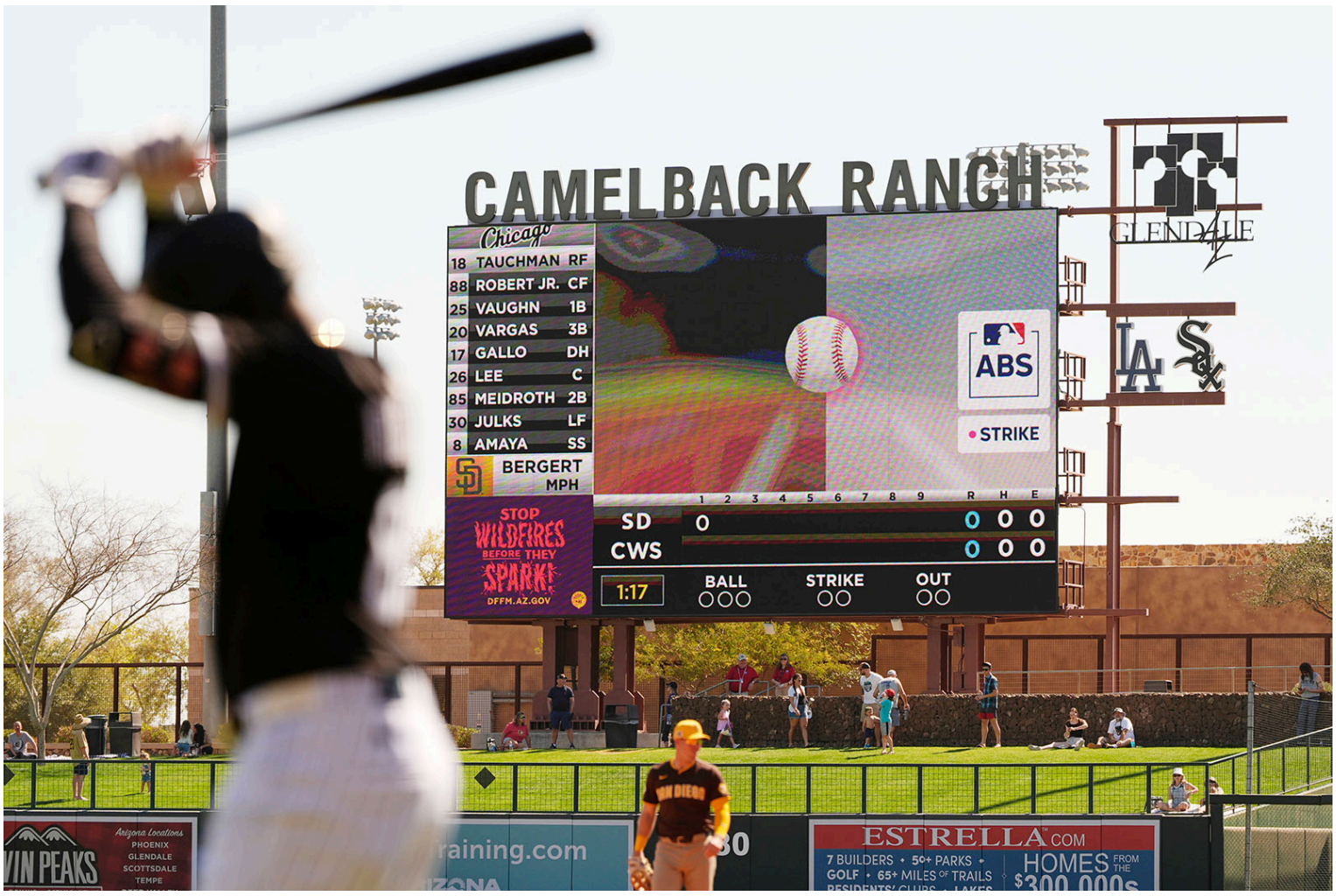
# EYES ON THE BALL

A “robo ump” that calls balls and strikes in Major League Baseball makes its World Series debut this week. It has to be near-perfect

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Major League Baseball first tested the Automated Ball-Strike Challenge System during spring training in 2025. CAROLYN KASTER/AP

**PETCO PARK IN SAN DIEGO—**At 6 a.m. on 8 October, Kyle Wait and Tyler Danby towed Pelican cases and duffel bags filled with gear onto the home field of baseball’s San Diego Padres. The night before, the team had lost a heart-wrenching game here, silencing 47,712 roaring fans and eliminating the Padres from the playoffs.

