

Optical beam scanner with reconfigurable non-mechanical control of beam position, angle, and focus for low-cost whole-eye OCT imaging

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Abstract: Whole-eye optical coherence tomography (OCT) imaging is a promising tool in ocular biometry for cataract surgery planning, glaucoma diagnostics and myopia progression studies. However, conventional OCT systems are set up to perform either anterior or posterior eye segment scans and cannot easily switch between the two scan configurations without adding or exchanging optical components to account for the refraction of the eye’s optics. Even in state-of-the-art whole-eye OCT systems, the scan configurations are pre-selected and cannot be dynamically reconfigured. In this work, we present the design, optimization and experimental validation of a reconfigurable and low-cost optical beam scanner based on three electro-tunable lenses, capable of non-mechanically controlling the beam position, angle and focus. We derive the analytical theory behind its control. We demonstrate its use in performing alternate anterior and posterior segment imaging by seamlessly switching between a telecentric focused beam scan to an angular collimated beam scan. We characterize the corresponding beam profiles and record whole-eye OCT images in a model eye and in an *ex vivo* rabbit eye, observing features comparable to those obtained with conventional anterior and posterior OCT scanners. The proposed beam scanner reduces the complexity and cost of other whole-eye scanners and is well suited for 2-D ocular biometry. Additionally, with the added versatility of seamless scan reconfiguration, its use can be easily expanded to other ophthalmic applications and beyond.

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1. Introduction

Optical coherence tomography (OCT) is a non-invasive biomedical imaging technique that provides high-resolution cross-sectional images of a sample by detecting low-coherence, near-infrared light, backscattered by the sample’s refractive index inhomogeneities. OCT found its prime clinical application in ophthalmology [1,2], where it became the gold standard for morphological assessment of the posterior eye segment and related structural biomarkers and manifestations of disease. OCT is also important for similar morphological assessments of the anterior eye segment to image pathologies and surgical anatomy [3]. Other clinical applications require structural information from the eye as a whole. A common example is ocular biometry, *i.e.*, the measurement of the physical dimensions of the eye, which is crucial in cataract surgery planning [4,5] to estimate the power of the intraocular lens to be implanted. OCT is the gold standard for such measurements, either employing low-coherence interferometry [6] or, more recently, Fourier-Domain FD-OCT, especially with the advent of long-coherence length source

in swept-source SS-OCT [7,8]. When it comes to determining the axial length (the distance between the anterior corneal surface and the retina), the measurement is obtained by a single A-scan, usually along the foveal fixation axis, precluding lateral imaging of the retina [9].

However, there are several clinical and vision science applications where it is required to have both anterior and posterior OCT images and whole-eye biometry in 2-D for both segments. Some examples are narrow-angle glaucoma and myopia progression studies [9,10]. In narrow-angle glaucoma, an anterior segment OCT scan provides information about the irido-corneal angle [11] but only a posterior segment OCT scan can show the retinal nerve fiber layer thickness. Similarly, for a patient with high myopia, a biometric measurement of the axial length is important to evaluate the associated risk of myopia progression; however, peripheral eye length measurements coupled with lens biometry data could help evaluate peripheral defocus, and understand its role as driver of further myopia. Also, clinically, a retinal OCT scan can inform on potential myopic maculopathy and pathologic myopia [12]. Lastly, even in ocular biometry for cataract surgery planning, imaging of the posterior segment is important to provide accurate and repeatable measurements, and this includes ruling out patient's motion during acquisition. A small-angle OCT scan around the retinal foveal pit is used to evaluate motion blur, and therefore, ensure the patient was still during the measurement of axial length [13–15].

The reason why whole-eye OCT scanners are not common is that different focus and scanning configurations are needed to image each ocular segment, as the anterior segment is effectively a compound lens that refracts and therefore alters the scanning configuration used for imaging the anterior segment, thus preventing its use for posterior segment imaging. While for imaging the anterior segment of an eye a typical scanning configuration involves displacing a beam, focused on the anterior segment, parallel to the OCT sample lens axis; for imaging the posterior segment of an eye a typical scanning configuration involves pivoting a collimated beam at the nodal point of the eye (ideally) such that the light beam is focused on the retina by the cornea and the crystalline lens without affecting the scanning direction [16]. Thus, conventional OCT systems are set up to perform either anterior or posterior segment scans and cannot easily switch between the two modes unless some optical components of the system are changed or added to account for the refraction of the eye's optics, leading to the common separation between anterior and posterior segment OCT systems.

Another important consequence of this separation is cost. In fact, in most cases, the ophthalmic or optometry practice will have to separately procure an anterior segment OCT system, a posterior segment OCT system and an OCT biometer. This is particularly taxing for practices in low-resource settings and emerging economies, where, for example, the prevalence of cataract is higher than in developed countries [17], and the cost of the newer swept-source OCT biometers alone can be in excess of 40 kUSD [18].

A wide variety of approaches have been proposed to overcome this physical limitation by imaging each ocular segment either sequentially or simultaneously within the same acquisition of a subject's eye. For sequential imaging of each ocular segment the use of mechanical actuators (*e.g.*, a bi-stable rotary solenoid [19], or a fold mirror [20]) has been proposed to switch between two static sample arm configurations suitable for each segment. Alternatively, the split between two static sample arm configurations has been achieved optically. Kim *et al.* proposed a polarization-encoding approach to separate the anterior and posterior segment scan paths, and an optical switch has been used to interlace the acquisition of each interferometric A-scan signal at the detector, a necessary step due to the short axial range of spectrometer-based OCT systems [21]. For simultaneous imaging of both segments of the eye, Fan *et al.* [22] used dichroic mirrors and two wavelength bands for the anterior and posterior segment, respectively. However, this approach requires two sources and two detectors. This requirement was relaxed by Kim, *et al.*, when using the previously-proposed polarization-encoding approach in combination with two synchronized photodetectors in a swept-source OCT system [23]. Owing to the longer coherence

length of MEMS-swept VCSEL sources and the coherence revival effect, McNabb, *et al.* [24] demonstrated a polarization- and pathlength-encoding approach that required only one source and one detector and that scanned a wide field of view for anterior and posterior segment, respectively.

