Adaptive liquid crystal lenses (ALL). Keeping focus with no moving parts

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ABSTRACT

The ALL project has brought together lens technology developed at a public university with an SME with experience in commercial liquid crystal electronics. The patented lens technology is based on cascading liquid crystal devices inducing optical vortices. Changing the electric addressing of the cascaded devices changes the lens focal length. The resulting lenses can be tuned at video rate and enables the consortium to present the lens attractively to both mayor lens manufacturers and to potential investors. During the ALL project the partners have identified applications for non-imaging adaptive lenses, *i.e.* LIDAR for wind speed measurements in the context of wind turbines.

Keywords: Adaptive Optics, Liquid Crystal, Flat Lens

1. INTRODUCTION

Lenses are ubiquitous in modern life. We wear them on our noses, use them in our mobile cameras and employ them in all kinds of projection and lightning applications. The focus of our lenses is normally fixed but may be shifted by combining various lenses and moving them relatively to one another. Alternatively, our lenses can be shaped so that the focal distance varies, when looking through different sections of them. These solutions require either complicated micro mechanics (as in our mobile phones), or imaging compromises (as in our progressive reading glasses).
The ALL lenses provide a dynamic, yet mechanically rigid, alternative by cascading a linear polariser with two transparent liquid crystal (LC) devices each with a few tens of electrodes. Both the working principle of the lenses and the driving electronics resembles those of the simplest displays found in household electronics and may be implemented in all kind of applications at a very low cost.
The developed driver makes it possible to address the lenses at video frequency, which in camera and display applications means that the focal distance can be optimised for each of the primary RGB colours sequentially, eliminating any chromatic aberrations. With conventional LC technology the devices work with low driving voltages ~5V , making it possible to use even in eye contact lenses. The driver also allows for very high voltages, which opens for the use of blue phase LC that do not require the use of polarisers[1], which will be relevant in applications limited by light.

2. STATE OF THE ART

LC lenses have already been presented both as a single electrode [2]–[6] and more complex nested[7] or multilayer[8] electrode structures, but these devices are characterised by limited tuning range, diameter, compromised lens shape and/or complex manufacturing.
Other transparent lenses, not based in LC technology exist, even as commercial devices. Several are based on adaptive liquid lenses using piezo-electrics [9] or elastic membranes[10], electrowetting or dielectrophoresis as reviewed by Ren and Wu[11]. All these technologies are based on physically shaping a structure with a given refractive index, different from the surrounding matrix.
At present the two most active commercial players are the European companies Optotune (CH) and Dynamic Optics (IT). The former of the two employs electromagnets, to reduce or increase the amount of liquid situated between two deformable polymer membranes, the second uses 18 piezo-electric actuators to deform the thin glass sheet windows in a constant volume cell.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The new lenses feature discrete emulation of Fresnel lenses for arbitrarily large lens diameter, with a focal range unprecedented by any existing non-mechanical tuneable flat lens technology. Unlike the above-mentioned commercial competitors, the new lenses do not require any mechanical motion of liquids, which allows for very fast, and repetitive action.

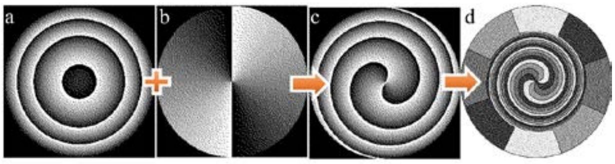

Fig. 1. The electrode design process. The tangentially symmetric Fresnel diffractive lens (a) is added to a radially symmetric spiral phase plate (b) generating the characteristic spiral diffractive lens (c), which is then approximated by discrete electrodes (d), that may be addressed peripherally, unlike the concentric circles, that would generate the Fresnel diffractive lens directly.

The lenses are based on LC technology, which is a mature technology. Consequently, each lens unit featuring a small or moderate size lens (10 mm diameter) will have a large-scale production cost well below 1 €, including the driving electronics. Smaller lenses for use in mobile phones will have even lesser cost.

The theory sustaining the lenses is intuitively understandable, as described in the underlying patent[12] and in the paper pending publication: Tangential (lens shaped) and radial (spokes in a wheel) symmetries are added mathematically to create a spiral. This spiral is then used to generate a device with spiral shaped electrodes that addresses an LC (Fig. 1).

