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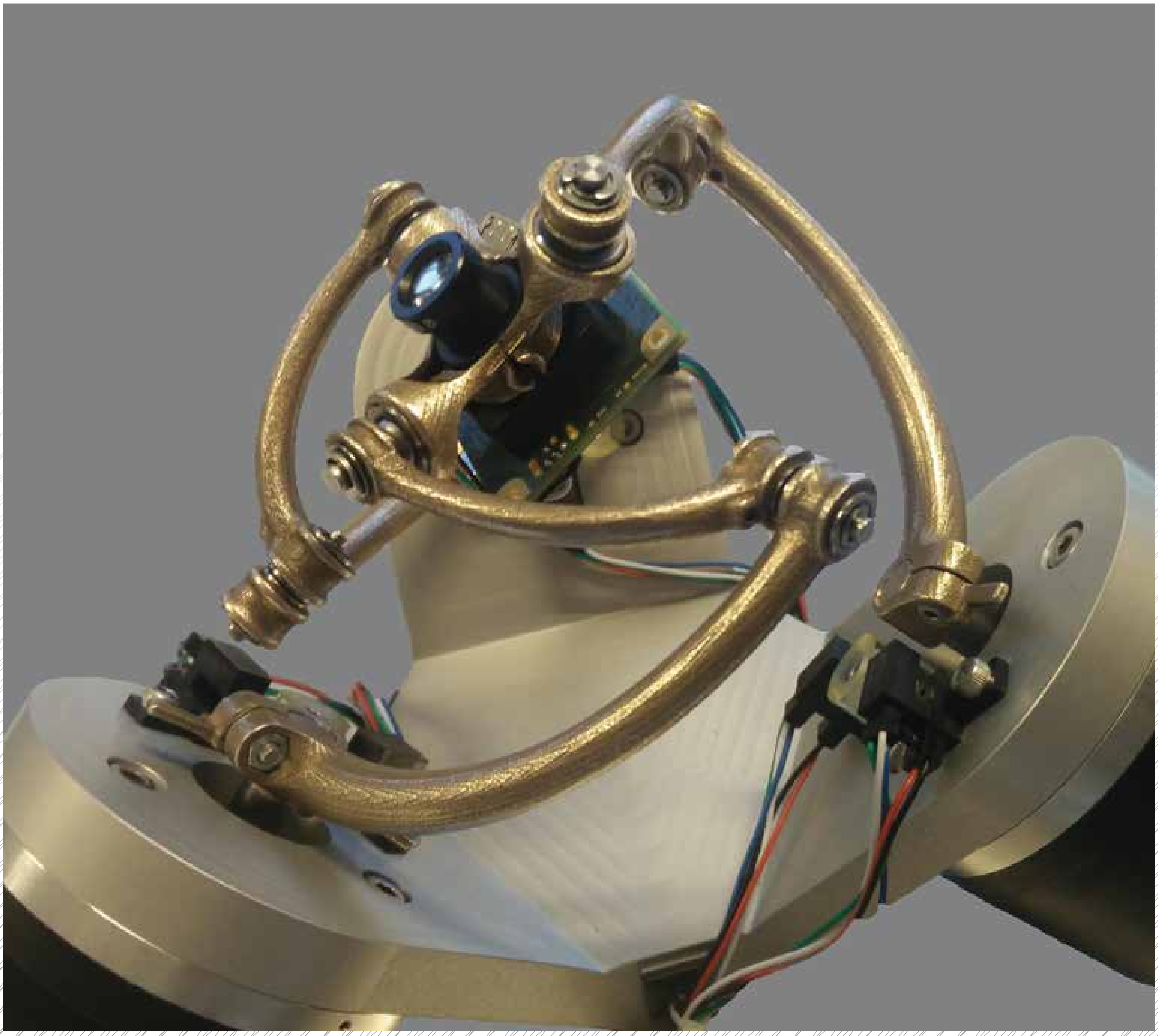
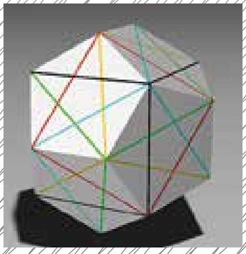
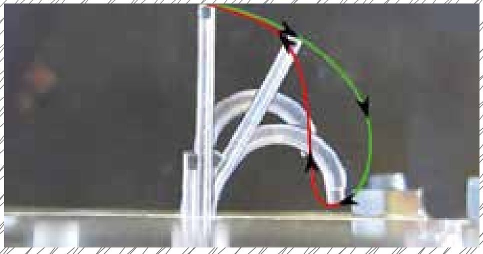