The system of McNabb, *et al.* [24] included a lens mounted on a motorized translation stage to provide dynamic posterior segment optical beam divergence control and therefore diopter correction for patient defocus without adjusting any optics used for imaging the anterior segment. Beam divergence control for diopter correction and more generally for focus tuning has also been used in an example of dynamic whole-eye scanner by Grulkowski, *et al.* [25], but via an electro-tunable lens (ETL), instead. Taking advantage of its high focal-tuning speed, the ETL has been set to sequentially attain a focused beam in the anterior segment and in the retina, respectively. However, in this case, only a single static scanning configuration was present, which was a trade-off between the aforementioned typical scanning configurations for either segment. By pivoting the beam axis in front of the cornea, the OCT signal-to-noise ratio (SNR) at the cornea is reduced, and the retinal scan angle is likely limited by the aperture of the iris.

Therefore, having the same flexibility afforded by focus tuning in switching between two or more scanning configurations, without the need for duplicating or requiring expensive components, would result in improved image quality at a reduced cost. Moreover, a dynamically reconfigurable scanning configuration would also allow customization for specific applications even beyond whole-eye imaging. In order to incorporate an additional degree of versatility in the selection of the scanning configuration, *i.e.*, the control of beam axis displacement and deflection, several non-mechanical components for beam steering could be used [26]. ETLs are the most promising for lower-cost applications, and they have already been implemented in devices such as an adjustable beam expander [27], where two ETLs were arranged on axis in a telescope configuration, and a wide-angle beam steering system [26,28], where two or more ETLs were arranged at an offset from their respective axes.

In this work, we present the working principle and experimental characterization of a novel, low-cost, optical beam scanner based on the combination of three ETLs for performing both dynamic focusing and changes in the scanning configuration [29]. To the best of our knowledge, our proposed optical beam scanner is the first optical beam scanner that, without requiring any mechanical displacement of the optical components, allows to independently select the divergence and direction of the output beam. Thus, it allows to image a 2-D cross section of both ocular segments in the desired scanning configurations, by, iteratively and rapidly switching between the anterior and posterior imaging configurations. We designed and assembled a prototype of our reconfigurable beam scanner, and we measured beam profiles for each scan configuration to characterize its performance. Finally, we connected it to the sample arm of a SS-OCT system and recorded whole-eye OCT images in a human phantom eye and in an *ex vivo* rabbit eye.

2. Instrumentation

2.1. Working principle and system design

The low-cost, non-mechanical, reconfigurable, optical beam scanner we propose can dynamically control the output beam divergence, and reconfigure the scanning configuration, by providing independent control of the beam axis displacement and deflection. The main optical components of the beam scanner are a fiber collimator, three ETLs, a hollow-roof mirror (HRM), a flat mirror (M), and a periscope system (P).

To better explain the working principle, we will analyze various sets of components before combining them. For example, only two ETLs are needed to control the displacement and deflection of the output light beam. The two ETLs (ETL_1 and ETL_2) are placed on axis at a fixed distance d between them. For the system to work, the input light beam from a collimator must be incident at an offset h_{in} from the optical axis of the two ETLs (Fig. 1(a)). We obtained the equations for the desired transversal displacement of the beam at the principal plane of ETL_2 ,

h_{out} , and the output deflection angle, θ_{out} , with respect to the optical axis of the ETLs, from the ABCD formalism under the paraxial approximation (Eqs. (1),(2)) [30].

$$h_{out} = h_{in} \left(1 - \frac{d}{f_1} \right) + d\theta_{in} \quad (1)$$

$$\theta_{out} \cong \theta_{in} \left(1 - \frac{d}{f_2} \right) - h_{in} \left(\frac{1}{f_2} + \frac{1}{f_1} \left(1 - \frac{d}{f_2} \right) \right) \quad (2)$$

where f_1 and f_2 are the focal lengths of ETL_1 and ETL_2 , respectively, and θ_{in} is the input angle to the optical axis of the ETLs.

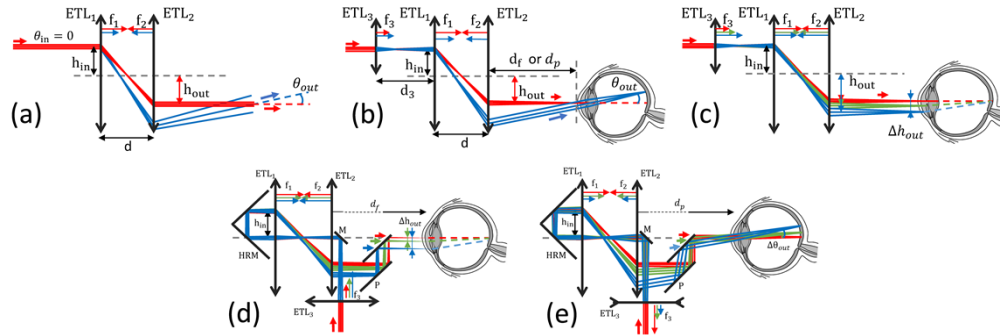


Fig. 1. Optical schematic of the proposed beam scanner with step-by-step illustration of its working principle: (a) different combinations of the focal length of ETL_1 and ETL_2 allow the control of the output beam displacement and deflection angle, while (b) the addition of ETL_3 on axis with the input beam allows the control of the output beam divergence. An example of (c) telecentric displacement of the output beam in a single pass setup of the beam scanner, and (d) in a double pass setup of the beam scanner, where the variation of the beam magnification along the transverse direction is compensated for. (e) An example of angular displacement of the output beam in a double pass configuration.

From these formulae, we can derive the combinations of f_1 and f_2 required to perform either a telecentric scan, as typically performed for anterior segment scans; or an angular scan, as typically performed for posterior segment scans. For simplicity, we will only consider the case where $\theta_{in} = 0$.

For a telecentric scan, the output angle θ_{out} must be always zero, and the transverse displacement h_{out} must vary linearly with time. This leads to the condition that the sum of the focal length f_1 and f_2 is equal to the distance d between the two ETLs, i.e., $f_1 + f_2 = d$. ETL_1 and ETL_2 form a telescope and the output transverse displacement h_{out} varies as a function of the telescope magnification (f_2/f_1), i.e., $h_{out} = -\frac{f_2}{f_1} h_{in}$. It is useful to rearrange Eqs. (1),(2) and solve for the variables that we directly control, i.e., the focal lengths f_1 and f_2 , and explicitly introduce the dependency with time (Eqs. (3)–(5)).

$$f_1(t_i) = \frac{d h_{in}}{h_{in} - h_{out}(t_i)} \quad (3)$$

$$f_2(t_i) = d - f_1(t_i) \quad (4)$$

$$\theta_{out}(t_i) = 0 \quad (5)$$

For an angular scan, the desired distance d_p of the output beam pivoting point from the principal plane of ETL_2 must be constant and the output angle θ_{out} must vary linearly with time.

