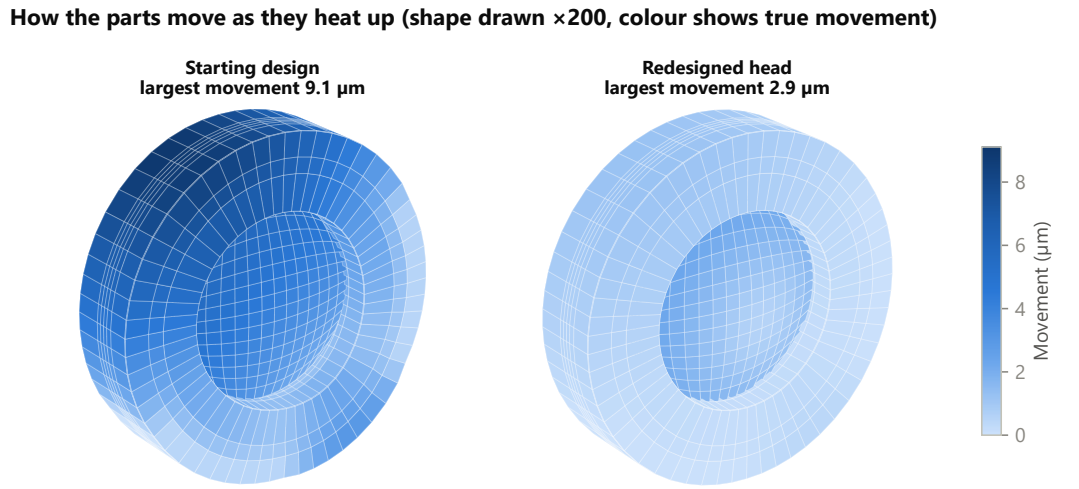
Solved temperature of the lens and its cooled collar. The two searches arrive at the same mount, bond and coolant split, so one redesigned head is shown.



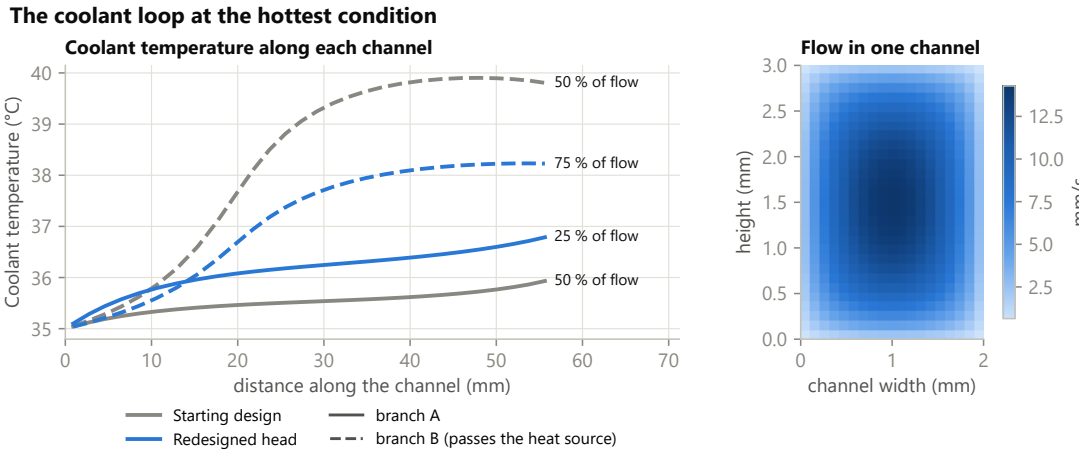
Temperature in the plane of the lens, looking along the optical axis.



Temperature across the lens front face. The redesign nearly halves the temperature difference across the glass.