- DEMO DESIGN: **AGILE EYE**
- **MICROFLUIDICS**: NATURE'S WAY
- **SUB-NM** COMPACT FIBRE INTERFEROMETER
- **DIAMONDS** ARE FOREVER





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The main cover photo (featuring the VIRO Agile Eye) is courtesy of VIRO. Read the article on page 10 ff.

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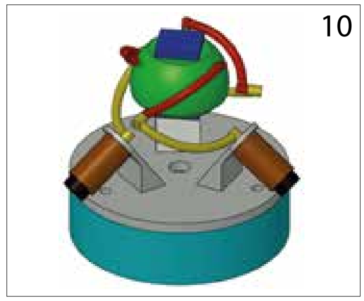

FEATURES

PRECISION ENGINEERS REQUIRE MORE **DIGITAL SKILLS**

Thirty years ago, I worked with robots operating with 1 mm precision. Higher accuracies were already possible with CNC machining, thanks to expensive, programmable numerical controllers. CAD, CAM and CIM (Computer Integrated Manufacturing) were the abbreviations of the day. It was only in the nineties that mechatronics was introduced.

Today, it is all about the fourth industrial revolution. Smart Industry means the digitalisation of our industry. The Internet of Things is connecting everything to everything, resulting in smart manufacturing, smart products, smart services, etc., and digital twinning, artificial intelligence and blockchain are accelerating this revolution. It has become possible to reduce delivery times, while zero-defect has become a must. More and more we see that all processes need to be under precise control, with every production step controlled 100% to stay within specs. Simple random inspection is not enough. And with artificial intelligence/machine learning, we can continuously improve control algorithms.

Thirty years later, and with a lot more processing power and software, wafer stepper mechatronics++ enables us to achieve overlay positioning in the order of 1 nm at speeds CNC could only dream of 30 years ago. All this would not have been possible without the digital skills of the many architects and engineers involved. Digitalisation is rapidly providing more opportunities to create new solutions. For example, with advanced digital controls, TNO is now able to manufacture freeform optics. So now we need to be able to design such optics. That also requires digital design tools.

Precision engineering is and will stay a mechanical design science, but today it is also about digitalisation and digital skills. My message in this editorial is that skilled people should understand their profession thoroughly, including all the newest digital means. In Smart Industry, we see that craftsman aged 35 years and older face the problem that 20 years ago, in 1997, their schools did not have Internet access. These people will work for another 35 years (or so) until retirement at 70. We can't afford to lose them. So, with the acceleration of digitalisation, we now need to develop their digital skills to complement their initial professional training. The challenge for Smart Industry is to enable life-long learning for everyone.

The demand for more digital skills from precision engineers and system architects will also accelerate. It might be that in the future we will not position objects more precisely by making them stiffer, but by using digital control we will position them more intelligently. The success of lithography machine world market-leader ASML, at the borders of technological capabilities, lies in the multidisciplinary attitude of Dutch science and engineering. To continue to make a difference as a small country, we now need to focus on training and retraining everyone, including precision engineers, even at 35, 45, 55 and 65 years old, to boost their digital skills.

