Applications of pm/√Hz Rasnik displacement sensors in gravitational wave detectors

H. van der Graaf[1], J.V. van Heijningen[2,✉], A. Bertolini[1] and B.Bouwens[1]

[1]National institute for subatomic physics Nikhef, Science Park 105, 1089 XG, Amsterdam, The Netherlands
[2]Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, Louvain-la-Neuve, Belgium
✉joris.vanheijningen@uclouvain.be

Abstract

The Rasnik alignment system was developed in 1993 for aligning the ATLAS muon chambers. More precise CMOS technology became available and Rasnik gained precision [1]. Now, Rasnik will also be used in gravitational wave (GW) instrumentation.

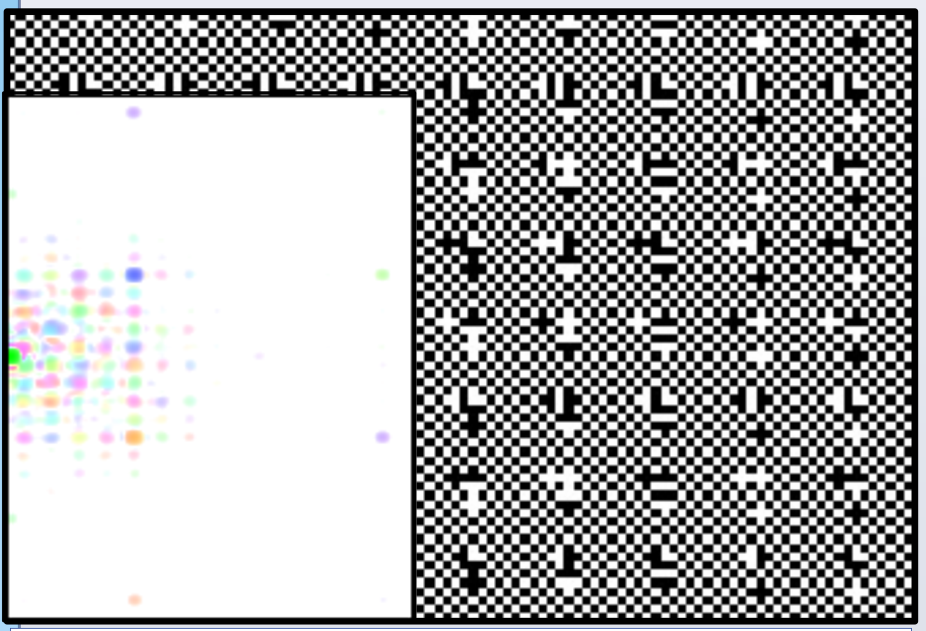

Figure 2. Rasnik ChessField image with 9-by-9 arrays of squares, where some provide code around the edges for course positioning and the others are used for precision. Taking a 2D FFT of the image results in the figure shown in the inset; peak fitting will determine the alignment of mask, lens and sensor by shift estimation with a reference image.

How does Rasnik work?

Fig. 1 shows the basic components of a Rasnik, and the pattern of the mask is explained in fig. 2. Rasnik is simple, robust, cheap, requires no feedback and, because of the clever chessboard pattern, all degrees of freedom (DoF) can be determined out of 1 image with no cross-coupling between DoFs.