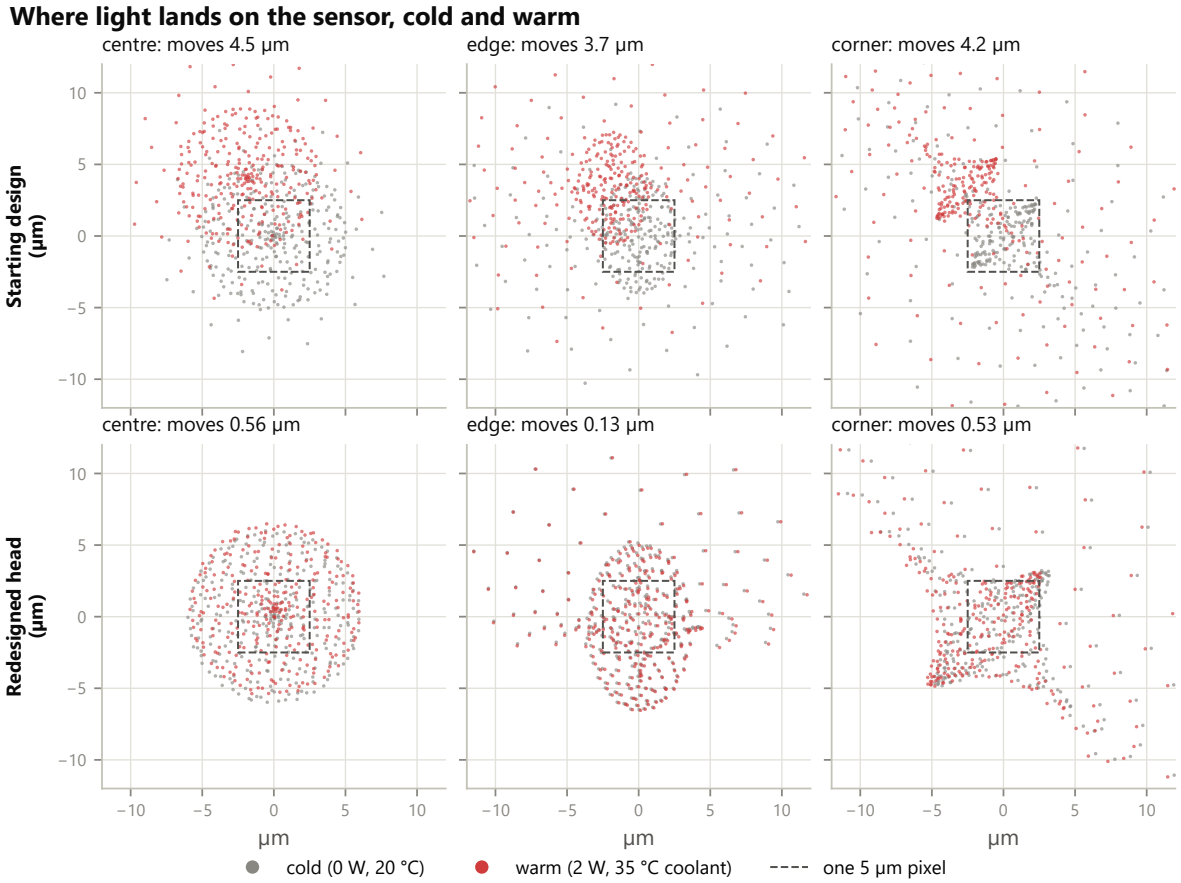
How the parts move, shape exaggerated so it is visible. Colour is the true displacement in micrometres.



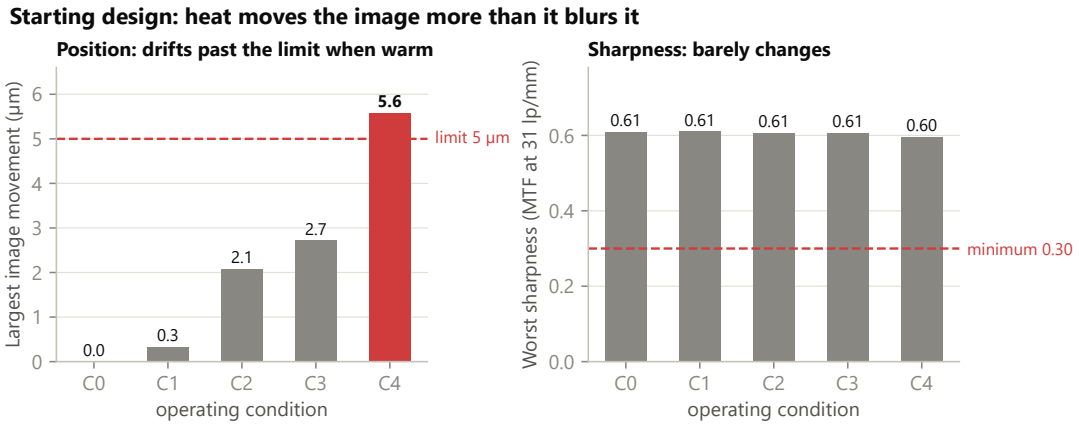
Left: coolant temperature along both channels. The redesign sends three quarters of the flow down the branch that warms most. Right: the solved flow profile inside one channel.

The consequence: the image moves

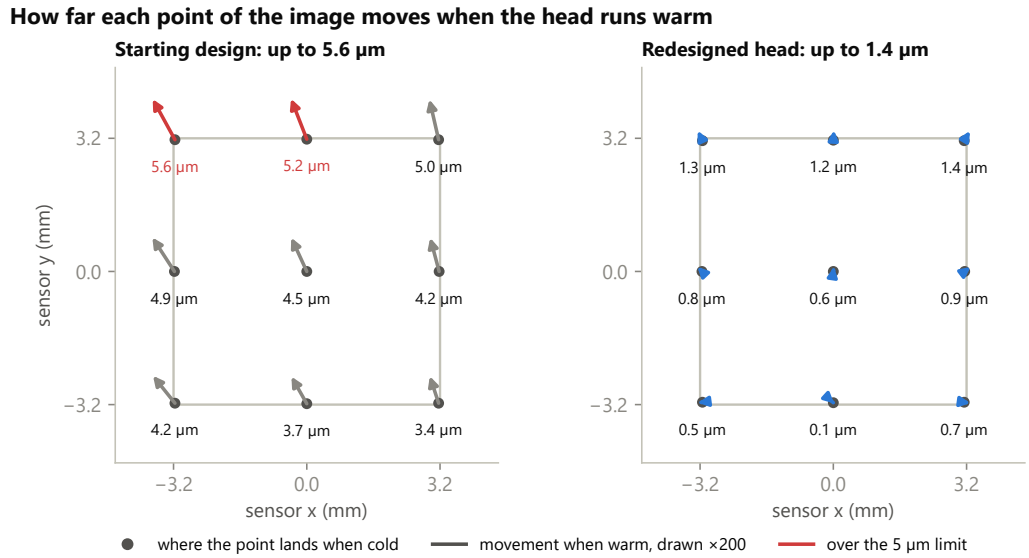
We turned every heated, deformed state back into a real optical system and traced it. In the starting design, the image stays almost as sharp (0.610 → 0.596) but slides **5.6 µm**, more than a pixel. On the ground that is about 0.09 mm. That fits inside the robot's 0.25 mm positioning budget, but it uses up a third of it before vehicle motion, plant height or tool alignment are counted. The 5 µm limit keeps the optics' share small.