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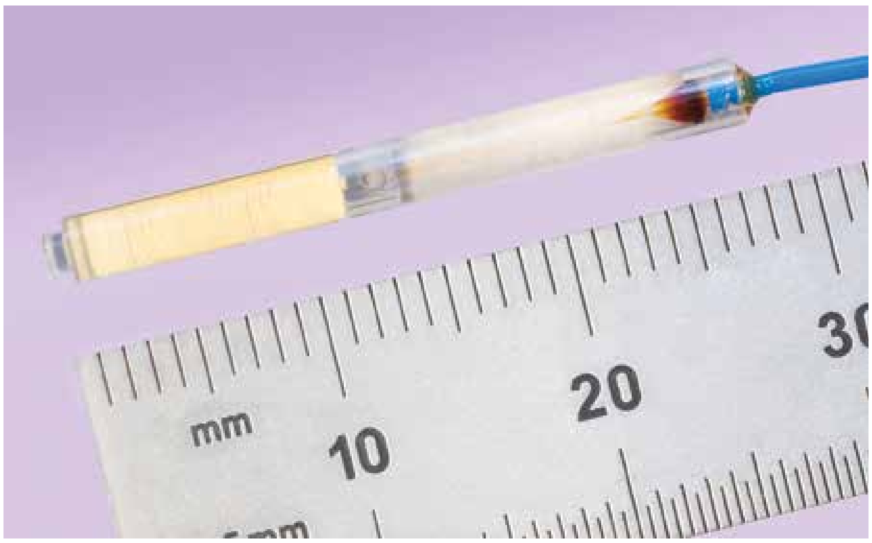
ABSOLUTELY: SMALL SENSOR, BIG PERFORMANCE

Interferometric metrology is the mainstay of many precision positioning applications. Interferometers typically measure displacement, i.e., changes in position rather than the absolute position. The short-range fibre interferometer system described herein combines the traditional advantages of interferometric systems with the ability to measure the absolute position of a target with sub-nm precision, all in an ultra-compact sensor envelope.

VIVEK BADAMI AND ERNESTO ABRUÑA



AUTHORS' NOTE

Vivek Badami is a senior scientist within the Innovations Group at Zygo Corporation, headquartered in Middlefield, CT, USA. He has worked on the development of new interferometric measurement technologies (among other things), taking a precision and systems engineering perspective.
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Introduction

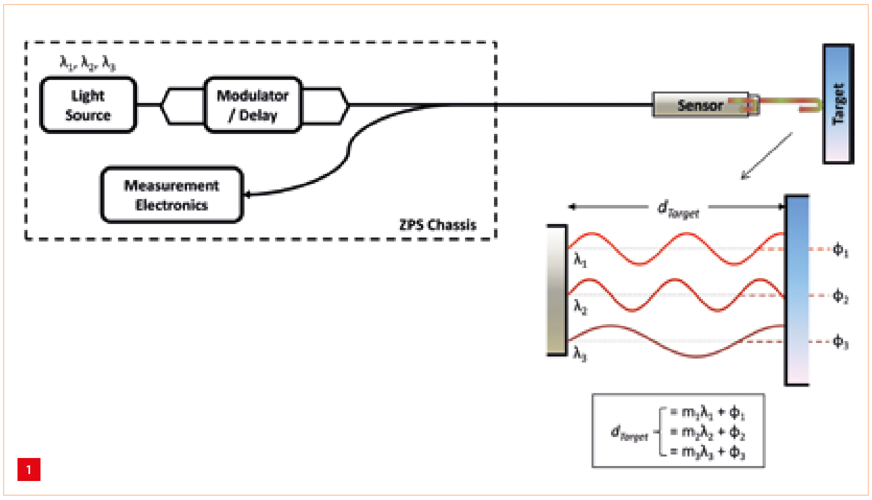
Interferometric displacement metrology is the method of choice for precision positioning applications, finding use in both measurement and control. In many applications, interferometric systems using bulk free-space optics monitor tens of displacement axes simultaneously. These systems often require measurement of displacement over hundreds of millimeters, e.g., steppers and scanners used in photolithography, using heterodyne interferometry in conjunction with a single frequency-stabilised Helium Neon (HeNe) laser source to obtain exceptionally high signal-to-noise performance [1].