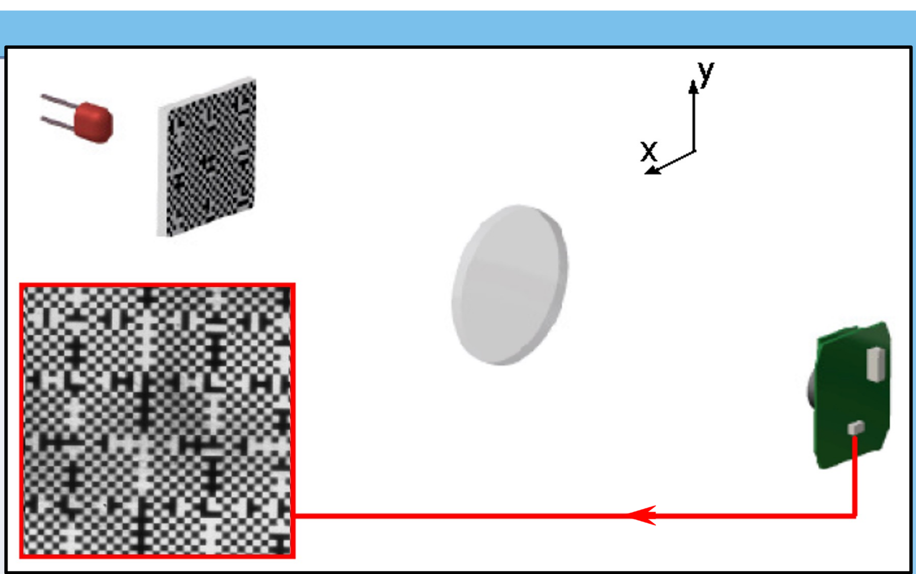

Figure 1. A basic Rasnik: an image of the back-illuminated coded mask is projected, by means of a positive singlet lens, onto the image pixel sensor. If the lens and image sensor are fixed together (forming a camera), Rasnik turns into a system that monitors the 4D position of the mask. From [1].

Range, only determined by the mask size, can be made arbitrary large. Only *x* and *y* (see fig. 1) are high precision DoFs. Fig. 3 shows the best precision we obtained of 7 pm/√Hz. Only image blurring and the photon flux quantum fluctuation falling onto the image sensor pixels [2], is limiting the resolution. Rasnik can therefore be used…

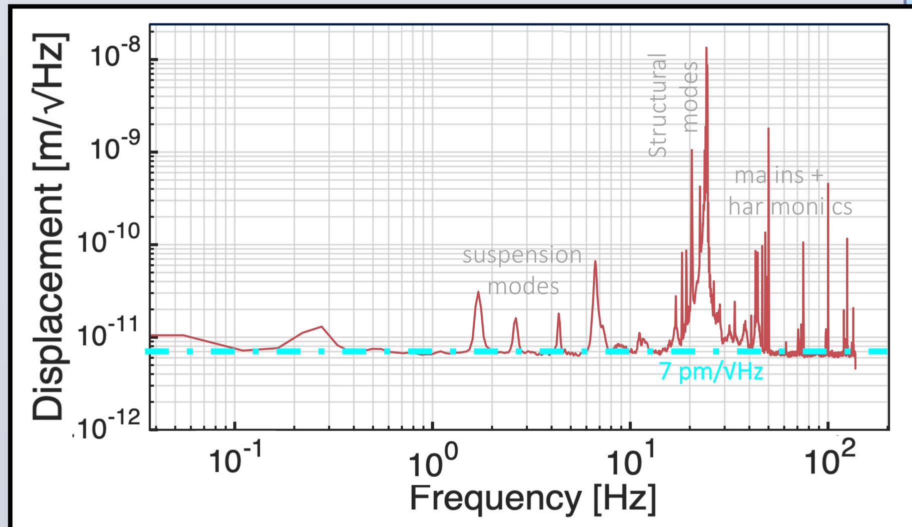

Figure 3. A sensitivity of 7 pm/√Hz is reached with a suspended, rigid Rasnik. The explanations for the observed peaks are added in the graph. From [2].

