Designing a tabletop instrument that could someday revolutionize mass measurement

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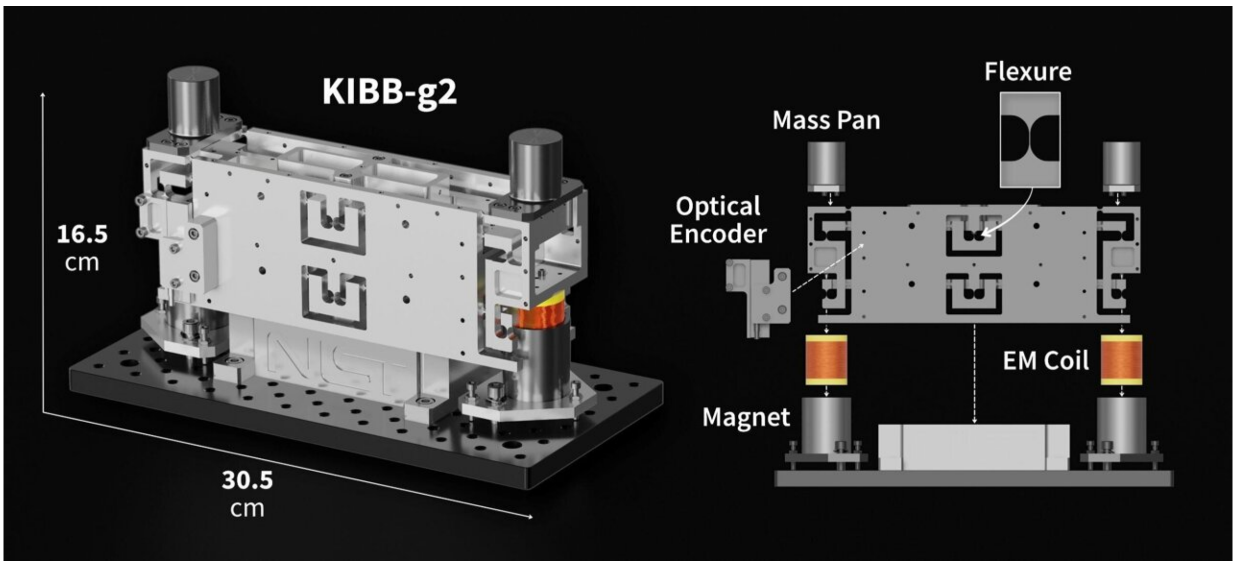

A diagram of the second-generation tabletop Kibble balance being built at NIST. In this version, movement is restricted to two dimensions using flexures, metal strips that only bend on one axis. (See animated GIF below.) The mass pan holds the physical object being weighed. An electromagnetic (EM) coil sits on each side of the device. Magnets provide a magnetic field through which the electromagnetic coils move. An optical encoder, which detects light and converts it into electrical signals, measures the movement of the coil. The whole device is roughly the size of a ream of printer paper. Credit: Sean Kelley/NIST

NIST is working on a big project in a small package.

When you want to weigh something—anything—in the United States, whether it's a truck full of cargo or a sack of potatoes from the grocery store, you have to use a scale that's been calibrated. As of May 20, 2019, the calibration relies on a measurement done with a specialized machine in the basement of a laboratory in Maryland, at the National Institute of Standards and Technology (NIST).

The machine, called the NIST-4 Kibble balance, is the size of a walk-in closet, and scientists use it to measure a mass of roughly 1 kg to within three millionths of 1%.

Researchers and manufacturers who need accurate mass measurements have to send their physical objects, called artifact mass standards, to NIST periodically to have them calibrated against the Kibble balance. But some people envision a world where, for measurements that don't require extreme accuracy, we don't have to send artifacts to a central Kibble balance anymore. What if, instead, Kibble balances could be smaller and simpler—less capable but amply sufficient for everyday purposes?

In service to this goal, NIST has been working to develop a small, robust, tabletop Kibble balance that could be used by a wider number of people.