There also exist an entire class of applications that not only require many synchronised axes, but also the ability to measure absolute distance (as opposed to displacement) from a datum over much shorter (~millimeter) measurement ranges. Such applications abound, including metrology of deformable mirrors, monitoring of structural deformations in high-precision machines, positioning of lens elements within a lens assembly, position control of short-stroke fine stages, in-situ metrology of synchrotron mirrors, and so on.

In nearly all these applications, the ability to return the system to a known initial position (homing) to nanometer levels is critical – a functionality lacking from traditional displacement interferometers. One example of this requirement is the need to return the elements of a lens assembly to their optimal positions after transporting the assembly to the customer site, e.g., after powering down the system, to produce a desired wavefront. In such an application, a solution that can regain the absolute position of components within the system after the system has been power-cycled, transported and otherwise perturbed is key.

This type of functionality is analogous to that of a capacitance gauge with the key difference that an interferometric sensor does not suffer from the range vs. resolution trade-off typical of capacitance gauges. This allows for a superior dynamic range (picometer-level resolution over millimeter range) as compared to that of a capacitance gauge of comparable size, as well as absolute position measurement with higher (sub-nanometer) precision and stability.

An interferometric system to meet these requirements requires a completely new approach, which is embodied in the new Zygo ZPS™ system [2]. Some key details and applications of this system are discussed in the following sections.



1 *Light source cycles through three discrete output wavelengths (λ_1, λ_2, λ_3), while the electronics measure the associated phase (φ_1, φ_2, φ_3). Simultaneously solving the system of equations for the fringe order (m_1, m_2, m_3) gives the distance to the target d_{target}. The complete process takes approximately 1 second regardless of the number of channels.*

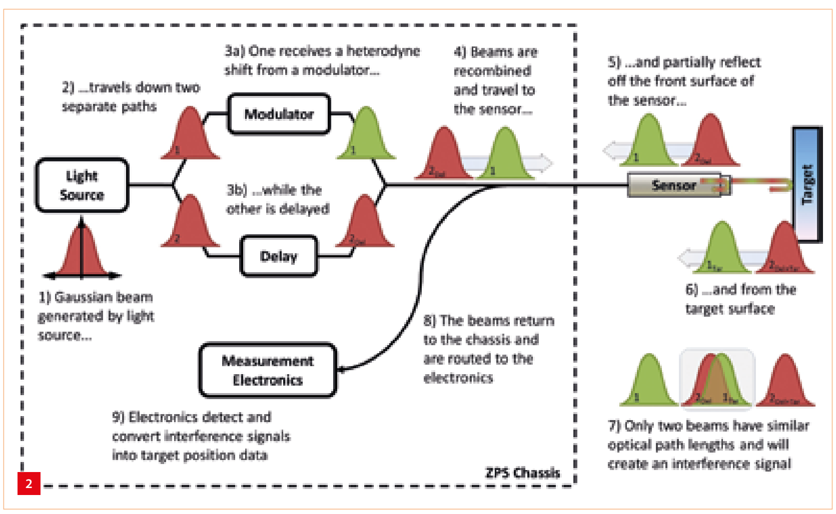
Table 1. Summary of key specifications.

Measurement channels	up to 64
Working distance	3.5 mm
Full stroke range	±0.6 mm
Tilt range	±1 mrad
Noise density (3σ)	0.02 nm/√Hz
Stability	1 nm/day
Absolute position repeatability (3σ)	0.5 nm
Nonlinearity	±1 nm
Digital resolution	0.01 nm
Data rate	up to 208 kHz
Operating wavelength	~1,550 nm
Data interface	sRIO, Ethernet

Table 1 summarises the salient specifications of the sensor system. The system is a low-noise absolute distance measuring device with ±0.6 mm (1.2 mm total) range around a working distance of 3.5 mm. Key to its function as a homing device are its excellent long-term stability and absolute position repeatability. The noise specification as a spectral density allows the user to calculate the performance based on the bandwidth of the measurement. The worst-case value at the extremes of the measurement range is specified, with significantly better performance (0.005 nm/√Hz) at the center of the measurement range, as discussed in the following sections. The system can handle high-bandwidth applications with a maximum data rate exceeding 200 kHz, using a high-speed sRIO interface. An Ethernet interface is provided for lower-bandwidth applications. The sensors are vacuum-compatible.