Aside from 2 dozen pristine baseballs, known as pearls, the men brought no baseball gear into the still-dark ballpark. But their high-speed cameras, tripods, lasers, rulers, plumb lines, radars, and a custom-built, piston-powered cannon that fires baseballs had everything to do with a question key to every game: whether a pitch is in the strike zone, crossing home plate at just the right height and depth, or misses the zone—a ball.

Wait and Danby, who both work at the Sports Science Laboratory run by Lloyd Smith at Washington State University (WSU), worried about the darkness of the field, where most of the light towers were shut off, and the beer-flavored mist from the cleanup crew’s power washing. At the invitation of Major League Baseball, they were about to do a “ground truth” of a technology introduced this year that represents one of the biggest changes ever in MLB’s 123-year-old history: the Automated Ball-Strike (ABS) Challenge System, more commonly known as “robo ump.” And their cameras, which cost more than $100,000 each, thrive on light and hate moisture.

After a flurry of emails and phone calls, the stadium lights started to blaze. The cleaners retreated. It was game on.

Over the next 3 hours, the two photographed 100 cannon-shot pearls crossing home plate at about 90 miles per hour, images they will analyze back at WSU to calibrate the park’s camera-based ABS system. (*Science* style is to use metric measurements, but baseball decidedly does not.) “I love doing this,” said Wait, an erstwhile wildlife ecologist who once used cameras to track carnivores and has worked as a ground truth specialist checking MLB’s 30 stadiums for 7 years. “Perfecting our methods is just a constant battle,” Danby says.

The core confrontation in baseball is between a pitcher and a batter, but there’s another important player in that drama—the home plate umpire, who decides in a split second whether an unswung pitch is a strike or a ball. Players and managers in the past could not, officially, challenge the ump’s decision. But that didn’t stop grown adults from swearing, wildly gesticulating, and acting like spoiled children when they disagreed with a call, risking

ejection from the game. Given that three strikes end a batter’s turn and four balls wins them a walk to first base, the stakes are high.

Even umps knew calls were regularly missed—19 in one 2022 game made especially memorable by a star slugger’s temper tantrum over the incorrect calls. So MLB has turned to an ABS system made by Hawk-Eye Innovations that uses five cameras around the baseball field to check the umpire’s calls. For an industry that grosses $12 billion a year, with games, careers, and more billions in bets riding on the fate of pitches, the system has to be near-perfect. “People ask, ‘We know you use Hawk-Eye to grade the umpires, but who grades Hawk-Eye?’” says electrical engineer Clay Nunnally, a baseball scientist at MLB. “WSU grades Hawk-Eye.”

With MLB’s ABS system, a pitcher, catcher, or batter can now challenge an umpire’s call of a ball or strike by tapping the top of his helmet or cap within 2 seconds. A few seconds later, the pitch’s trajectory appears in slow motion on the stadium’s jumbotron, showing the precise location of the baseball when it crossed the halfway point of home plate (see graphic, below). Teams start games with just two challenges, which are only retained if calls are overturned.




Players who want to challenge an umpire’s call must tap their helmet or cap within 2 seconds. ANDREW RITTER/MLB PHOTOS VIA GETTY IMAGES

MLB’s regular season this year saw 10,557 ball or strike challenges, and corrected calls changed games significantly. Three weeks ago, an extra-innings playoff contest ended on an ABS appeal, which turned a called ball into strike three. When a call gets overturned, fans sometimes go wild. But the robo ump calms down emotions on the field: Ejections over ball-strike disputes plummeted from 110 last season to 11, because the digital evidence leaves less room for contention.