This implies that the output transverse displacement $h_{out}(t_i)$ must vary accordingly, as dictated by trigonometry. It is also convenient to choose the same conditions as in the telecentric scan for the initial output transverse displacement $h_{out}(t_0)$ and for the initial output deflection angle $\theta_{out}(t_0)$, e.g., $h_{out}(t_0) = -h_{in}$ and $\theta_{out}(t_0) = 0$ (Eqs. (6)–(8)).

$$f_1(t_i) = \frac{d h_{in}}{h_{in} - h_{out}(t_i)} \quad (6)$$

$$f_2(t_i) = \frac{d h_{out}(t_i)}{h_{out}(t_i) - h_{in} + d \theta_{out}(t_i)} \quad (7)$$

$$h_{out}(t_i) = h_{out}(t_0) + d_p \tan(\theta_{out}(t_i)) \quad (8)$$

The next feature of the proposed beam scanner is the control of the output beam divergence for focus tuning. In fact, an anterior segment scan requires to focus the output beam into the anterior segment of the eye at a desired distance d_f from the principal plane of ETL_2 . Conversely, a posterior segment scan requires to make the output beam incident on the eye pupil collimated. Independent control of the beam divergence from control of the beam direction can only be attained using an additional ETL. ETL_3 must be placed on axis with the input light collimator before ETL_1 , at a distance d_3 from it (Fig. 1(b)).

Figure 1(c) shows three transverse steps of an anterior segment scan, where the focal lengths of the three tunable lenses are selected to generate a telecentric displacement Δh_{out} of the beam while the focal distance d_f is maintained at the cornea. In this schematic, we can observe a variation in the beam numerical aperture, as the scan progresses. This variable magnification generates an undesirable variation of the transverse resolution during the scan [31].

This drawback is reduced by converting the system from single pass through the $ETL_1 - ETL_2$ sub-system into a double-pass configuration. Figure 1(d),(e) show the full system design. Firstly, light from a collimator is incident on axis on ETL_3 and propagates over a distance d_3 until ETL_2 . The propagation direction along this path is redirected orthogonally to the initial direction as the beam reflects off the mirror M to then propagate on axis through ETL_2 and ETL_1 . Secondly, the hollow-roof mirror HRM, at a distance d_{HRM} from ETL_1 , induces the offset h_{in} as it redirects the beam back towards ETL_1 and ETL_2 parallel to their optical axis. Lastly, a periscope P system compensates for the previously induced offset h_{in} . This double-pass propagation compensates, in part, the undesirable magnification, as it can be seen in Fig. 1(d) compared to Fig. 1(c). However, a residual beam numerical aperture variation during a scan is still present in the current design both for the anterior and the posterior segment scans (Fig. 1(d),(e)), respectively).

Using the thin lens equation of the geometrical optics formalism under the paraxial approximation [30], the equation of the focal length f_3 of this third lens ETL_3 , Eqs. (9a)–(9e), was obtained as a function of the desired working distance d_f from ETL_2 and the fixed distances of the system (d_3 , d and d_{HRM}) as well as the previously obtained focal lengths f_1 and f_2 for a given displacement and deflection of the beam.

$$f_3 = d_3 - i_{22} \quad (9a)$$

$$\text{with } i_{22} = f_2(t) \cdot \frac{d - i_{12}}{d - i_{12} - f_2(t)}, \quad (9b)$$

$$i_{12} = f_1(t) \cdot \frac{2d_{HRM} + h_{in} - i_{11}}{2d_{HRM} + h_{in} - i_{11} - f_1(t)}, \quad (9c)$$

$$i_{11} = f_1(t) \cdot \frac{d - i_{21}}{d - i_{21} - f_1(t)}, \quad (9d)$$

$$i_{21} = f_2(t) \frac{d_f}{d_f - f_2(t)}, \quad (9e)$$

where i_{21} is the conjugate distance to d_f from ETL_2 , i_{11} is the conjugate distance to the intermediate focal plane at i_{21} from ETL_1 after a first pass, i_{12} is the conjugate distance to the intermediate focal

plane at i_{11} from ETL_1 after a second pass, and i_{22} is the conjugate distance to the intermediate focal plane at i_{12} from ETL_2 .

In summary, we can set combinations of the focal lengths of the three ETLs to perform both a telecentric scan while focusing the output light beam at a constant working distance and an angular scan while maintaining a collimated output light beam pivoting at a specific distance. This shall prove particularly useful for whole-eye imaging.

2.2. System components selection and parameters optimization

We chose low-cost, off-the-shelf components for an experimental prototype of the optical beam scanner (see Table 1).

An analysis of the system parameters, such as the fixed mechanical distances between system components, was performed to optimize the design of optical beam scanner. This analysis was performed using Eqs. (1)–(9a), with the goal of maximizing the scanning range of the optical beam scanner in both scanning configurations, *i.e.*, Δh_{out} and $\Delta \theta_{out}$ for the telecentric and angular scans, respectively. During this analysis, two parameters of the beam scanner in the double pass setup were considered: the input offset h_{in} and the distance d between ETL_1 and ETL_2 . The detailed results of this analysis are presented in Supplement 1. In summary, the largest output transverse displacement is obtained for h_{in} equal to 2.5 mm, as shown in Fig. S1, which is half of the semi-aperture of ETL_1 . In both scanning configurations, the scan ranges Δh_{out} and $\Delta \theta_{out}$ increase with the distance d until d equals 150 mm, as shown in Fig. S2. However, when d becomes bigger than 150 mm the limiting factor is no longer the shortest available focal length of ETL_1 but the clear aperture of ETL_2 that starts vignetting the beam.