…as displacement sensor

In the setup that produced fig. 3, by replacing the used LED by a UV one, the refractive objective by a reflective one, and the pixel sensor by the one that can take in more light, the spatial resolution improves by a factor 7 [2]. The resulting 1 pm/√Hz is compared to the used differential displacement sensors in GW detectors in fig. 4. Below 100 mHz, the flat Rasnik outperforms all others and above that only interferometers do better. They require in-vacuum laser beams usually delivered by fibre and either feedback or ellipse fitting software. While Rasnik also requires (image analysis) software, the lack of lasers or many (polarising) optical components make Rasnik considerably easier to install, operate and maintain. While other sensors suffer for cross-coupling or misalignments in the optical readout, Rasnik reconstructs all 6 DoFs out of 1 single image. Therefore, no cross coupling is possible. The flat low-frequency Rasnik self-noise also makes it easy signal to use in control filters such as integrators. Fig. 5 shows how Rasnik could be a displacement sensor. Another use of Rasniks is for angular displacement. A curved mirror can act as a lens when attached to an object of which you want to monitor the angular DoFs. The Rasnik can act in a similar way as an optical lever (OpLev) with better sensitivity.

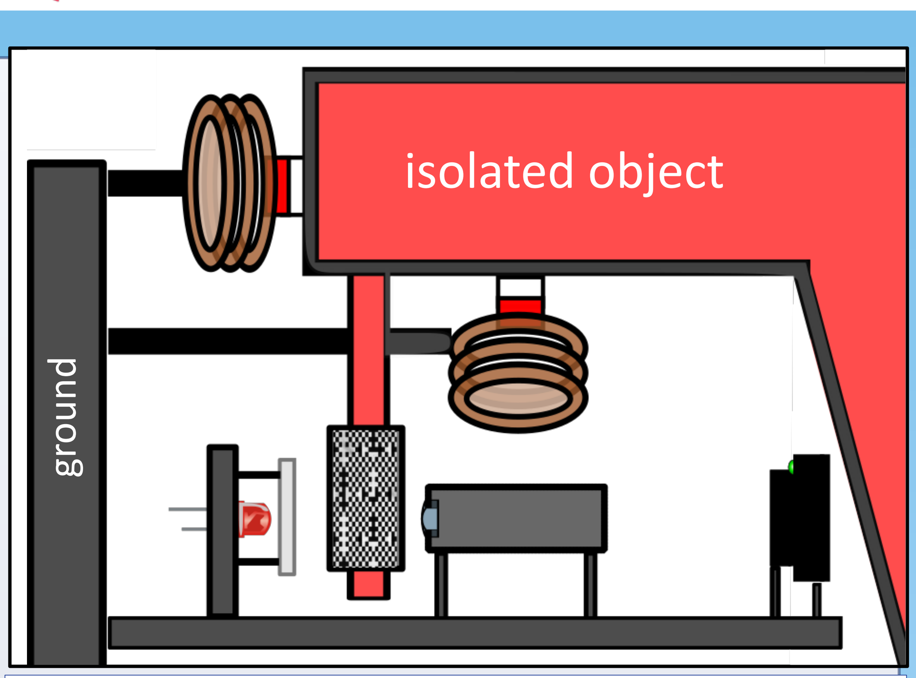

Figure 5. Example use of Rasnik as a displacement sensor. The motion of an isolated table is sensed in 2 DoF with pm/√Hz precision and a control system can damp the motion by actuating using the coils.

