

# REPLACING OPTICAL LINEAR ENCODERS?

Historically, positioning stage designers have integrated optical linear encoders as displacement sensors. Though cumbersome, these have proven robust and cost-effective. Yet with the global trend of miniaturisation, the ever more prevalent micro manufacturing technologies require more compact solutions that offer even better precision, so attocube developed an innovative, compact sensor, which tracks displacements over long range with the accuracy of interferometers. Additionally, it can diagnose complex systems in situ by sensing angular motions and analysing vibrations in real time.



PIERRE-FRANÇOIS BRAUN

**T**he pervasive miniaturisation trend raises extreme challenges, especially in precision mechanical engineering and micro manufacturing. We need new routines to machine or qualify tools and parts. We need new sensors to repeat ultra-precise displacements over ranges of several centimeters and still meet the highest quality standards. We need novel solutions to accurately appreciate and control mechanical vibrations, and thus ensure failure-free production processes.

If we failed in addressing these issues during, for example, a milling process, the workpiece would move erratically with regard to the cutter. This would lead to contouring errors or poor surface finishing [1]. The misshaped component would doubtlessly fail the ‘Six Sigma’ standard criteria (a state-of-the-art quality process [2]), and would even jeopardise the whole system’s assembly or safe operation.

## Encoder vs interferometer

Of course, in order to track linear displacements, laser interferometers offer ultimate resolution, accuracy, and versatility. However, they lack the crucial flexibility required to work in confined spaces difficult to access. Moreover, the prohibitive price and rather large footprint of modular commercial interferometers disqualify them for integration in industrial OEM (Original Equipment Manufacturer) products.

Therefore, precision stage designers use optical linear encoders as a back-up solution to read out position. But such encoders require dedicated stage design, prove difficult and time-consuming to align for long-range displacement and necessitate periodic recalibration. Indeed, they measure displacement away from the actual point of interest. Therefore, the output position overlooks misalignments (Abbe errors) or imperfections in guiding accuracy.

Attocube’s new non-invasive interferometric displacement sensor, the IDS3010, offers probe compactness (down to only 1 mm in diameter) without compromising measurement accuracy [3]. Its dimensions fit OEM requirements for integration. The system primarily consists of standard optical components, originally developed for mass production in the telecommunications sector (precision laser diodes, photo diodes, fibre optics, etc.). This reduces its manufacturing costs when compared to other commercially available interferometers.

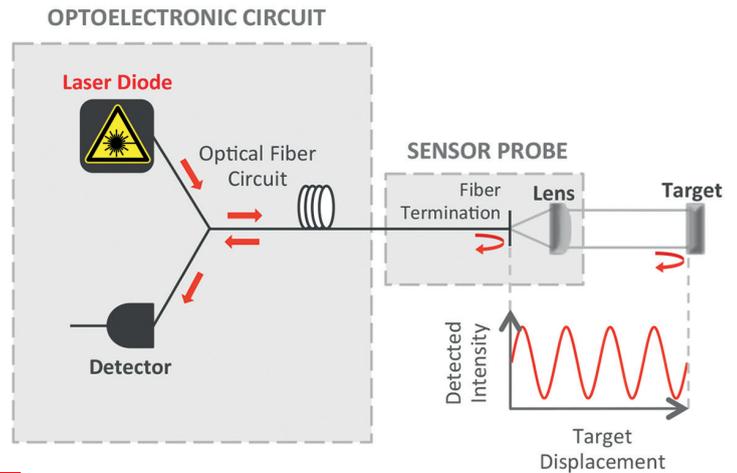
## Working principle

The innovative IDS3010 includes up to three sensor probes (Figure 1), either directly integrated or remotely connected through standard optical cables to an electronic unit. It notably embeds a laser diode that emits low-power infrared light and an optical fibre circuit, which routes the invisible and safe-for-the-eye beam to a sensor head (Figure 2). The optical fibre termination reflects part of the light back in the

### AUTHOR’S NOTE

Pierre-François Braun did his Ph.D. in the Quantum Opto-Electronics group of the Laboratory of Physics and Chemistry of Nano-Objects at the National Institute for Applied Science in Toulouse, France. In 2008, he joined attocube systems, a high-tech company supplying solutions for ultra-precise positioning and sensing. There, he developed the innovative technology presented in this article.

pierre-francois.braun@  
attocube.com  
www.attocube.com



1

2

optical circuit and outputs the rest in free beam toward a reflective target (e.g. a mirror, a polished surface, a piece of metal with low roughness). The light then reflects back into the optical circuit. This arrangement automatically creates a Fabry-Perot cavity: a space between two partially reflecting surfaces in which light rays can bounce back and forth.