Where light lands on the sensor at the centre, edge and corner of the field. In the starting design the warm spot slides off the cold one by about a pixel; after the redesign they overlap.



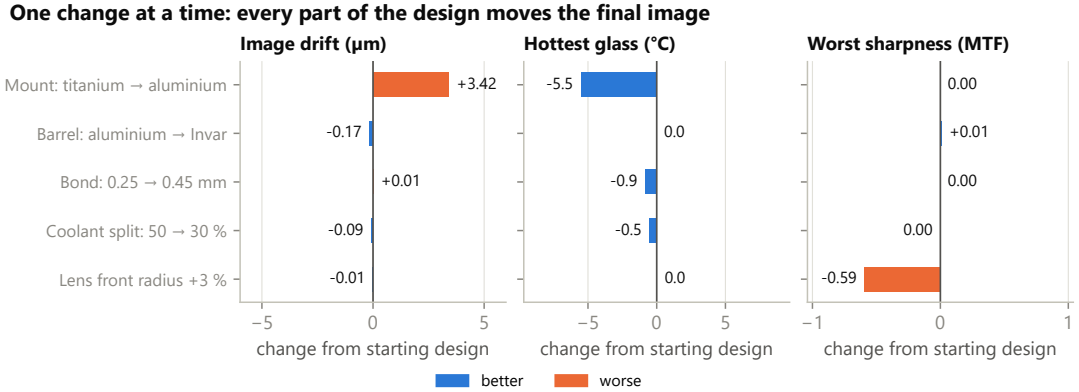
Starting design: drift and sharpness across the five operating conditions.



How each point of the image shifts on the sensor when warm, before and after the redesign.

Why the parts have to be designed together

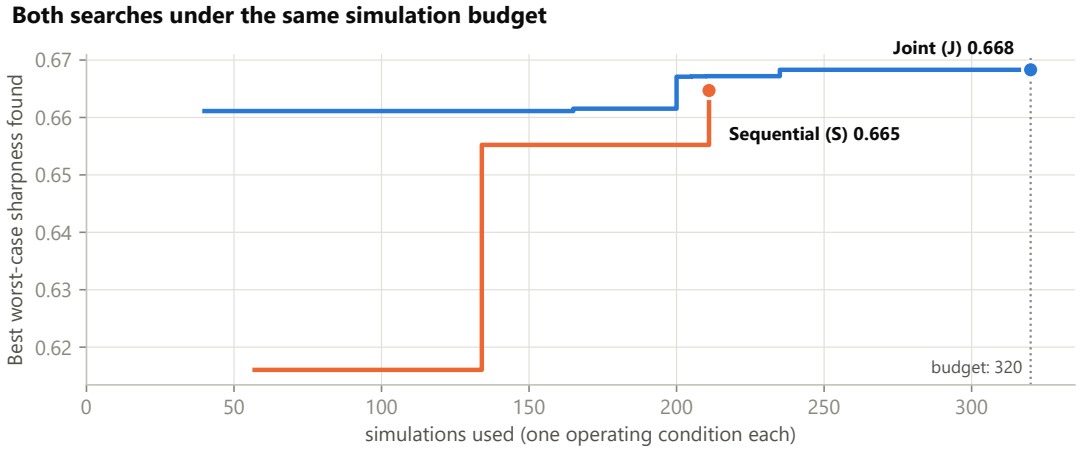
Before searching, we changed one thing at a time and watched the final image. Every part of the design mattered, and the effects cut across disciplines. The best example: an aluminium mount keeps the glass **5.5 °C cooler**, which a thermal engineer would welcome, yet it makes the image drift **3.4 µm more**, because aluminium expands and carries the lens sideways. The coolest design is not the most accurate one.



Effect of single changes at the 2 W / 25 °C condition. Blue is better, orange is worse. Each bar is a full coupled re-solve.

Two ways to design it

Sequential workflow. The way many teams work: the optics are optimised at room temperature, then the thermal choices, then the mechanical ones, each by its own discipline's criterion, with the full system checked after each pass.
Joint co-design. Every choice is open at once (lens position, assembly focus, mount metal, barrel metal, bond thickness and coolant split), and every candidate is judged on the final image across all operating conditions. Both got the same starting point, the same options and the same budget of simulations.



Best design found as the simulation budget is spent.