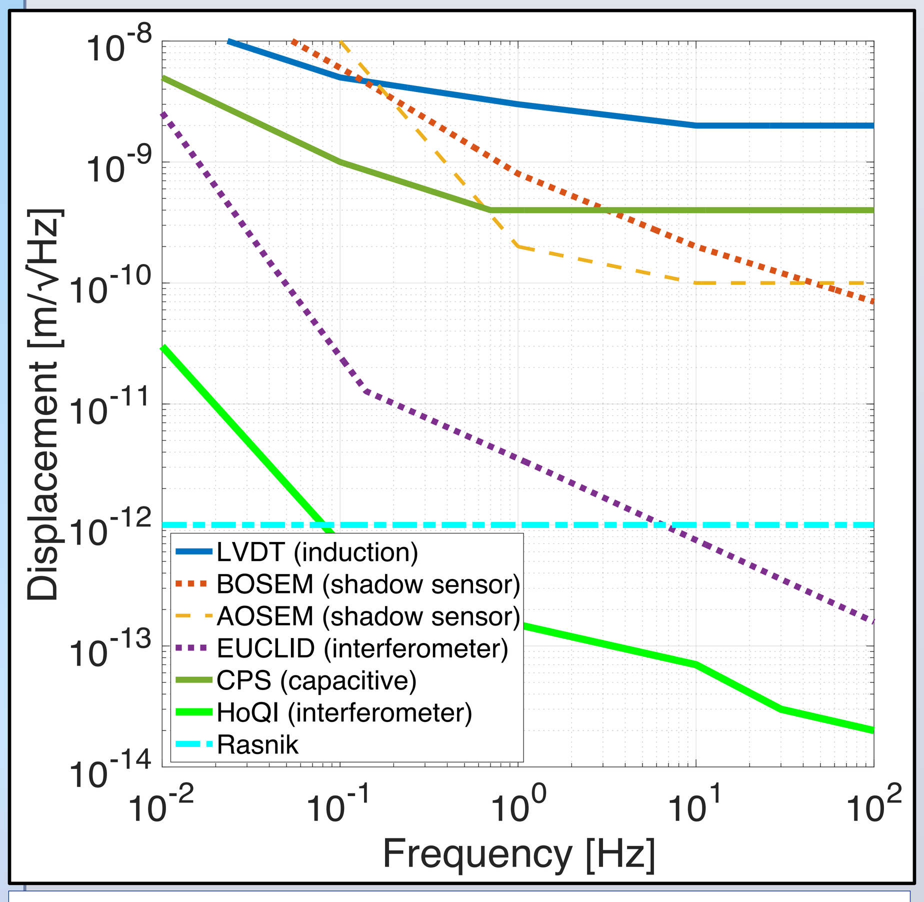

Figure 4. Minimal detectable displacement by displacement sensors used in gravitational wave detectors compared with a 1 pm/√Hz Rasnik. Legend indicates in brackets the used technologies.

…as inertial sensor readout

Using a Rasnik as a readout of proof mass that is suspended in some frame yields an inertial sensor. Fig. 6 shows an example inertial sensor: a Watt's linkage with a Rasnik readout. Rasnik has an arbitrary large range and can therefore always be operated in open loop. This greatly simplifies operation of the sensor and the lack of actuators leaves the *naked* mechanical loss of the Watt's linkage, which ensures thermal noise is not dominant in the noise budget. In fig. 7 this budget is compared to many commercial and custom GW sensors. Also plotted are the Peterson low noise model [13] indicating the expected spectrum on the quiet places on Earth. Clearly, commercial inertial sensor developers have no interest achieving sensitivities much below the Peterson models. The currently most sensitive sensors are AEI [16] and Virgo [17] Watt's linkages with LVDT [18] readout, the STS-2 seismometer and Nanometrics T360. Rasniks can also monitor the position of the end of suspended beams or crosses and form RasTilt: a rotational inertial sensor shown in fig. 8. RasTilt is compared to all custom angular accelerometers in the GW field in fig. 9. Other traces in the graph are of the Quartz Rotation Sensor (QRS) by Paroscientific Inc. [9], the Beam Rotation sensor (BRS) [10] the compact BRS (cBRS) [11], A Low Frequency Rotational Accelerometer (ALFRA) [12] – with future dotted projection of a 17 μm instead of current 40 μm flexure – and the Cylindrical Rotation Sensor (CRS) [13]. The black dash-dotted curve is a requirement for an angular inertial sensor to operate at LIGO set in a paper by B. Lantz [14]. A knife edge ensure low mechanical loss and therefore thermal noise. Across the 1 mHz – 1 Hz interval, RasTilt outperforms the GW field's custom rotational inertial sensors and is as sensitive as the 6D inertial system [15] below 30 mHz.