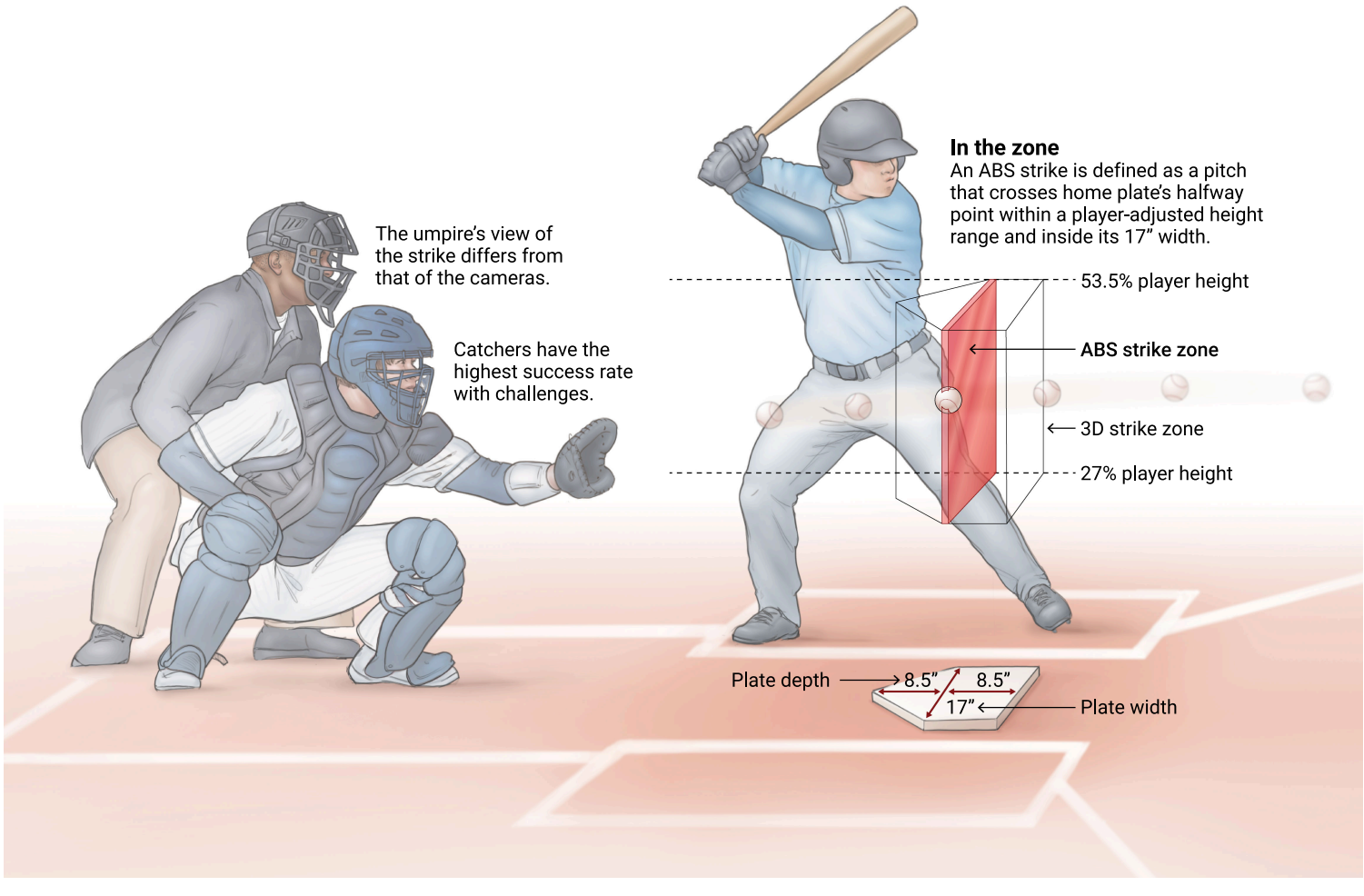
Tracking a ball traveling not much faster than a car on a freeway for less than 60 feet might seem a simple assignment for today’s technology. But the high stakes make fraction-of-an-inch precision crucial. Two ABS approaches, developed for different sports by a radar engineer and a computer scientist, competed for the major league job, with Hawk-Eye edging out its rival. And surprising variables can alter each system’s accuracy. “It’s not trivial to track the ball and figure out where it’s at,” Smith says. “There are a lot of things that come into play.”