Design	Stop-to-lens spacing	Assembly focus	Mount metal	Barrel metal	Bond	Coolant split A/B %	Worst sharpness (MTF)	Worst drift
Starting design	18 mm	+0.000 mm	Ti-6Al-4V	Al 6061-T6	0.25 mm	50 / 50	**0.596**	**5.57 µm**
Sequential workflow	22 mm	-0.030 mm	Invar 36	Invar 36	0.50 mm	25 / 75	**0.665**	**1.15 µm**
Joint co-design	22 mm	-0.033 mm	Invar 36	Stainless 316	0.50 mm	25 / 75	**0.668**	**1.37 µm**

Both approaches fix the drift. Both put the lens in a low-expansion Invar mount and route most of the coolant past the heat source. They also gain sharpness by setting the sensor 30 µm closer at assembly, so the lens is in best focus once warm.

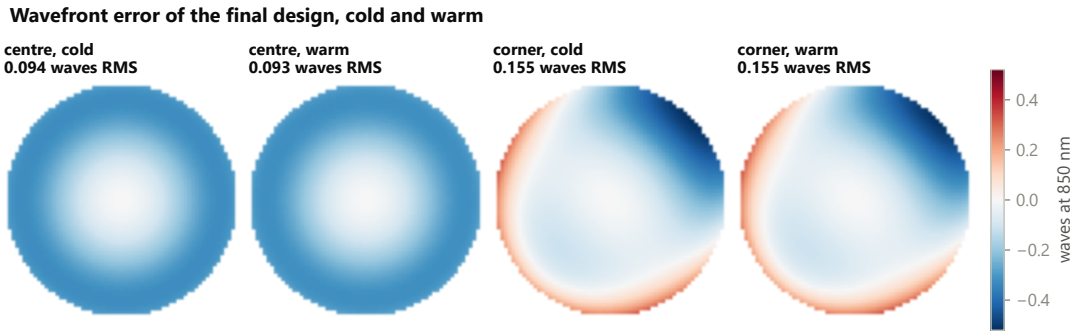
What the joint search found that the sequential workflow could not. The sequential team picks the barrel that moves the sensor least (Invar 36: 0.6 µm of sensor travel in the warm-supply case). The joint search, scoring only the final image, chose **Stainless 316**, which lets the sensor travel 7.8 µm, and paired it with a slightly different assembly focus (-0.0326 mm vs -0.0300 mm). The two choices only work together:

	sequential barrel (Invar 36)	joint barrel (Stainless 316)
sequential focus	0.6647	0.6637
joint focus	0.6587	**0.6683**

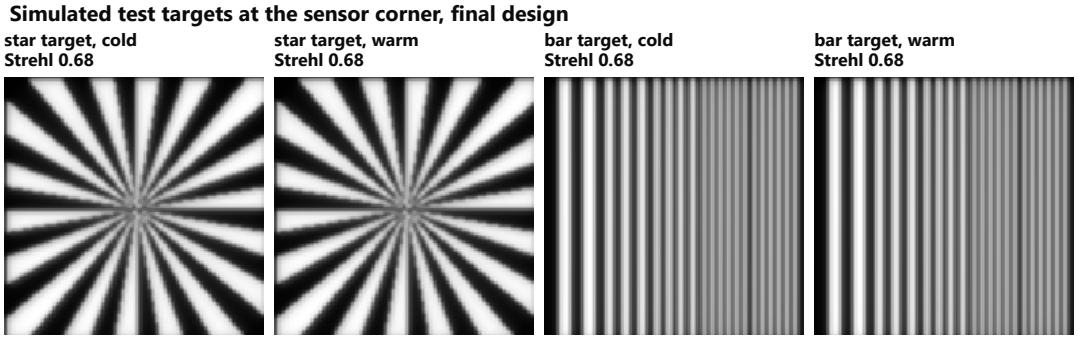
Worst-case MTF for the four combinations. The joint barrel adds 0.0096 with the joint focus but -0.0010 with the sequential focus, an interaction of 0.0106, about 5× the numerical noise. A workflow that tunes one block at a time against its own criterion never reaches the co-adapted pair.

The final design, cold and warm

The same lens, evaluated cold and at the hottest condition with the sensor fixed in place. The wavefront (how far the light's phase departs from a perfect sphere) and the simulated test images are almost unchanged: the redesigned head holds its optical quality as it heats.



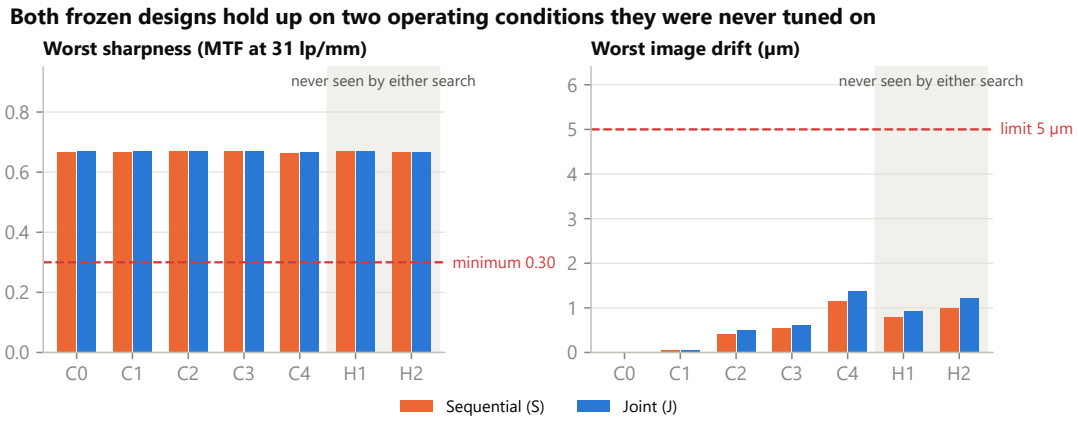
Wavefront error of the final design at the centre and the corner of the field, cold (0 W, 20 °C) and warm (2 W, 35 °C coolant).