Table 1. List of the selected off-the-shelf components for the optical beam scanner

Optical Element	Commercial component	Specification
Collimator	F220APC-850 (Thorlabs)	$1/e^2$ beam diameter @ $\lambda = 1060$ nm: 2.41 mm
ETL_1, ETL_2	EL-10-30-TC-NIR-12D (Optotune)	Clear aperture: 10 mm Focal range: from +50 mm to +120 mm
ETL_3	EL-3-10-NIR-26D (Optotune)	Clear aperture: 3 mm Focal range: from $-\infty$ to -77 mm and +77 mm to $+\infty$
HRM	HRS1015 (Thorlabs)	1" x 1" Hollow Roof Prism Mirror
M	#54-094 (Edmund Optics)	3 mm Diameter 45° Rod Mirror
P	MRA05-P01 (Thorlabs)	Right-Angle Prism Mirror, L = 5.0 mm

2.3. Expected system specifications

The optimal design of the beam scanner was based on the optical components listed in Table 1 and the analysis of the system parameter presented in Supplement 1. The input offset h_{in} and the distance d between ETL_1 and ETL_2 were set to be 2.5 mm and 150 mm, respectively. We chose a comfortable working distance d_f equal to 105 mm, similar to other ophthalmic scanners [32]. A summary of all set values for the mechanical distances is presented in Table 2.

Using the values in Table 2, we evaluated the focal lengths of ETL_1 – ETL_3 , according to Eqs. (3)–(9a), required for imaging the anterior and posterior segment, respectively. We also validated the required focal lengths with a simulation of the designed beam scanner in Zemax (OpticStudio).

Figure 2 shows the combination of the focal length of ETL_1 , ETL_2 and ETL_3 as a function of the desired displacement of the beam for both scanning configurations, telecentric and angular, and the desired divergence at the working distance d_f and d_p , respectively. Under these conditions, and considering the limiting factors, including the clear aperture of the ETLs, the beam scanner

Table 2. List of the optimized parameters for the optical design of the beam scanner when considering the commercial components in Table 1

Optical parameter	Specification
d_3	85 mm
d	150 mm
d_{HRM}	30 mm
h_{in}	2.5 mm
ETL_1 focal range	From +50 mm to +75 mm
ETL_2 focal range	From +68 mm to +100 mm
ETL_3 focal range	From $-\infty$ to -70 mm
d_f : working distance for the AS scan	105 mm
d_p : pivot distance for the PS scan	105 mm

was expected to have a telecentric scan range of 2.5 mm and an angular scan range of 1.2 deg. Zemax models for six specific transverse and angular displacements were simulated, and the corresponding focal lengths of ETL_1 - ETL_3 are represented with red dots in Fig. 2(a),(b). In both cases the Zemax simulations were in good agreement with the calculations from the analytical equations.

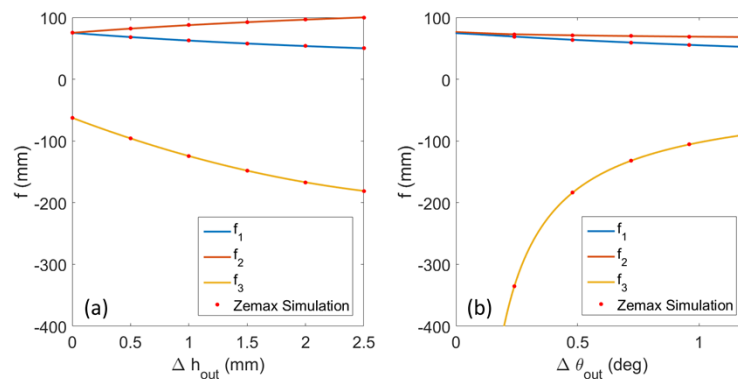


Fig. 2. Calculated (solid lines) and simulated (red dots) focal lengths of ETL_1 - ETL_3 as a function of the (a) transverse displacement in the anterior segment imaging configuration, and (b) angular displacement in the posterior segment imaging configuration, using the values of Table 2 and Eqs. (3)–(9a) and Zemax models, respectively.

We also analyzed the expected (residual) variation of transverse resolution along the transverse or angular position. To do this, we analytically calculated the beam diameter along the beam axis (z) as the collimated Gaussian input beam is transmitted through the beam scanner components, using Eqs. (3.2-5)–(3.2-9a) of [30]. The variation of the output beam spot size, *i.e.*, the beam diameter at the waist position, corresponding to the working distance d_f and d_p , is shown in Fig. 3(a) and Fig. 3(c) as a function of the transverse position for the anterior scan configuration and as a function of the angular position for the posterior scan configuration, respectively. Figure 3(b) shows the output beam diameter profile along the beam axis in the range of the working distance $d_f \pm 10$ mm for different transverse positions for the anterior scan configuration. Figure 3(c) shows the residual variation of the output beam spot size from 1.28 mm (at 0 deg) to 0.96 mm (at 1.2 deg) for the angular scan configuration at the pivoting point, ideally set on the eye

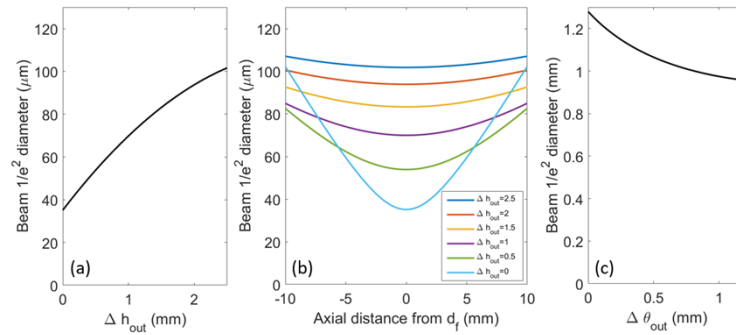


Fig. 3. Theoretical transverse resolution of the beam scanner for the telecentric scan (a-b) and the angular scan (c). (a) The variation of the spot size at the working distance d_f for the telecentric scan. (b) The axial beam diameter profile for the telecentric scan at various transverse output positions. (c) The variation of the spot size for the angular scan at the pupil plane.

pupil. To work out the beam spot size at the retina for the posterior scan, we used Eqs. (3.2-17) of [30] and we assumed a relaxed eye effective focal length of 22.2 mm [33].

Lastly, the spot size on the focal plane in the anterior segment and on the retina corresponds to the transverse resolution for either imaging configuration. As a result, the transverse resolution varies from 35 μm (at 0 mm) to 102 μm (at 2.5 mm) for the anterior imaging configuration and from 23 μm (at 0 deg) to 31 μm (at 1.2 deg) for the posterior imaging configuration. A summary of the theoretical imaging specs is presented in Table 3.