Principle of operation

The absolute position of the target relative to the reference surface of the sensor is established in a separate initial step using the Method of Exact Fractions [3], a well-known technique implemented to measure the absolute position (distance) of the target using multiple illumination wavelengths in succession as described in Figure 1. The system then tracks the position of the target using the displacement tracking modality described below. The absolute position measurement establishes the initial position of the target and reacquires the absolute position of the target if the beam is interrupted.



2 *Principle of operation of displacement tracking. Displacement is tracked with a data rate of 208 kHz.*

Figure 2 describes the operating principle of the displacement tracking modality of the system. A broadband emitter of carefully chosen spectral width functions as the light source. Light from the source divides into two paths, with phase modulation being applied along one path and a phase delay along the other. The modulation is the basis of heterodyne techniques to achieve measurement noise at the pm/√Hz level. Heterodyning is a spectral shifting technique that shifts the measurement signal from around DC to a much higher frequency to eliminate the noise contributions from the ambient and thermal/statistical sources which scale inversely with frequency [1].

The modulated and delayed copies of the source illumination combine and are delivered via an optical fibre to a sensor, where part of both are reflected from the sensor reference surface and the target. The short coherence length of the source ensures that interference signals are obtained only between pairs of reflections that have travelled the same optical path length. This means that only the unmodulated (delayed) light reflected from the reference surface interferes with the modulated light reflected from the target. These reflections travel back along the fibre and produce a signal at the modulation frequency at the detector; this signal is then processed by the measurement electronics to extract the phase change resulting from the changes in target position.

Position data are output at a maximum data rate of 208 kHz per channel, independent of the number of channels, making

DEMO DESIGN: THE VIRO AGILE EYE

A new design of the Agile Eye, a parallel manipulator with three rotational degrees of freedom, has been realised and validated. The original design was mechanically overconstrained, whereas the new design is not. Also, the advantages of 3D printing have been exploited in the link design. A real-time controller was developed that implements, by use of inverse kinematics, the motion planning for the intended applications: vision-based object tracking or laser manipulation. Performance in terms of workspace, velocity and acceleration is above specification. This paves the way for interesting vision and laser applications in robotics.

EDITORIAL NOTE

This article is based on the Bachelor thesis of Stijn Lohuis [1] and the internship reports of Mohamed Abdelhady [2] and Samer Abdelmoeti [3]. These students did their projects at VIRO under the supervision of Theo de Vries, department head Software & Control, Electro & Instrumentation at this company, and associate professor at the University of Twente, the Netherlands.

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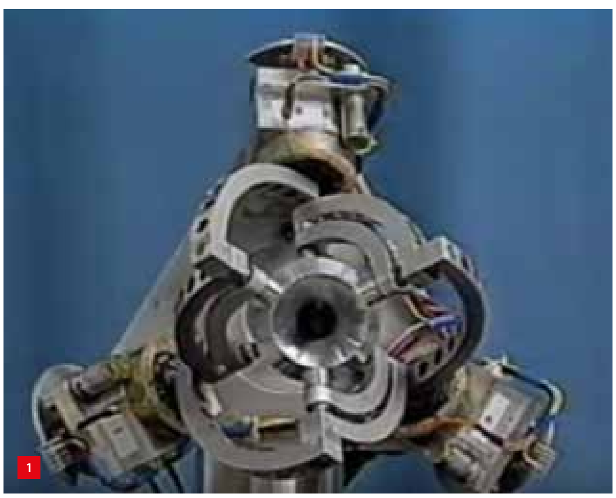
The Agile Eye is a spherical parallel manipulator capable of orienting a camera or a laser pointer with high speed and accuracy in three rotational degrees of freedom (DoFs). For vision applications, for example in robotics, this mechanism can achieve better performance than the human eye in terms of angular velocity and visual range. Also, it outperforms the classical serial mechanisms for tracking fast-moving objects due to its high acceleration and 3-DoF orientation. The first working prototype of the Agile Eye was designed 30 years ago [4] and constructed in 1993 [5] by the Laboratoire de Robotique of the Université Laval in Quebec, Canada [6]. See the video [V1] for an impression; Figure 1 gives a screenshot. More Agile Eye projects and simulations [V2] can be found online.