Simulated star and bar targets at the sensor corner, cold and warm (Paraxial image simulation).

Does it hold up?

We froze both designs and tested them on two operating conditions neither search ever saw. Both stayed sharp and inside the drift limit: worst drift 1.00 µm (sequential) and 1.22 µm (joint). We also re-solved the finalists on finer meshes to check that the conclusions don't depend on mesh resolution.

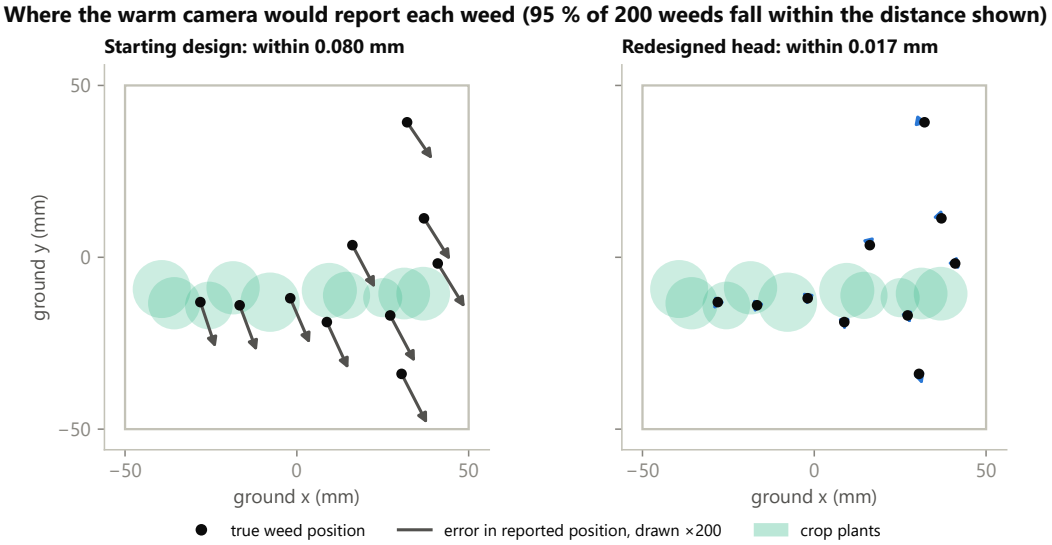


Training conditions C0–C4 and held-out conditions H1–H2 for the two frozen designs.

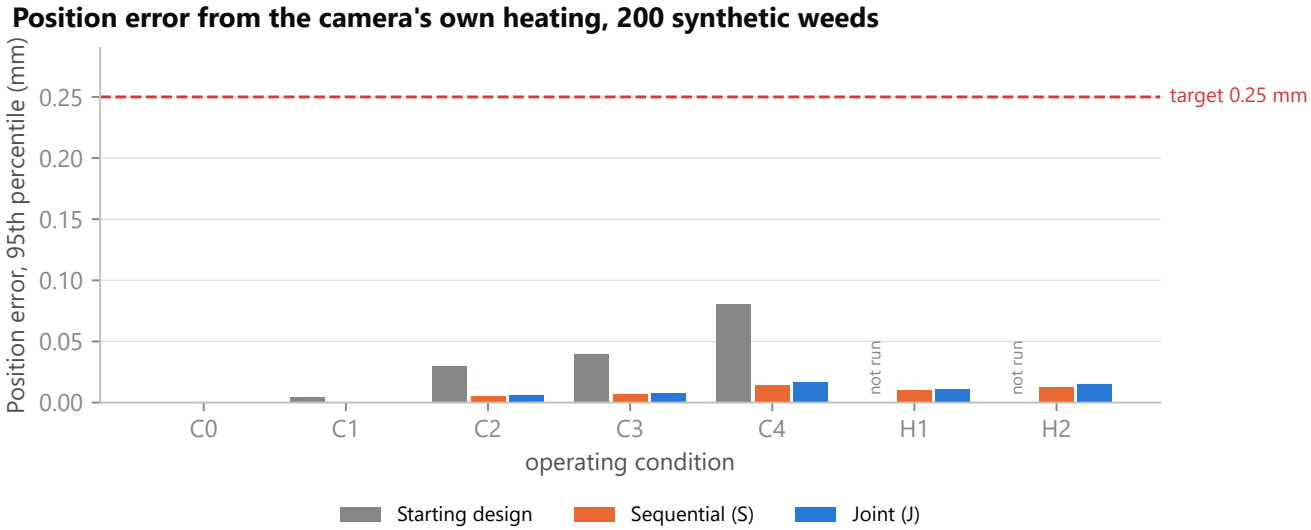
Verdict. Across every numerical check (mesh refinement and optical ray sampling) the joint design's worst-case sharpness stays between 0.6675 and 0.6683, against 0.6647–0.6668 for the sequential design. That passes our pre-registered test for a real difference, but only by 0.0007: about 0.1 %, far too small to matter in the field. On the two held-out conditions they are tied (0.6669 vs 0.6669). In sharpness the honest result is a tie; both designs meet every requirement. The joint search's contribution is *how* it got there, described above.