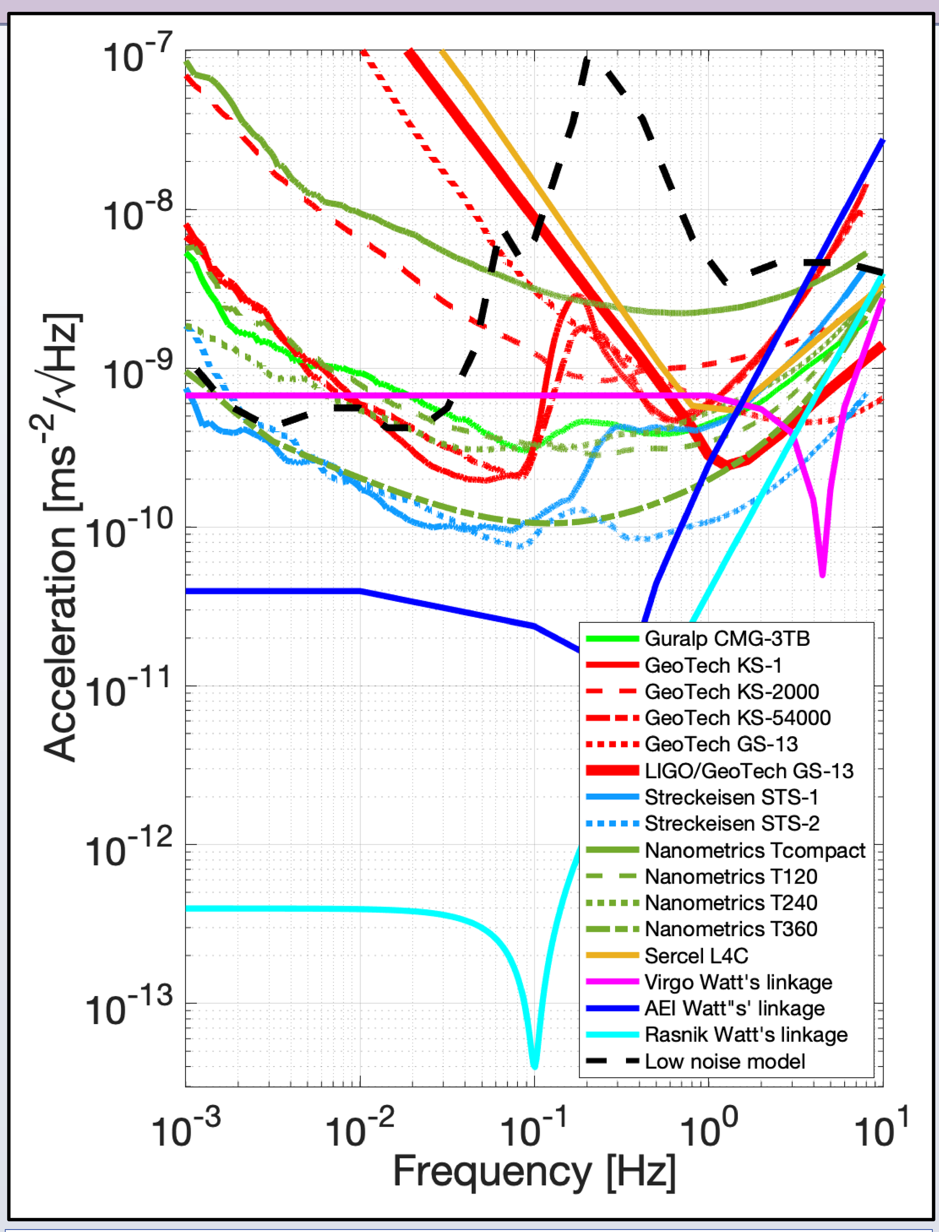

Figure 7. Minimal detectable inertial displacement by the world's best inertial sensors [14,15]. With the Watt's linkage tuned to a 0.1 Hz resonance, this device reaches excellent low-frequency sensitivity. More details can be found in the text.