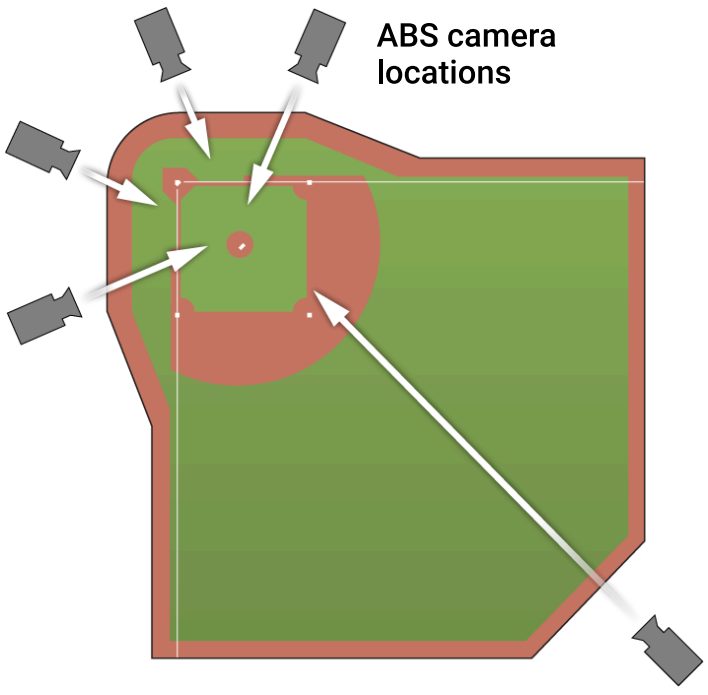
**AT MLB’S START** in 1903, the strike zone was a 3D concept. A baseball hit the zone if it crossed any part of home plate above the knees of a player and below his shoulders. For the Hawk-Eye ABS system this year, however, the strike zone is a 2D plane at the center of the plate that is adjusted for each player’s height. MLB measures each player, without shoes on, at the beginning of the season. The measurement is done both by hand—using stadiometers or sliding wall rulers—and with lasers. It takes place between 10 a.m. and 12 p.m. to avoid the spinal compression that occurs over the course of a day.

ABS systems don’t just capture the ball as it crosses home: They track its initial position, velocity, and acceleration throughout its half-second journey to the plate, calculating its trajectory toward the strike zone. “You gain overall precision in the measurement by using the full trajectory, rather than a single point,” says retired particle physicist Alan Nathan, a Smith collaborator who maintains a website called the Physics of Baseball.

### Umping the umps

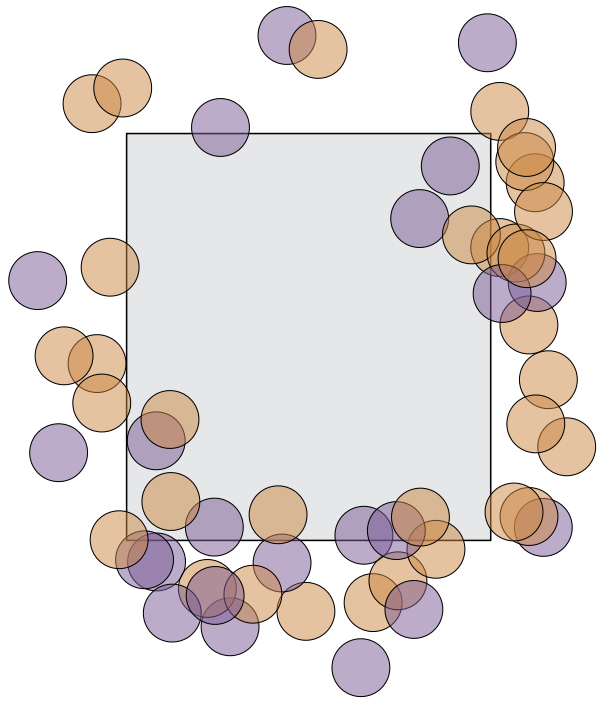
The camera-driven Automated Ball-Strike (ABS) Challenge System introduced by Major League Baseball this season allows the pitcher, catcher, or batter to contest pitch calls made by umpires.




**Points of view**

The ABS system designed by Hawk-Eye Innovations relies on five high-speed cameras around the ballpark. Because pitches can travel at more than 100 miles per hour, cameras might not capture the exact moment the baseball crosses midplate, so Hawk-Eye includes the trajectory of the ball in the equation that determines whether the pitch was a ball or a strike.



**Challenging calls**

This shows the location of all the called balls that were challenged by catchers or pitchers (orange) and the called strikes challenged by batters (purple) on the last day of the regular season, 27 September. The box represents the strike zone. Typically, catchers have the highest success rate. On this day, catchers only had 42% of their 33 challenged calls overturned, and batters won 50% of their 22 challenges. One call was overturned after being challenged by a pitcher.

N. BURGESS/*SCIENCE*

Pitch-tracking technology first came to MLB ballparks 20 years ago, but originally just to help coaches and players improve pitching and batting. It’s been used as an ABS system in MLB’s minor leagues for the past 5 years. “We test these things pretty significantly before we bring anything to the major leagues,” says Joe Martinez, a former MLB pitcher who’s now a vice president in the organization.