The optical fibre circuit then routes both beams (reflected from the fibre termination and the target) towards a detector embedded in the electronics. There, they recombine and generate an interference pattern: the luminous intensity measured on the detector varies according to the target displacement, as sketched in Figure 2. The IDS3010 electronics process this signal and output it in real time through industrial standard interfaces. The innovative and patented probe design [4] allows extreme compactness and unmatched mounting tolerance. Attocube offers various sensor head sizes ranging from 1.2 mm to 22 mm (Figure 3). In the remote electronics version, the sensor head connects by only one optical fibre (compared to optical linear scales, which require up to 11 electrical wires). This ensures robust and easy installation, and eliminates the usual trailing cables' vibration coupling of sensor probe to environment.

### Stability and accuracy

In order to perform truly accurate – i.e. metrological – motion tracking, the IDS3010 electronics lock the laser diode wavelength to a gas molecular absorption. Indeed, this process directly references the output displacement to international length standards. Moreover, this technique enables sensing with the highest stability, as shown in Figure 4. The sensor was operated in closed-loop tracking a moving stage over 1 µm in 100nm steps. The figure inset validates the device's sub-nanometer repeatability, proving that the device competes with state-of-the-art inter-

1 IDS3010: a laser interferometer that tracks displacements with picometer resolution over meter ranges, and performs on-the-fly frequency analysis. The sensor includes up to three sensor probes either directly integrated (right), or remotely connected through standard optical cables (left), to an electronic unit.

2 Working principle of the IDS3010. The electronic unit embeds an optoelectronic circuit to generate, route and analyse light radiations. The fibre termination and target reflect the laser light back in the optical fibre circuit to a detector and form a Fabry-Pérot interferometer; the detected intensity fluctuates when the target moves.

ferometers, which, for historic reasons, use expensive helium-neon lasers as light source.

Usually, fluctuations of environmental conditions (air temperature, pressure and humidity content) affect the air density and lower the interferometer's accuracy. This Achilles heel was successfully tackled. A simple, tiny electronic box neighbouring the measurement (the environmental compensation unit shown in Figure 5) monitors room temperature, pressure and humidity to enable correction for their variation.

To assess this technique, the national metrology institute of Germany (PTB) qualified the interferometers and ensured their traceability by certifying a displacement tracking accuracy better than 0.14 ppm. This corresponds to a 140 nm uncertainty over 1 meter range. The certified accuracy of the device then matches the theoretical specifications of the best optical linear scales when used in highly controlled conditions (the operator must stabilise the room temperature within only one degree Celsius when using the linear optical encoder). Yet existing optical linear encoders embed electronics, which heat the experimental set-up locally. In contrast, the new interferometer uses low-optical-power and electronics-free probes.

### Applications

The novel sensor fits a variety of industrial applications (as shown in Figure 6). It tracks fast linear stage motion with velocities up to 2 m/s (Figure 6e), while preserving the interferometer's ultimate resolution of one picometer. It can also monitor stage guiding accuracy in real time (Figure 6a). Indeed, the system's angular tolerance can exceed several degrees. A simple closed-loop set-up may then control the carrier displacement within six degrees of freedom.



3

Likewise, the real-time processing and high-bandwidth interfacing, which follows industry standards, enable on-the-fly diagnosis of part vibrations in a fast and accurate way. Using the contactless sensor avoids changing the mass of the object under study even minimally. This could otherwise induce dramatic shifts in vibration frequency/amplitude.

Figure 6b shows a typical frequency analysis result obtained by monitoring and recording the displacement of a motor housing. The sensor's remote electronics perform a Fast Fourier Transform (FFT) of the signal in real time. In this example the set-up vibrations are displayed versus frequency in the 5 Hz to 50 kHz range for the motor spindle rotating at 500 or 2,000 revolutions per minutes (rpm). The frequency analysis emphasises that the present motor design couples vibrations at the fundamental frequency to higher harmonics. At 2,000 rpm, these then feed device resonances, which drastically amplify the overall motor vibration amplitude, and even jeopardise the system's safe operation. This crucial information triggered a design modification of the motor, minimising the system response to vibrations and preventing potential system failures.