VIRO, an international engineering firm [7] specialising in engineering and project management, headquartered in Hengelo (Ov), the Netherlands, decided to develop a new version of the Agile Eye – designated as the VIRO Agile Eye for clarity – as a demonstration device matching the performance of the original Canadian prototype, and use rapid prototyping (3D printing) in the realisation phase, for increased design freedom and cost constraints. The video [V3] gives a short overview of the project.

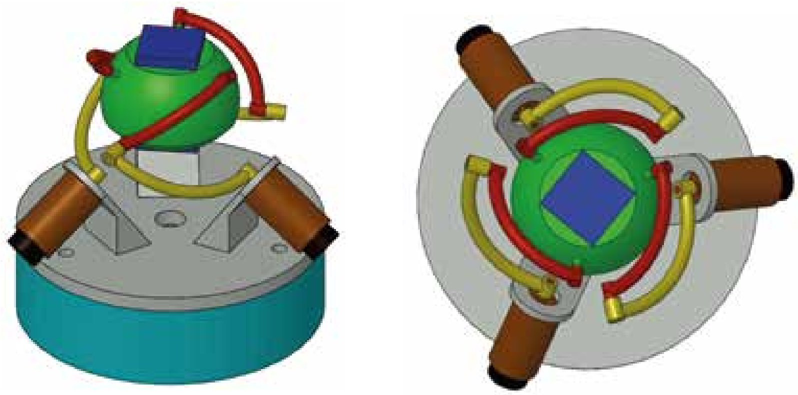


1 *Screenshot of a video [V1] demonstrating the original Agile Eye.*

Geometry

Figure 2 shows the mechanical concept of the VIRO Agile Eye. The central component, called the end-effector, can rotate in three directions and is driven by a symmetrical threefold parallel mechanism. Each part of the mechanism comprises a proximal link (fixed to the motor axis) and a distal link, connected via a line hinge to the end-effector. The proximal and distal links are connected to each other via a line hinge. Just as in the original prototype, the geometry has been designed such that all hinge axes intersect in the rotational centre of the mechanism, where the end-effector is positioned. However, the original design featured a perpendicular angle in the proximal link that was removed in the VIRO design (as has been done previously in other Agile Eye design projects).

An in-depth geometrical study [5] provided the design rules for choosing dimensions for the mechanism. From this study the optimal configuration of the line hinges was derived, yielding high stiffness and an unlimited orientation workspace not divided by singularity surfaces (which should be avoided, because otherwise the equations of motion do not yield unique solutions), and hence the largest rotational freedom of the end-effector. This configuration was found to be orthogonal: the intermediate hinge, connecting the proximal and distal links, is orthogonal to



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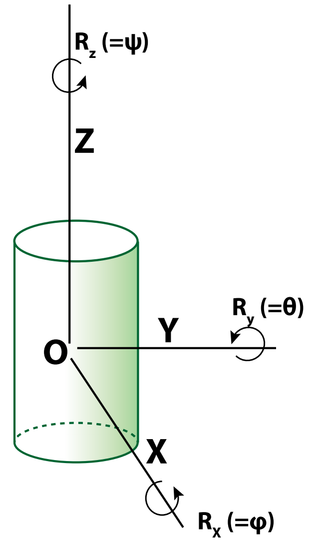

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2 Mechanical concept of the VIRO Agile Eye in side and top views. Turquoise: stable base frame and cabinet for electronics. Brown: motors. Grey: motor support. Yellow: proximal links. Red: distal links. Green/blue: end-effector.