Table 3. Theoretical imaging specification for the optical beam scanner with the components listed in Table 1 arranged according to the parameters listed in Table 2

Theoretical Imaging Specifications	Value
Telecentric scan range	2.5 mm
Angular scan range	1.2 deg
Telecentric scan transverse resolution at focus (on anterior chamber)	35–102 μm
Angular scan transverse resolution at focus (on the retina)	23–31 μm

2.4. Experimental beam scanner setup

A prototype of the optical beam scanner was experimentally implemented in the laboratory with the commercial components from Table 1 set according to the mechanical distances and values defined on Table 2. The control of the three ETLs was performed with a low-cost Arduino Nano board in combination with a custom Matlab GUI code that allowed to independently select the scan mode (telecentric or angular) and the working or pivoting distance of the output beam, d_f or d_p . The focal length or optical power of the ETLs was set by the duty cycle of a pulse width modulation (PWM) signal (Visualization 1) sent by the Arduino Nano board with 8-bit resolution to the lenses through a lens driver (DRV8833, Texas Instruments). Due to the high frequency of the PWM signal, the lenses are effectively subject to a voltage between 0-5 V proportional to the PWM signal. The focal length variation with voltage of each ETLs was characterized using a high speed focimeter [34] and adjusted when aligned in the beam scanner experimental setup.

The resulting calibration curves are presented in Fig. S3 of [Supplement 1](#). The total cost of the three ELTs and their control electronics was ~900 USD compared to ~2000 USD for a standard 1-axis galvanometer mirror scanner with control electronics, resulting in over 50% cost reduction for the beam scanning engine.

The optical performance of the experimental beam scanner was characterized by using a CCD camera (DCC1545M, Thorlabs) to profile the output beam around the working or pivoting distance. This CCD was axially displaced over a range of 25 mm to profile the output beam at different axial position. The analysis of the size and position of the beam in the CCD images allowed to characterize the two main features of the developed optical beam scanner: its capability of controlling the divergence and the direction of the output beam. This analysis was performed for the two scan configurations of interest for ocular imaging.

2.5. Whole-eye OCT experimental setup

The experimental prototype of the new optical beam scanner was integrated into the sample arm of a custom developed SS-OCT system to acquire whole-eye cross-sectional images of different ocular samples. The custom SS-OCT system was based on a fiber Mach-Zender interferometer configuration, similar to [32], as schematically shown in Fig. 4. The light source was a MEMS-based vertical-cavity surface-emitting laser (VCSEL) swept-source centered at 1060 nm with a sweep rate of 60 kHz over a spectral 10 dB-bandwidth of 100 nm (SL100060, Thorlabs), producing a theoretical axial resolution of 11 μm . The interferometric signal was acquired with a dual balance photodetector with a 3 dB-bandwidth from 3 kHz to 1 GHz (PDB481C-AC, Thorlabs) and digitized by a 12-bit 8-lane PCI Express digitizer (ATS 9360, Alazartech). The experimental axial depth range was ~33 mm, when sampling the interferogram at 1 GS/s.

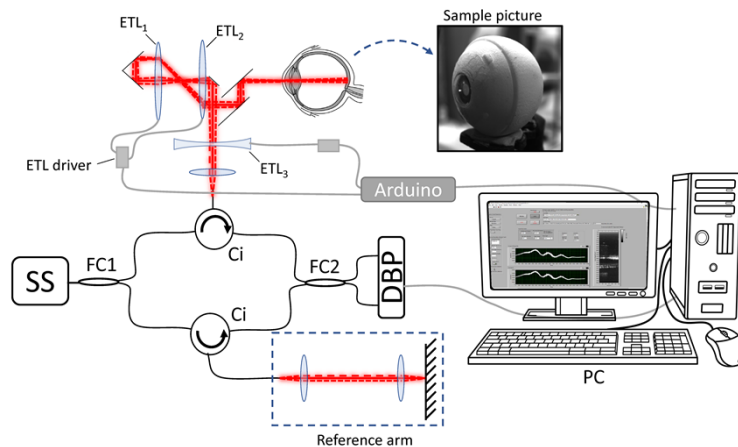


Fig. 4. Schematic of the custom SS-OCT system coupled with the proposed optical beam scanner, where SS: swept laser source, Ci: circulators, FC: fiber coupler, PC: computer, DBP: dual balanced photodetector. Sequential acquisition of the anterior and posterior segment scans is recorded in alternated B-scans.

We compared the cross-sectional images acquired with the proposed optical beam scanner with those acquired with a standard telecentric scan system, a typical approach in anterior segment scans. Such scan system was based on galvanometric scanning mirrors (Saturn 1B, ScannerMAX, Pangolin, USA) placed at the back focal distance of a 2" aperture f-theta telecentric scan lens (LSM05, Thorlabs, USA), which allowed to perform a telecentric scan over a transverse field of view of 8 mm. The custom SS-OCT system could be connected interchangeably with either sample arm and the paired pathlength-matched reference arm by flipping a mirror. A custom

LabView program was used for synchronizing the OCT acquisition with the control of either scanner. With the proposed optical beam scanner, the two scan configurations were sequentially alternated without any mechanical adjustment to obtain a whole-eye B-scan image. Table 4 reports the image acquisition specifications for either system.

Table 4. Image acquisition specifications for the proposed whole-eye beam scanner and a standard galvo-based anterior segment scanner used for comparison

Image acquisition specifications	Proposed whole-eye beam scanner	Standard Galvo-based anterior segment scanner
Telecentric scan range	2 mm	8 mm
Angular scan range	1.2 deg	NA
Number of A-scans in a B-scan	120	300
A-scan period	2 ms	17 μ s
B-scan repetitions (for averaging)	100	100

To visualize the beam profiles we made use of a nano-particle-embedded point spread function (PSF) phantom (Tomlins Analytics, UK) [35]. To compare the images with either scanner we used an OCT model eye (Modell-Augen Manufaktur, Germany), as it mimics realistic components of the human eye in both the anterior segment (the cornea and the crystalline lens) and the posterior segment (the main retinal layers as well as the macula and the optic nerve). We also acquired images of an *ex vivo* rabbit eye, obtained from a local slaughterhouse, to demonstrate whole-eye scan of an animal eye.

3. Results

Figure 5 shows an overlay of a picture of the experimental prototype with ray tracing of the beam at the starting position of the anterior scan of the model eye. Visualization 2 shows the same view as in Fig. 5, with a sequence of four different transverse displacements for the anterior scan and, subsequently, four different angular displacements for the posterior scan.



Fig. 5. Overlay of a picture of the experimental beam scanner prototype with the ray tracing of the beam through the beam scanner for the starting position of the anterior segment scan configuration. Visualization 2 shows the sequence of eight discrete positions for the anterior and posterior scan configurations.