Among other attributes, the novel sensor also tolerates measurements on curved and milled surfaces. It can then directly measure the actual runout of a rotating shaft. As an example, the bearing errors of a standard electromagnetic motor were characterised (Figure 6c en 6d). Likewise, the in-plane motion of a rotating milling machine workpiece was monitored, showing the difference in vibration spectra arising when the milling process takes place as compared to the idle state (Figure 6c).

As opposed to optical linear encoders that designers integrate in the positioning stage holding the actual piece to mill, the new device targets the object of interest directly and avoids any in-between error sources such as stage bearing imperfection or slight angular encoder misalignment.



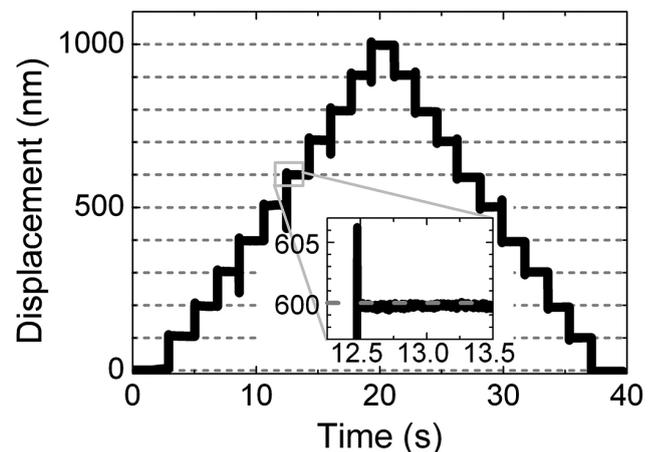
4

- 3 Ultra-compact and robust sensor probes, the smallest one reaching 1.2 mm in diameter.
- 4 Closed-loop control of a positioning stage, which performs a displacement over 1  $\mu\text{m}$  in steps of 100 nm. Inset: zoom on one step end that clearly shows sub-nanometer position stability.
- 5 Environmental compensation unit used in compensating for any changes of room temperature, pressure, and humidity.