What it means for the robot

To turn optics into position, we placed 200 weeds and 200 crop plants across 20 synthetic plots. We traced where each weed lands on the sensor through every heated lens, and converted back to ground position using the calibration each camera had when cold. With the starting design, 95 % of weeds are placed within 0.080 mm at the warm-supply condition. After the redesign, that tightens to 0.015 mm (sequential) and 0.017 mm (joint): about five times less of the robot's 0.25 mm budget spent on the camera's own heating. It stays that way on the held-out conditions (0.013 and 0.015 mm at H2).



One of the 20 synthetic plots at the hottest condition.



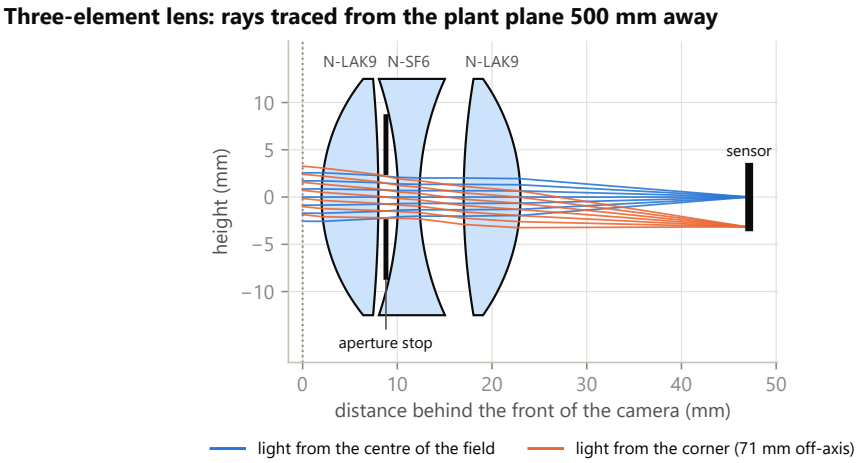
Position error across all 200 weeds in each operating condition. This is a geometry benchmark: it measures where the optics place each weed, not whether software recognises it. The starting design was not run on the two held-out conditions.

Vibration

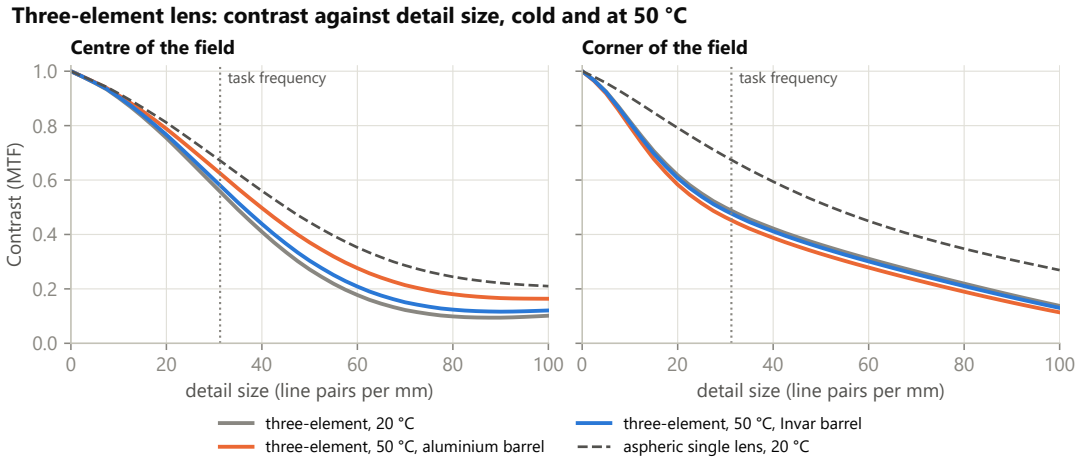
A field robot shakes. We ran the same lens and mount through a random-vibration screening spectrum (0.22 g RMS, 20–500 Hz, each sideways axis). The line of sight moves 6.1 µrad RMS, and the lowest mount resonance sits at 1697 Hz, well above the excitation band. At the 31 lp/mm task frequency that costs less than 0.1 % of contrast, so vibration is not what limits this camera.

A three-element version

The cooled design uses one aspheric lens. Many cameras need more glass, so the agent also designed an all-spherical **three-element** version of the same camera (LAK9 / SF6 / LAK9, 47 mm from front to sensor) and took it through coupled thermal, deformation and optical analysis. It meets the sharpness requirement (0.47 against 0.40), though the aspheric single lens is sharper (0.67).