Figures 6,7 show the results of the experimental characterization of beam size and direction via beam profiling at several axial positions, as described in Sec. 2.4, for four displacements in each of the anterior and posterior segment scan configurations.

Figure 6 shows a perspective view of the beam profile images at the three axial positions, namely 12.5 mm before, at, and 12.5 mm after the working distance, $d_f = 105$ mm from ETL_2

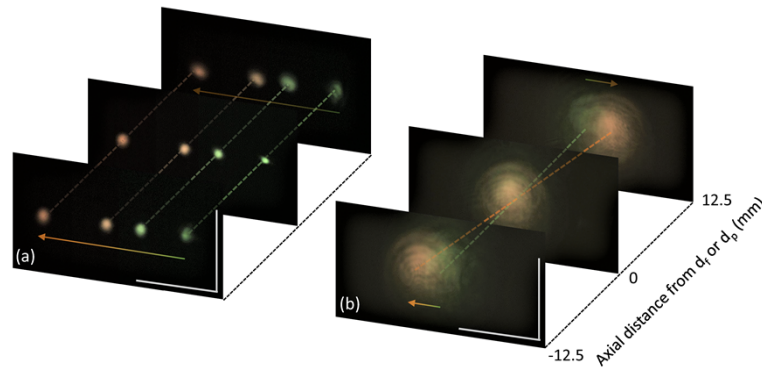


Fig. 6. A perspective view of the beam profile images at the three axial positions, namely 12.5 mm before, at, and 12.5 mm after the working or pivoting distance, d_f or d_p . (a) Anterior segment scan overlay of four transverse displacement profiles. (b) Posterior segment scan overlay of two angular displacement profiles. The arrows represent the scan direction with time. The scale bars represent 1 mm.

and also equal to the pivoting distance d_p . Figure 6(a) refers to the anterior segment scan configuration. We can observe the beam divergence and the focus at the working distance by noticing the variation in the spot size between the central and the two other axial positions. It is also evident that the beam axis is maintained parallel to itself and to the optical axis of the system throughout the scan. Figure 6(b) depicts the posterior segment scan configuration, only between two angular positions. In this case, we can observe that the beam diameter is much larger than for the anterior scan configuration and rather constant in size for the three axial positions, denoting a collimated output beam pivoting about the central position.

The dynamic performance of the beam scanner can also be seen in [Visualization 3](#), which displays a video of 120 beam profile frames, corresponding to each A-scan position for both scan configurations, recorded at the working distance position, d_f , (set equal to the pivoting distance d_p). [Visualization 4](#) shows a macro-style video of two consecutive anterior and posterior scans and corresponding close-ups on the PSF phantom, where the scattering by the dispersed iron oxide nanoparticles creates a visible trace of the profile with depth inside the phantom on a video camera sensitive to infrared light.

The quantitative analysis of the beam diameter and direction from the beam profiles recorded at seven and five different axial positions for the anterior and posterior segment scan, respectively, is shown in Fig. 7. The origin of the axial distance axis is set at the working distance, d_f . Figure 7(a) shows a graph of the experimental axial profile of the beam diameter (evaluated for the $1/e^2$ value of the peak intensity) for four transverse displacements in the anterior segment scan. The experimental data was also fitted to the theoretical axial profile of a Gaussian beam with the minimum root-mean-square error from the experimental data points. The focal planes for the four transverse displacements all lie within a range of 2.5 mm, confirming our ability to set a constant working distance throughout the scan. The beam diameter increased and, conversely, the transverse resolution decreased during the transverse scan, from 58 μm to 122 μm , due to the variation in the focal length of ETL_3 required to maintain the focal plane at the set working distance. The spot size at each transversal position was in relatively good agreement with theory, as the measured spot size deviated less than 30 μm from the analytical results of Fig. 3. The transverse resolution degradation by a factor of 2.1 was less severe than the 2.6 factor expected from the analytical results.

A side effect of the reduction of transverse resolution is the increase in depth of field, equal to twice the Rayleigh range of the associated beam. Figure 7(b) shows the beam axis for the four

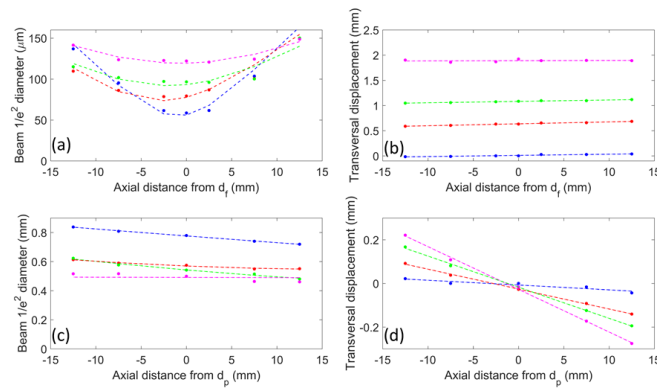


Fig. 7. Experimental axial profiles of (a), (c) the beam diameter and (b), (d) the beam axis direction for four displacements in (a), (b) the anterior segment telecentric scan and (c), (d) the posterior segment angular scan, respectively.

beams at the increasing transverse displacements considered in Fig. 7(a). This demonstrates the ability of the beam scanner to perform a telecentric scan as the deviation of the beam axis from a propagation direction parallel to the optical axis of the system was less than $\pm 0.1^\circ$ for every beam transverse displacement.

Figure 7(c) shows a graph of the experimental axial profile of the beam diameter for four angular displacements in the posterior segment scan. In this case, the experimental data was fitted to a line. The divergence of the beam was less than 0.3° for all the angular scan positions, demonstrating the ability to produce a highly collimated output beam throughout the angular scan. We also observed the expected reduction of the beam diameter during the scan, as predicted by the analytical analysis of Sec. 2.3. The experimental spot sizes were smaller, by 0.46 mm on average, than the ones expected from the analytical results in Fig. 3(c). Figure 7(d) shows the beam axis for the four beams at the increasing angular displacements considered in Fig. 7(c). This demonstrates the ability of the beam scanner to perform an angular scan pivoting at a constant position. The pivoting point was measured at a distance of 103 mm from ETL_2 , only 2 mm off the expected position, and all measured beam axes crossed each other within a range of 1.5 mm.