"The 'Kibble balance uprising' shifts the metrological authority from NIST to the people," said NIST's Leon Chao, tongue in cheek. "The grand vision is to populate every mass lab with a group of two to three Kibble balances, each covering a subset within the range of 1 mg to 1 kg. This would mean that these labs would no longer need to mail in their mass standards to NIST for calibration every year or two. They could directly realize mass on site."

"We're excited about the project to see if it's actually possible," said the U.S. Army's Russell Kauffman. "This is just a small step, and it's a few years out, but we're trying to work toward modernization and do a lot with less equipment."

There has already been a first-generation tabletop Kibble balance, which Chao refers to as KIBB-g1. But there are a lot of improvements to be made, he said. The second-generation tabletop Kibble balance currently being developed for the Army, KIBB-g2, will look very different.

In general, full-scale Kibble balances, including NIST-4, share the same basic anatomy. They indirectly compare mechanical power to an equivalent amount of electrical power. More specifically, they measure the downward pull of a gravitational force on a mass by counteracting it with an upward electromagnetic force.

The NIST-4 design is effectively a pulley system. A large wheel at the top connects the two sides whose connection rests on a knife edge. On one side sits the mass being tested, as well as a small motor that can drive the machine up and down at a constant rate. On the other is a coil of wire suspended between a pair of powerful magnets.

A single measurement consists of two modes. In "velocity mode," power to the coil is turned off, and the motor drives the coil up and down through the magnetic field created by the pair of permanent magnets. This allows researchers to gauge the strength of the magnetic field. In "weighing mode," researchers run electrical current through the coil to turn it into an electromagnet. As the coil's field interacts with the permanent magnets, an upward force is created. This force is proportional to the current and can be measured. How much force is required depends on the mass of the object being weighed.

A laser interferometry system—which uses wavelengths of light to determine distance with high accuracy—measures the position and movement of the coil. Finally, electronics measure the induced voltage in velocity mode and the electrical current applied in weighing mode.

Following in the footsteps of its big sister NIST-4, KIBB-g1 also utilized a pulley wheel to keep the motion linear, but this time it was attached to an air bearing, which uses a layer of air to separate moving components. Like NIST-4, KIBB-g1 also relied on laser interferometry to measure the coil's motion. For KIBB-g2, though, researchers ditched the wheel and the air bearing—the largest source of uncertainty in KIBB-g1—and instead achieved linear motion using flexures which bend in predictable ways to only allow motion in a single dimension. The movement of the coil is also measured by an optical encoder, a machine that detects light and converts it into electrical signals, instead of by an interferometer.

The Army has requested the machine work with an accuracy of about 20 parts per million, in keeping with ASTM E617 Class 3 specifications. KIBB-g1 already surpassed that, able to realize 1- to 10-gram masses with an accuracy of under 10 parts per million. But the machine wasn't as robust or user-friendly as it will need to be for commercial uses, Chao said.

They also plan to make it faster. The turnaround time for measurements with the first prototype was on the order of hours. But the ultimate goal is an instant-read analytical balance, where measurement scientists get their result in seconds.

Finally, the new prototype will get a needed boost in hardiness.

"We want KIBB-g2 to be like a microwave oven, in the sense that you can unplug it, pick it up, move it to another location, plug it back in, and it still works," Chao said. "With KIBB-g1, if you moved it, it took quite a bit of effort to realign things."

And since KIBB-g1 was more accurate than the Army needs, there is room to streamline parts of KIBB-g2 to put reduced cost and ease of use above achieving the highest levels of accuracy when needed.

"It's not that we want the best," Kauffman said. "That would drive cost up. Instead, we're looking for the same uncertainty that we have right now, but we want to minimize the frustration of the guys in the field. They need something where they can sit down, set it up, use it, and then maybe walk away. And it goes through what it needs to do, and then when they come back it's finished and they've got a measurement."

Even with eventual widespread use of commercially available tabletop Kibble balances in lab spaces, NIST-4 will still have a place.

"Right now, NIST-4 has not lost its prestige yet as it's the only 1-kg primary instrument in the U.S.," Chao said. "Once industry finds a way to 'mass produce," pun intended, then, someday, NIST-4 can retire as a tool to disseminate the kilogram. This is what we want.

"We're trying to put ourselves out of business."

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