An early two-camera ABS system, PITCHf/x, used in the minor leagues between 2006 to ’15, claimed an accuracy of half an inch and got TV viewers used to seeing whether a ball was truly in the strike zone. But then Fredrik Tuxen, an electrical engineer from Denmark who knew nothing about baseball growing up, offered a more precise technology.

Tuxen had helped develop Doppler radars for the military to track missiles. Owners of golf driving ranges approached him and asked whether he could create a Doppler device to gauge the distance of their balls. A devoted golfer, Tuxen already knew it could be done: He had pulled out his clubs at the U.S. Army’s Yuma Proving Ground 10 years earlier when he finished testing a missile-detecting radar. “After 2 hours, I managed to actually track a golf ball, but the problem was I had a $2 million radar,” he says.

## SUCCESSFUL CHALLENGES

Catchers, who arguably have the best view of the strike zone, have the greatest success at overturning an umpire’s call. Pitchers rarely challenge calls, and for good reason: They’re bad at it.

**40%**

**pitchers**

**49%**
batters

**59%**
catchers

This led Tuxen in 2003 to co-found a company called Trackman, which developed a much cheaper radar that could fit into a large briefcase but still follow a golf ball. Sales took off. “People immediately said, ‘Hey guys, you need to take this to baseball, they’re crazy about data,’” he recalls.

The Trackman system sends out roughly 24,000 pulses of radio waves during a pitch’s brief flight. Receivers capture the reflections from the ball, which reveal its speed, position, and—by tracking the ball’s stitched seams—how fast it spins. The aerodynamic forces that spin creates, known as the Magnus effect, can deceive batters by causing a ball to deviate from a straight path. Many players and coaches didn’t immediately see the value of the machine. “For years, players have looked with their eyes and talked about stuff—‘This was a nasty pitch’ and all that—and to me as an engineer, that didn’t make sense,” Tuxen says. “I need numbers.”

By 2010, Trackman delivered the numbers, putting science into the art of pitching. It showed, for example, that an MLB pitcher’s average curveball spins at 2450 revolutions per minute (rpm) and revealed the degree at which it tumbles or twists. Pitchers learned for the first time that a curve spinning faster than 2600 rpm was more likely to fool a batter to swing and miss—a strike.

Trackman initially provided entertainment for MLB broadcasts, distinguishing pitch types—the eye can’t easily tell a cutter from a slider—and trajectories, as well as pitch locations. To improve Trackman, Tuxen hired Smith’s team to do ground truths.

Then MLB decided to assess umpires with an ABS system. “That’s where I got involved,” Smith says. “If you’re going to use that to evaluate people, especially if there’s a union, you have to have some independent system that says, this actually works.”

Tuxen has been delighted to watch the robo ump gain traction in the sport. “It’s interesting when you have an old game like baseball, with all this culture around it, including having an umpire,” Tuxen says. “Now you have modern technology meeting it. How do you bridge that?”

**MANY OF THE PEOPLE** who work on ABS systems played baseball themselves, but not Smith. “I would have been voted the least likely to be an athlete,” he says. He came to the game via his expertise in composite materials. Collaborating with Nathan, a lifelong amateur ball player, he began studies of the performance of different kinds of bats—wood, metal, and composite. The work involved firing baseballs at stationary bats, and Smith was hooked. “I kind of got into this by coincidence, but I found the research so interesting, and who wouldn’t enjoy a career building cannons?” he says.

MLB only allows wood bats, but colleges and other leagues permit other materials. That market is large, and the income from bat research allowed Smith to create the WSU sports lab, which has nearly 2 dozen staff. Together they have published more than 50 papers about baseball and softball, in journals ranging from *Sports Engineering* to *Composite Structures*. More than 2 dozen graduate students have come through with theses examining cricket bats, ice hockey sticks, shuttlecock drag, taekwondo, and the aerodynamics of baseball’s oddest pitch, the knuckleball.

When Smith began to evaluate Trackman, his team soon discovered subtle factors can affect the radar results. The weight of a sellout crowd, for example, can cause a stadium to sag. “The radar orientation might change a 100th of a degree, but that translates into inches at the plate, and inches matter in baseball,” Tuxen says.