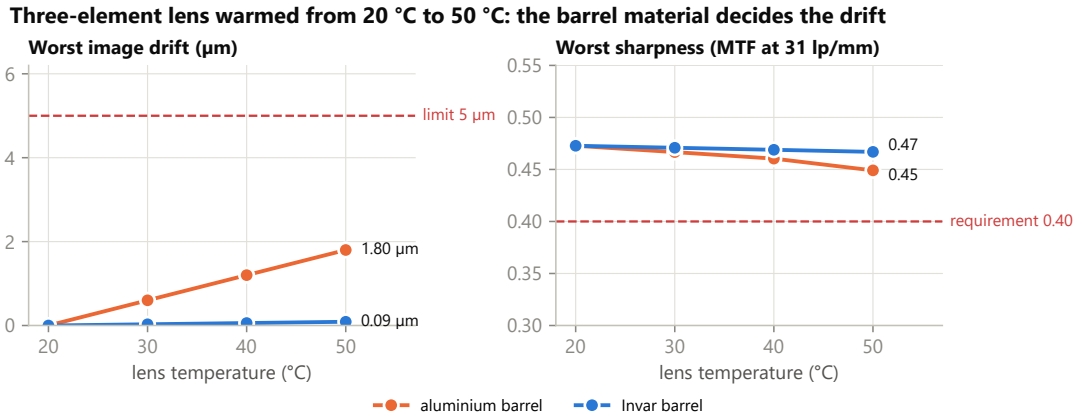
Ray trace of the three-element lens: two positive elements around a negative one, with the aperture stop between the first two.



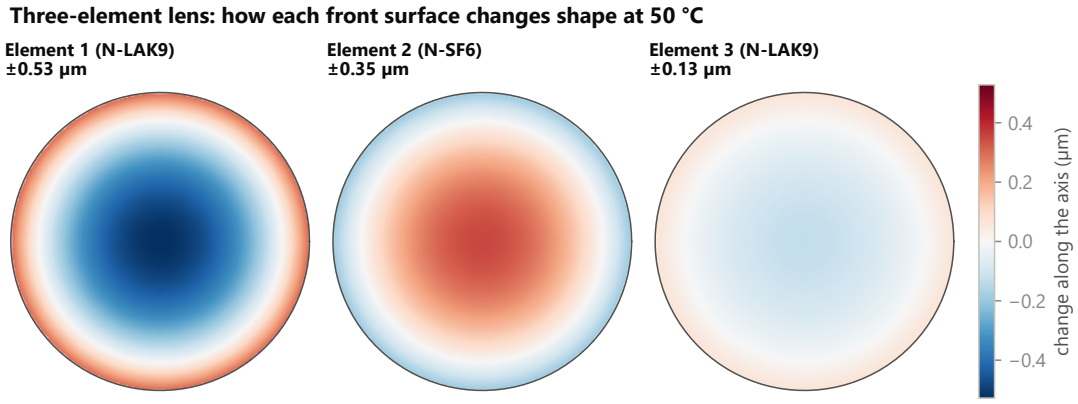
Contrast against detail size (mean of the two orientations) at the centre and corner of the field, with the aspheric single lens for comparison.

Uniform warming, 20 °C to 50 °C

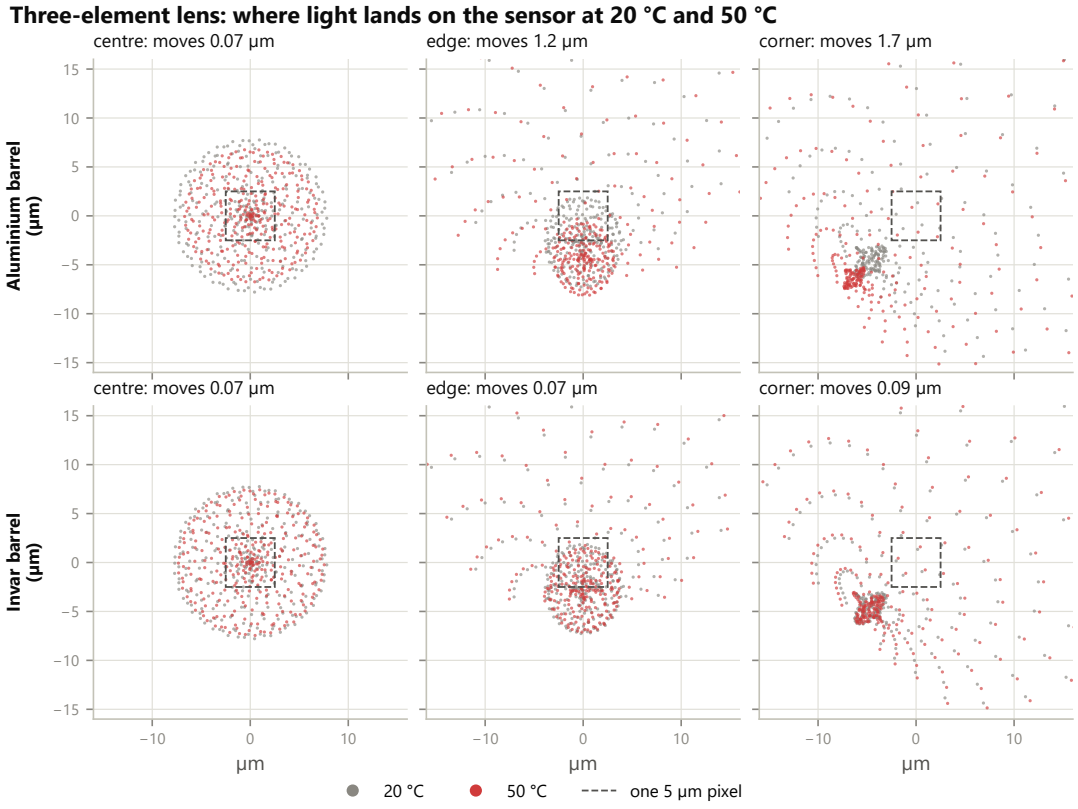
Each element expands and changes shape, its glass changes refractive index, and the barrel carries the sensor away from the lens. With an aluminium barrel the image drifts 1.80 µm at 50 °C. With Invar it drifts 0.09 µm. The barrel lesson from the single-lens design carries over.