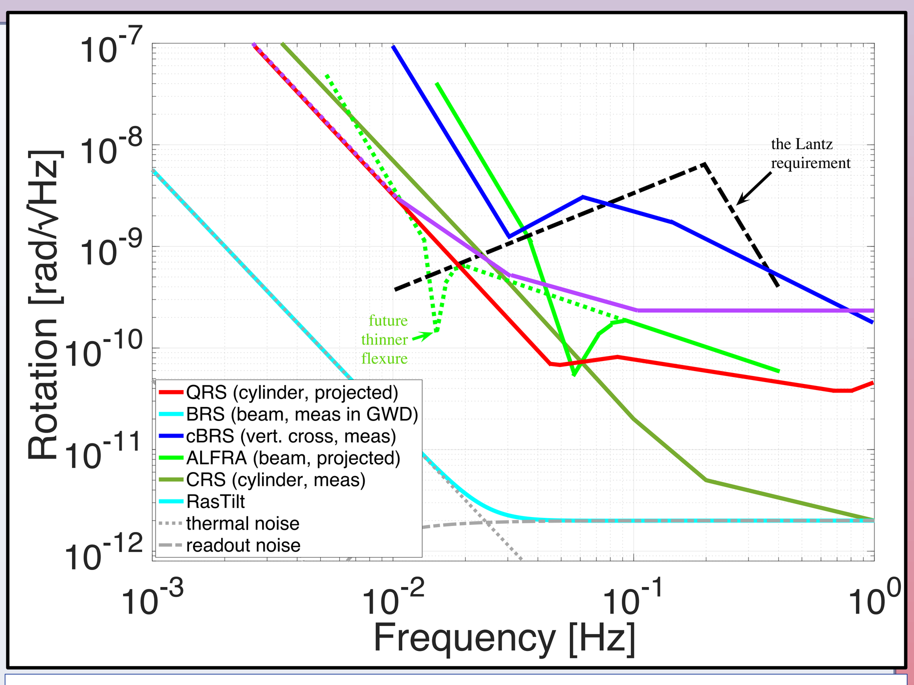

Figure 9. Minimal detectable displacement by displacement sensors used in gravitational wave detectors compared with a 1 pm/√Hz Rasnik. Legend indicates in brackets the used technologies.

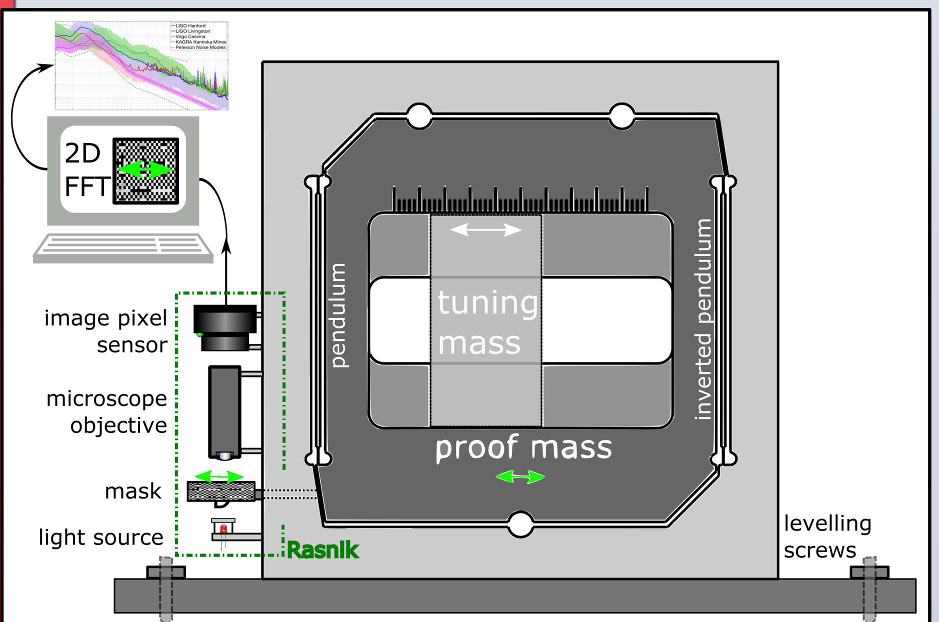

Figure 6: A Rasnik detects the proof mass motion of, for instance, a horizontal Watt's linkage.