3 Functional system architecture. Sub-systems 3 to 6 define the VIRO Agile Eye.

4 Definition of the end-effector rotational coordinates.

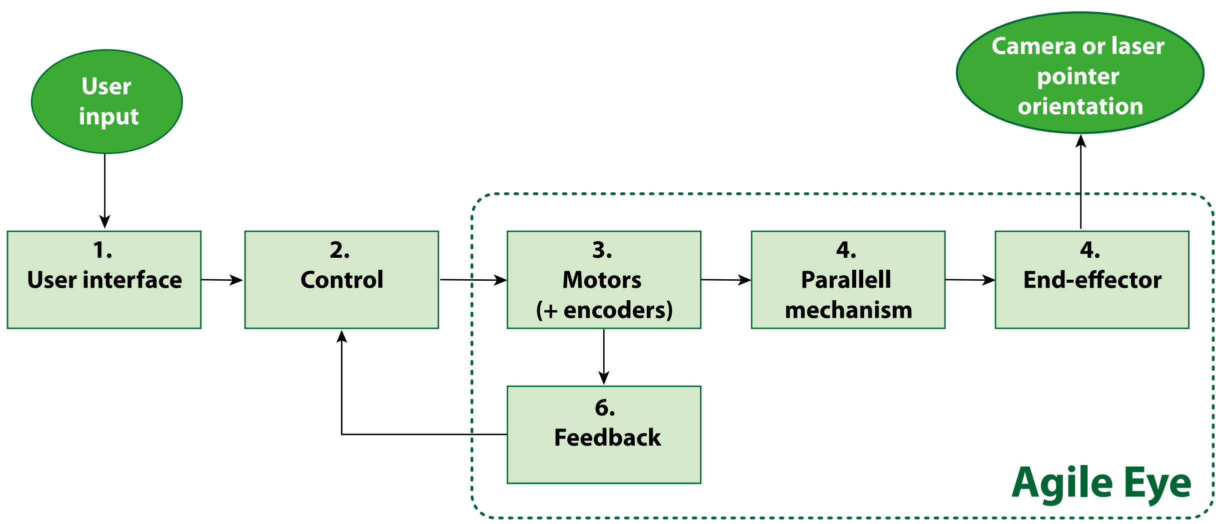
the motor axis as well as to the end-effector line hinge. Within this design space, a trade-off can be made between workspace and attainable speed/acceleration; this trade-off is parametrised by the angle of the motor axis relative to the base platform. For the VIRO Agile Eye, the optimal angle of the motor axis with the base platform was determined to be 54.74°.

A straightforward realisation of the Agile Eye mechanism is overconstrained, i.e. there are more mechanical constraints than DoFs. Using Grubler's analysis [8], the number of overconstraints can be determined. Seven bodies (three proximal links, three distal links and one end-effector) each with six DoFs yield a total of 42 DoFs. With three DoFs to be left unconstrained, 39 DoFs remain to be constrained by the mechanism. The constraints are provided by nine line hinges (three at each motor axis joint, intermediate joint and end-effector joint), defining five DoFs each (and leaving one DoF unconstrained), yielding a total of 45.

This analysis thus presents a (45 – 39) sixfold over-determination. In practice, this means that for a straight-forward realisation, manufacturing tolerances have to be tight, to prevent excessive friction or even blocking of motion. For the VIRO Agile Eye, it was decided to resolve the overdetermination by adapting the design of the line hinges. This is elaborated further below.

Requirements

For the complete system six sub-systems can be distinguished; see Figure 3.
Two modes of operation have been defined for the VIRO Agile Eye:
- tracking a trajectory with a laser pointer (pointing/ writing);
- tracking an object with a camera attached to the end-effector (vision-in-the-loop).



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