Figure 8 shows an overlay of the OCT B-scans of the model eye obtained with the proposed beam scanner and the standard telecentric galvanometric scanner described in Sec. 2.5. The scans obtained with the experimental prototype of the optical beam scanner were overlapped with the larger B-scan obtained with the galvanometric scanner.

Figure 8(a) shows the comparison for the entire eye. The anterior segment of the model eye, including the cornea, iris and crystalline lens, can be observed in the partially transparent background image acquired with the standard scanner. In the green inset, we can see the corresponding anterior segment scan performed with the proposed beam scanner. A close-up on the anterior segment scans in Fig. 8(b) permits to verify that all anatomical features and biometric dimensions clearly match. However, it is in the posterior segment that the value of the proposed scanner becomes evident when seamlessly reconfigured for posterior segment scanning. Without the ability to switch to an angular scan, the standard telecentric scan rays get refracted towards a small area, and the beam itself diverges, creating a defocused spot on the retina. This leads to the artifactual image of a low-resolution, laterally unresolved, retinal depth profile, as seen in Fig. 8(a) or in the posterior segment close-up in Fig. 8(c), where the same issue affects the image of the retina in the green box, obtained with our scanner set for anterior segment scanning.

However, when the scanning configuration is switched to posterior segment scanning (yellow box), different features of the model retina were clearly observed. To verify and co-locate those

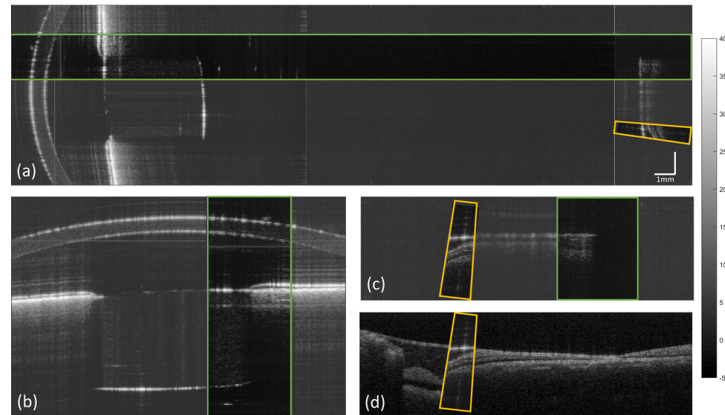


Fig. 8. Overlay of the OCT B-scans of the model eye obtained with the proposed beam scanner and the standard telecentric galvanometric scanner described in Sec. 2.5 for comparison. (a) B-scan of the entire eye. The boxed areas represent the whole-eye scans obtained with the proposed beam scanner, in green and yellow for the anterior and posterior segment scan configurations, respectively. (b) Close-up on the anterior segment. (c) Close up on the posterior segment, where only the image in the yellow box is artifact-free. (d) Co-location of image features in the posterior segment scan with model retina landmarks. The scanned area is at the edge of the model optic nerve.

features with a larger field of view on the retina, we also scanned the posterior segment with the standard telecentric scanner. This was possible, as the model eye is composed of two halves, comprising the anterior and posterior segments, respectively, that can be unscrewed and separated. Figure 8(d) illustrates that the area scanned by the proposed beam scanner perfectly matches the edge of the model optic nerve.

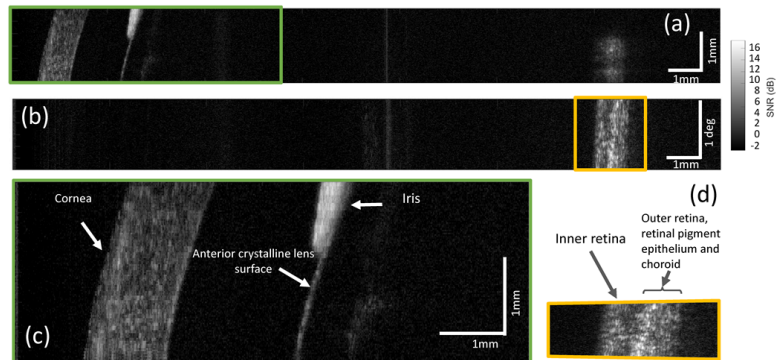


Fig. 9. Whole-eye OCT B-scan of an *ex vivo* rabbit eye acquired with the proposed beam scanner only. (a) B-scan acquired with the anterior segment scan configuration. (b) subsequent B-scan acquired with the posterior segment scan configuration; (c) close-up view of the anterior segment from the boxed area in (a). (d) close-up view of the posterior segment from the boxed area in (b), where the aspect ratio and scale are maintained as in (c) for reference.

We also imaged an *ex vivo* rabbit eye with the proposed beam scanner. Figure 9(a) shows the B-scan recorded with the anterior scanning configuration. Figure 9(b) shows the subsequent B-scan recorded with the posterior scanning configuration. Figure 9(c) is a close-up view of the

anterior segment in Fig. 9(a), where the cornea, iris and lens of the rabbit eye are clearly seen. Similarly, Fig. 9(d) shows a close-up view of the posterior segment of Fig. 9(b). As the posterior segment scan configuration pivots in the eye pupil, details of the inner and outer retina are now visible, unlike in Fig. 9(a) where the posterior segment image was hindered by the shadow cast by the iris and otherwise a repeated artifactual image of a retinal depth profile was caused by the eye refraction.

4. Discussion

We presented an optical beam scanner with the ability to reconfigure the scanning and focusing configuration via low-cost non-mechanical components, and we employed it to provide quasi-simultaneous whole-eye imaging, albeit over a limited field-of-view. The device employs three ETLs, and several mirrors. We characterized its dynamic scanning and focusing capabilities in an experimental proof-of-concept setup. We benchmarked whole-eye OCT images of a model eye against those produced with a standard galvanometric scanner, and then acquired whole-eye OCT images of an *ex vivo* rabbit eye, revealing details comparable to those seen in conventional anterior and posterior OCT scanners.

We derived the analytical equations describing the relationship between the focal length of the three ETLs and the desired output beam position, direction and divergence and optimized the mechanical distances between off-the-shelf components to maximize the transverse and angular scanning range of the proposed beam scanner. The optical characterization of the experimental prototype showed a good agreement between theoretical and measured beam profiles. However, the measured beam spot sizes in the anterior segment scan configuration were slightly larger than expected, especially for the smallest spot size, hinting to the presence of aberrations preventing a diffraction limited spot size. The predominant aberration appears to be astigmatism, followed by spherical aberration and coma. This is not entirely unexpected, as the working principle requires the beam to be incident off axis from the ETL axis, and the scan progresses toward the periphery of ETL_2 , where the impact of aberrations is higher. While these aberrations may affect the resolution, we verified that they did not affect the scanning accuracy and range. Nevertheless, larger ETL clear apertures would be beneficial in reducing the effect of system aberrations.