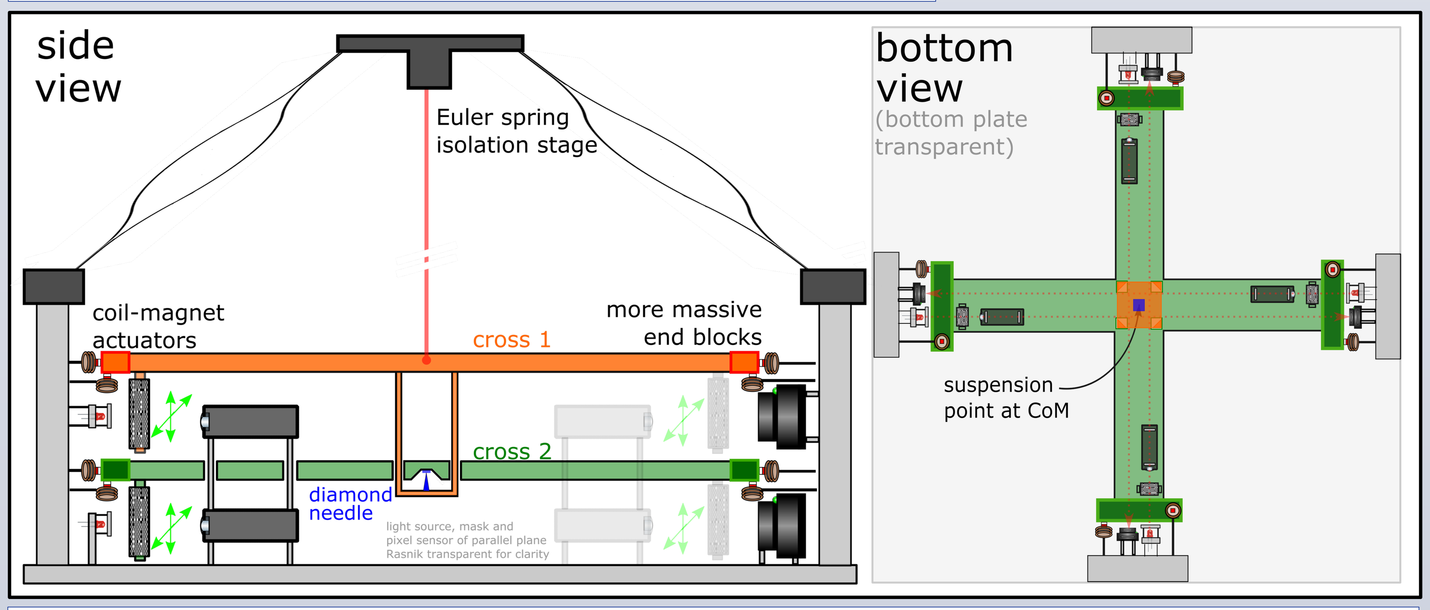

Figure 8: A Rasnik detects the motion of suspended horizontal cross ends. This RasTilt enjoys single image multi-DoF readout resulting in a lack of cross-coupling.

Conclusion

Rasnik can be applied as an (angular) displacement sensor and as part of a (rotational) inertial sensor. Its pm/√Hz precision makes it very competitive while being simple, cheap (< 1k€ per Rasnik), not requiring any feedback system and with no cross-coupling between sensed DoFs.

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