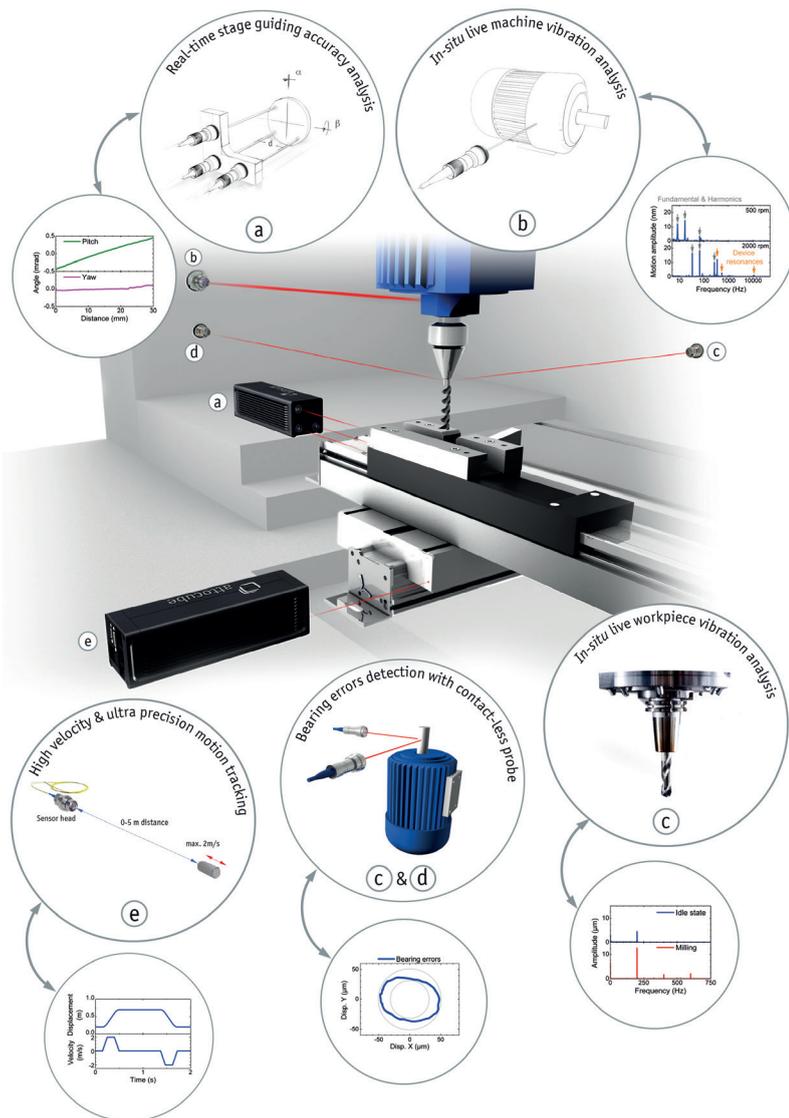
### Conclusion

A new device for ultra-precise linear displacement sensing was presented. Figure 7 summarises its specifications. The new solution either integrates processing and optical components in one system or remotely connects an extra-compact sensing probe to a remote electronics unit by a single and robust optical fibre. These designs ensure easy sensor integration and portability, so the system fits industrial requirements for OEM manufacturing. The IDS3010 tracks motions over the wide DC to 10 MHz range with picometer resolution. Users may benefit from high angular tolerance to characterise a stage guiding accuracy.

In brief, the IDS3010 enabling technology permits a variety of industrial applications: calibrating CNC machine axes, positioning linear stages for example in coordinate measuring machines (CMMs), controlling motions with the most demanding precision (as in semiconductor lithography set-ups), performing vibrometry, etc. For example, the frequency analysis tool allows on-the-fly diagnosis of machines in a production line without disrupting the manufacturing process. Production teams can then trace back unbalanced, misaligned, damaged or



5



loose components and trigger service or maintenance on time. This improves part quality and minimises machine downtime. As this solution remains cost-effective, it matures in a viable solution for complementing or even replacing optical linear scales. Therefore, by complying with standard industrial communication protocols and operating through a user-friendly web interface, the new sensor qualifies for the 'Industry 4.0' challenges.

Up to now, machine tool manufacturers have embedded optical linear encoders in their products and then qualified their machine with an optical interferometer. Yet, by directly using attocube's OEM solution at similar expense, they can eliminate this process, ensure higher system accuracy and even avoid regular instrument recalibration. Additions to this product portfolio will be introduced, for example, a new product line adding absolute referencing to the present displacement tracking feature. ■

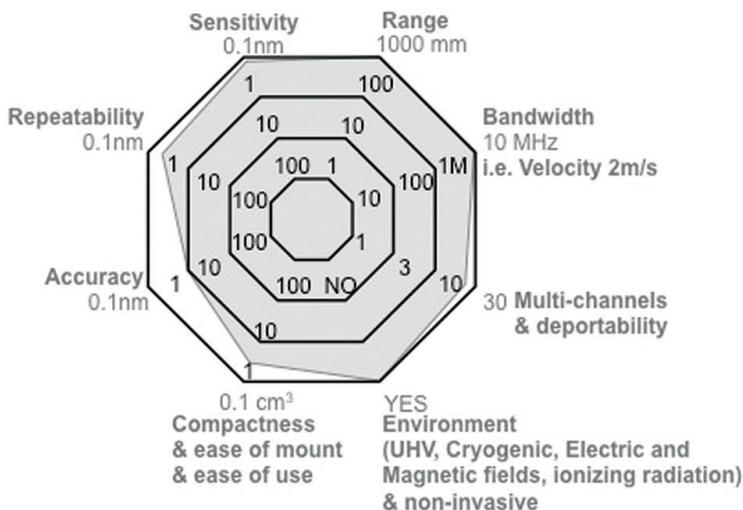
REFERENCES

- [1] Stone, B., *Chatter and machine tools*, Springer International Publishing, Switzerland, 2014.
- [2] Eckes, G., *Six sigma for everyone*, John Wiley & Sons, New Jersey, 2003.
- [3] Karrai, K., inventor; attocube systems AG, assignee. "Device for position detection", United States Patent 20100259760, 2013 Oct 29.
- [4] Karrai, K., Braun, P.-F., inventors; attocube systems AG, assignee. "Device and method for acquiring a position with a confocal Fabry-Perot interferometer", United States Patent 2011211199, 2014 July 08.

6 Examples of typical applications targeted by the IDS3010 in a milling machine environment.

- (a) Real-time stage guiding accuracy analysis.
- (b) On-the-fly non-contact diagnosis of part vibrations.
- (c) In situ monitoring of rotational object motions in plane (such as a milling machine workpiece).
- (d) With (c): Direct detection of bearing errors and runout behavior.
- (e) Linear stage motion tracking over meter range with picometer resolution.

7 Spider chart mapping the sensor's principal specifications.



6

7