The variation of transverse resolution along the scan direction is undesirable. Even though the double pass configuration through ETL_1 and ETL_2 provides a smart way to partly compensate this effect, as the magnification in a single pass is undone in the double pass, that is only valid for a collimated beam impinging on the ETL_1 - ETL_2 telescope. Therefore, for the scanning configurations considered here, there is some residual beam size variation, and hence, transverse resolution variation. One solution to prevent this variation would be the addition of a variable beam expander (*i.e.*, a telescope made of two additional ETLs) to place between the collimator and ETL_3 in order to fully pre-compensate this residual variation. However, this solution adds to the device cost and footprint.

The minor experimental imprecisions found in the position of the focal spots or beam axes intersection with respect to the working and pivoting distance could be removed by employing a more precise control of the ETL focal lengths by using a microcontroller with better digital resolution than the Arduino (*e.g.*, the ESP32, 16-bit resolution) and implementing a temperature control of the electrotuneable lenses [36].

A limitation of the current experimental implementation of the beam scanner is the switching frequency between adjacent scan positions. Although the experimental data reported in this work was acquired at 500 Hz, the selected ETLs could respond at faster rates, up to 1 kHz and beyond for small diopter increments [37]. Future works will explore their use at greater speeds, achieving motion artifact-free *in vivo* images. This will be important to ensure that biometric readings are accurate, both within a single scan and across anterior and posterior scans.

Another important limitation of the current experimental implementation is the limited transverse and angular scan range. The characterization of each scan configuration led to a field of view of 2.5 mm and 1.2 deg for the telecentric (anterior segment) and angular (posterior segment) scan configurations, respectively. Again, larger ETL clear apertures and wider focal ranges, especially towards smaller focal lengths, would enable larger transverse and angular scan ranges. For example, there are off-the-shelf ETLs with a clear aperture 6 mm larger than the one we used for ETL_2 in our prototype, and which could achieve a similar focal range to ETL_2 , with the help of an offset lens, leading to more than twice the scan ranges we presented.

Another option to increase the field of view of the beam scanner would be the addition of a magnifying two-lens telescope at the output of the beam scanner, such that the first telescope lens would be placed a focal length away from the working distance (and pivoting point) of the proposed beam scanner. This telescope would increase by the magnification factor the transverse anterior scan range and the transverse resolution for the posterior segment scan. However, it would also reduce the transverse resolution for the anterior segment scan and the posterior angular range by the same factor. Therefore, the only effective solution for increasing both transverse and angular ranges, at the expenses of transverse resolution though, is the use of an adaptive telescope, where the second lens is another ETL, such that it creates a magnifying and demagnifying telescope for the anterior and posterior segment scan configurations, respectively.

It is also important to notice that in our experimental setup we only used a semi-aperture of the ETLs. By rotating the hollow roof mirror HRM and the periscope P by 180 deg, we could double the scan range for both anterior and posterior segment configurations, as the full aperture of the ETLs would be exploited. This would already lead for the current setup to a field of view of 5 mm for the telecentric scan and 2.4 deg for the angular scan. This feature would require to simultaneously rotate HRM and P about the beam scanner axis, which can be done with a simple low-cost DC or stepper motor (and a transmission system). Such actuation unlocks the potential of performing full 3-D scans by building radial sections or circular/spiral scan patterns through synchronization of the motor and the ETLs control (see [Visualization 5](#)).

Nevertheless, the current implementation can already find good use in low-cost biometry by providing anterior segment 2-D central anatomy for detection of lens tilt and decentration, for example, and posterior anatomy, such as the foveal pit for fixation checks. In fact, commercial biometers, such as the Zeiss IOL Master 700 [13], already implement a small angular scan around the foveola, a central pit of the fovea, about 0.35 mm in diameter (or ~ 1.2 deg) [38], where only cone photoreceptors are present and which is specialized for maximum visual acuity [39]. Hence, it is the part of the retina engaged in fixation. By detecting a distorted image of the foveal pit, one can assume poor fixation, likely caused by the patient's eye motion, and therefore apply a quality check on the biometry reading. With the proposed beam scanner, fixation check and central 2-D anterior segment biometry will be readily available. Additionally, by displacing the transverse field of view to the corneal limbus, regions of diagnostic interest, such as the iridocorneal angle, could be evaluated for close-angle glaucoma diagnostics.

5. Conclusion

In summary, we presented a novel optical beam scanner with reconfigurable non mechanical control of beam position, angle and focus using three low-cost ETLs and applied it to quasi-simultaneous whole-eye OCT imaging. We derived the analytical equations for the focal lengths of ETL_1 - ETL_3 to control the beam axis position, angle and focal distance from the device, and we set them for alternately providing a telecentric scan of a focused beam for anterior segment imaging and an angular scan of a collimated beam for posterior segment imaging. The expected scan range was 2.5 mm and 1.2 deg, and the expected transverse resolution was varying in the range 35–102 μm and 23–31 μm , for the anterior and posterior segment scans, respectively. We characterized the dynamic scanning and focusing capabilities of an experimental setup through

beam profiling, after a thorough calibration procedure. The experimental measurements were in good agreement with the analytical expectations. We integrated the proposed beam scanner in a SS-OCT system and acquired whole-eye OCT images of a model eye and of an *ex vivo* rabbit eye, revealing details comparable to those seen in conventional anterior and posterior OCT scanners.

The proposed beam scanner reduces the complexity and cost of other proposed whole-eye scanners based on mechanical switching or polarization multiplexing between the two segment scan configurations. Additionally, it provides the ability to reconfigure the scan configuration to best suit the specific application, *i.e.*, it is not limited to using only pre-selected scan configurations. The current system would already prove useful in low-cost biometry applications to provide 2-D anterior segment anatomy and fixation checks for improving the repeatability of biometry readings and leading to fewer refractive surprises. Sourcing larger aperture ETLs will enable to overcome the current limitations on the transverse and angular scan ranges and expand its use to diagnostic and scientific application to glaucoma, myopia studies and beyond, in several other fields.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See [Supplement 1](#) for supporting content.

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