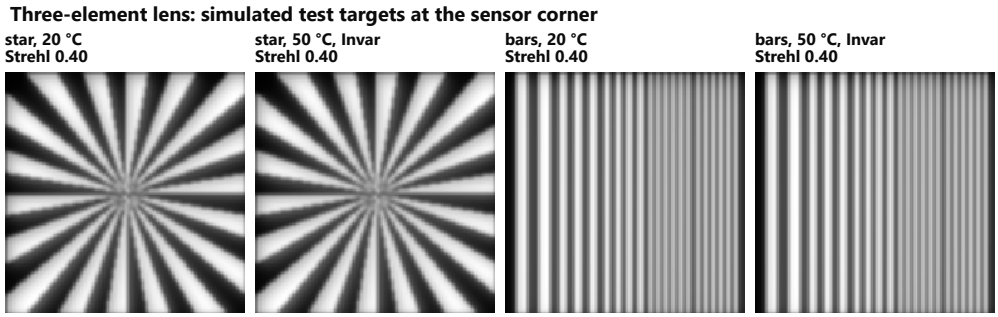
Each point is a coupled solve of all three elements, rebuilt as a heated lens and re-traced.



Solved change in shape of each front surface at 50 °C. The negative middle element bows the opposite way to the two positive ones.



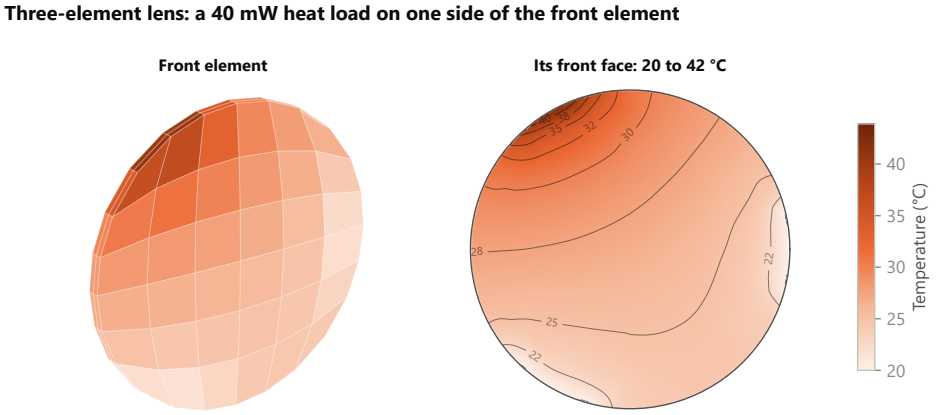
Where light lands on the sensor at 20 °C and 50 °C, with an aluminium barrel and with an Invar barrel.



Simulated star and bar targets at the sensor corner, cold and at 50 °C with the Invar barrel.

One-sided heating

We also put a one-sided heat load on the front element, enough to take one edge of the glass from 20 °C to 44 °C. The image moves 0.27 µm and worst-case sharpness holds at 0.47.



Solved temperature in the front element with a 40 mW heat load on one side.

How long it took

Each complete design check covers five operating conditions, each a coupled flow, heat and deformation solve followed by a full optical analysis of the deformed lens. It takes about **15 seconds**. The sequential workflow ran 211 condition-level simulations in 25 minutes; the joint search ran 320 in 15 minutes. The whole study used 633 coupled simulations and 609 re-traced heated lenses, across 14,044 API calls.

All of it was done agentically. No one operated the software by hand. The agent chose the lens family, ran the optimizer, launched each coupled simulation, decided what to try next from the results, and ran the verification. From reading the brief to the verified designs took about three hours of working time.

How the numbers were made

Every value comes from Paraxial's multiphysics and optical engines. For each design and condition: laminar coolant flow, heat conduction and thermal deformation are solved together, the deformed lens is rebuilt as an optical system, and sharpness and image position are measured at 9 field points. The sensor is fixed at assembly, with no refocusing or recalibration. Heat loads and targets are proposed benchmark inputs, not measured robot data.