To improve accuracy, Trackman added a camera to its system, supplementing the radar with optical data. In 2015, MLB put Trackman in all 30 of its ballparks in conjunction with the rollout of its own data analytics platform, Statcast. Trackman data helped teams evaluate future players, and some professional pitchers bought units to sharpen their “stuff.” Professional baseball teams in South Korea and Japan began to use the radar system for analytics, too.

MLB didn’t test Trackman as a robo ump until 2019, however, and the next year, it switched to Hawk-Eye, which relies entirely on cameras to track the ball. MLB won’t comment directly on the decision, but Hawk-Eye was equally accurate, possibly cheaper, and provided more information. At the time, “it was much more sophisticated,” Tuxen acknowledges.



Five strategically placed Hawk-Eye cameras track every pitch from its release to the ball crossing home plate. MLB

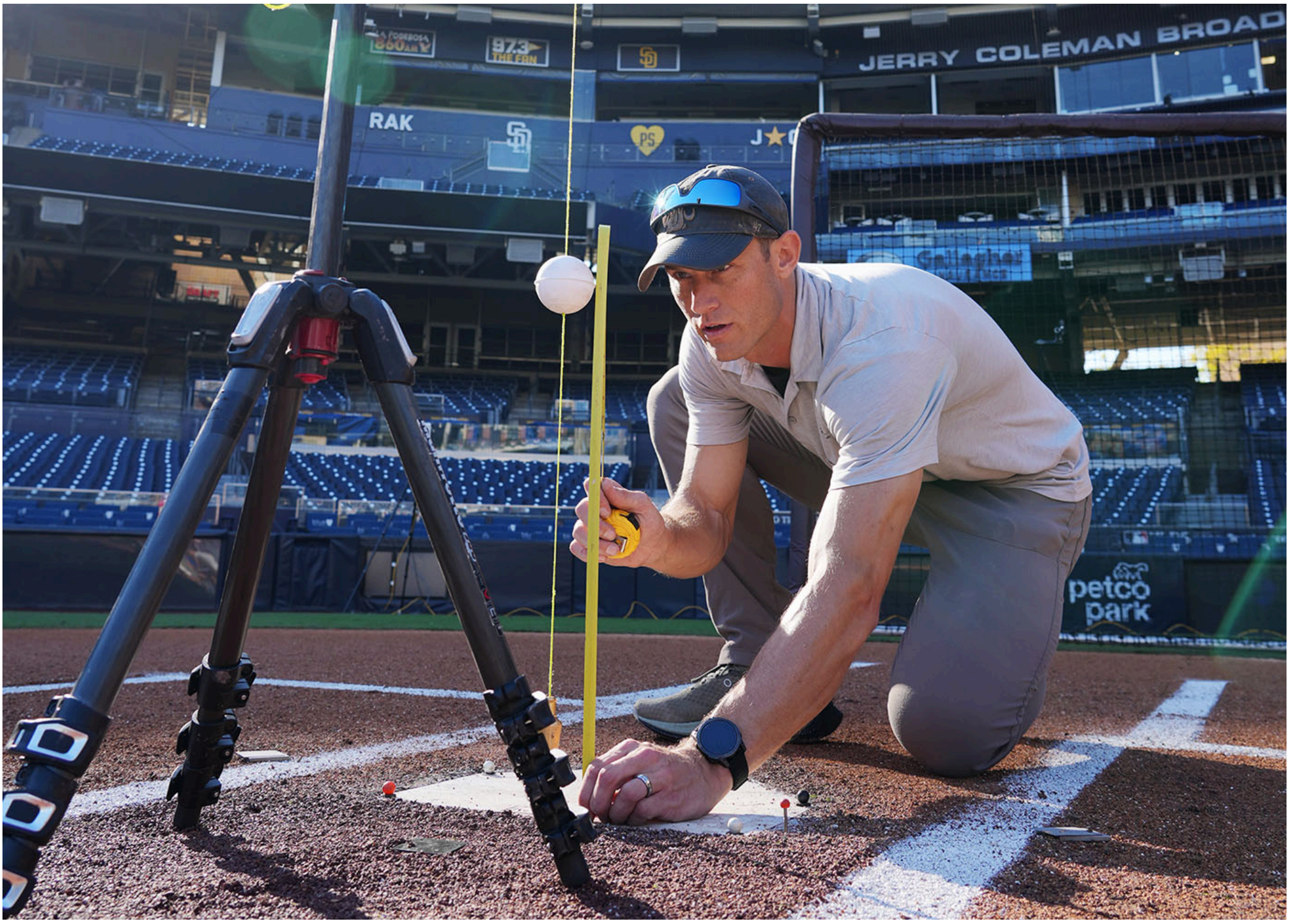
A U.K.-based company started in 2001 by computer scientist Paul Hawkins, Hawk-Eye first set out to adjudicate difficult calls in cricket, his first love. Purchased by Sony 10 years later, Hawk-Eye is now used in some 20 sports, including tennis, soccer, football, and rugby. For baseball, Hawk-Eye initially relied on 10 cameras, but added an 11th to detect the ball’s spin and then another just because the computers could handle its data. Some of the cameras track player movements, but five focus on the ball, imaging its flight at 300 frames per second. “We’re now at a point with optical tracking that we’re measuring the actual orientation of the ball’s seam,” says Matthew Gaydon, a baseball tech manager at Hawk-Eye.

Even that fast frame rate may still miss capturing the ball at the moment it enters or misses the 2D strike zone now used by MLB. “The ball travels about 5 inches in between raw measurements and we’d have to be lucky to get an actual measurement right at the plane of the strike zone at midplate,” Nunnally says. So like Trackman, Hawk-Eye calculates a trajectory and extrapolates it across the strike zone.

By combing data from 3000 test pitches evaluated by WSU with both Trackman and Hawk-Eye, MLB has determined the median ABS “error” for both systems is now 0.17 inches. “Even though we call this ‘error,’ it is more a gauge of uncertainty,” Nunnally says.

**MANY FACTORS** can degrade Hawk-Eye’s performance, and MLB had to pause its ABS system eight times this year during games. Hawk-Eye cameras can go out of alignment because of intense heat, the ground shifting under the ballpark, or having lenses cleaned during a game because of rain, fog, or sea spray. That’s why WSU’s team is here at Petco Park to evaluate how Hawk-Eye’s five ABS cameras—four of them set on beams above the nosebleed section, the highest tier of seats behind home plate, and one in the outfield—have held up.






Washington State University (WSU) sends a team to do ground truth testing of Hawk-Eye at every Major League ballpark. At Petco Park, Tyler Danby (first image) fired pitches from a WSU-made cannon at home plate, and Kyle Wait (second image) dropped a plumb line at home plate so they can later precisely calibrate the height at which the balls crossed. MATT ALIOTO

The testers use two of their own cameras, which at 2500 frames per second operate much faster than the ABS ones. After using a level, laser, and a plumb at home plate to precisely calculate the height, width, and depth of a 3D strike zone, Wait and Danby record 100 pitches fired by the cannon on the mound, each accompanied by a boom and a puff of condensation as the compressed air expands and cools. At Hawk-Eye’s control room in Atlanta, technicians simultaneously run Petco’s ABS cameras. The technicians can remotely focus them if need be, combating changes in lighting from clouds or the Sun, which they did during each of the 2430 games played in MLB this season.

The ground truthing goal is to test how accurately the system measures position, velocity, and spin. Danby orients each pearl in the cannon’s claw so the cameras can follow the seams and the writing printed on the ball, including the word “OFFICIAL” flanked by two stars. “To do spin rate, we track surface markers,” Wait explains.

The WSU team will calculate the “offsets” between its coordinates and the ones recorded by Hawk-Eye cameras, but the academic ball location evaluation is far slower than the ABS system’s in live play. “The crazy thing is, the pitch is thrown, and they know the [strike zone location] instantly,” Wait says. “We’ll do this, and I’ll tell you next week what the answer is.” Hawk-Eye will then adjust its cameras to correct for imprecisions.

Gaydon thinks the automated ump revolution is just beginning. He expects Hawk-Eye technology will make its way down to high school games or even Little League contests, with smartphones in fixed locations providing the cameras. “I can’t wait for the day where the parent who’s invested everything into their 9-year-old starts arguing with the poor umpire, and he’s like, ‘I didn’t make the call. The camera way up there did,’” Gaydon says.

Besides making the umps’ job less contentious, the ABS system has given them some heartening news. MLB’s comparisons of human pitch calls with automated ones showed that this season, human umps were correct 93.5% of the time. Martinez, the former MLB pitcher, isn’t surprised. “Everybody, even more so now than ever, appreciates the jobs the umpires do back there.”

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PHYSICS

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