The LC device introduces spiral shaped zones with different retardation of incident light. By cascading this device with second LC device with radial symmetry, with opposite sign with respect to the original symmetry, one recovers the original lens shaped deformation of the incident light beam, *i.e.* recovers the lens. By concertedly addressing the two devices, so that radial symmetry is always eliminated, a number, depending on the number of electrodes, of perfect discrete emulations of Fresnel lenses with both positive and negative focal length can be generated (Fig 2.). *The radial symmetry added to the lens in the design, is eliminated in the implementation.*

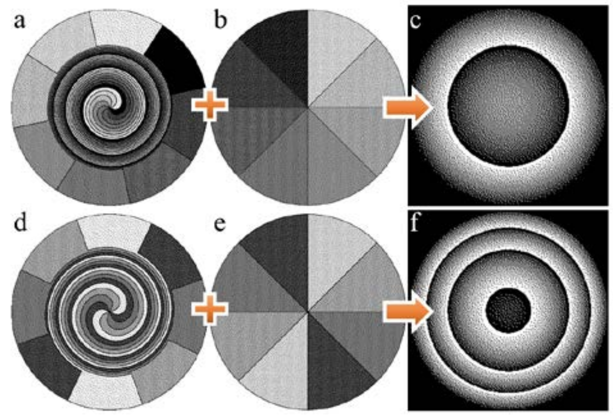

Fig. 2. Cascading the spiral diffractive lens (a, d) with the spiral phase plate (b, e) emulates Fresnel lenses (c, f) with a focal distance depending on the electric addressing of the LC devices. The same device can dynamically be addressed, changing the focal distance. Two cascaded oppositely spiralled diffractive lenses may also emulate a Fresnel lens.

One limitation of the lenses is the inherent chromatic aberration, characteristic of all tuneable single lenses.However, the speed of the lens, allows for sequential captures, optimised for each colour, which enables the capture of images free of chromatic aberrations.

Another limitation is that the lenses only works for linearly polarised light. This limitation may be overcome by either duplicating the lens system, by including a polariser, or by employing the above-mentioned blue-phase-liquid crystals [1].

These aspects make the lenses highly attractive in both high value products, such as medical endoscopes, or machine vision and on longer terms in mobile phones.

4. PROJECT RESULTS

The project has exceeded the expectations, since already the first batch of the lenses outperformed the expectations. The second batch, already 25mm diameter, only confirmed these results. A third batch of lenses, in which the number of electrodes should have been increased from 24 to 72 was postponed since the second batch already outperformed expectations.

Hence, the ALL project partners have been able to generate 25 mm lenses with associated drivers. Two kinds of these lenses were manufactured. The first lens was designed to span ±4 dioptres, in 25 steps (cascading two identical spiral lenses) However, it became obvious that although applications with a need for such a wide tuning range may exist, then such a wide range would have little relevance to an imaging system, and furthermore be difficult characterise, and hence document, employing conventional optics. Consequently, a second version of the second batch of lenses was manufactured spanning ±2 dioptres, in 25 steps, combining one spiral lens with one phase plate as indicated previously in Fig. 2, and implemented in Fig. 3. Both the addressing and performance would be similar, or identical, for the ±2 and ±4 dioptres lenses.

The image formation of the lenses exceeded the expectation, creating fair quality images for the two most extreme configurations that the characterisation system was able to image (Fig. 4).

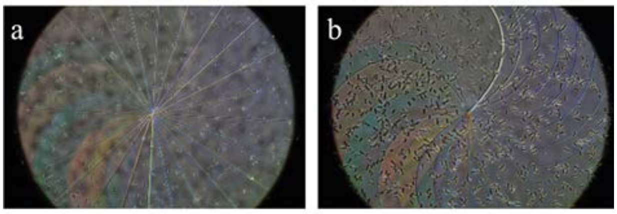

Fig. 3. Cascading the spiral diffractive lens (a) with the spiral phase plate (b). Observing the lens between crossed polarisers, while addressing each electrode differently facilities the alignment. The spacer particles seen scattered measures 9 µm.

Fig. 4. Two full frame images showing the lens performance when used in front of a digital camera (inset). Changing only the ALL lens electrical addressing images could be captured at 0.5 and 12 m distance to the camera. The camera depth of field was deliberately minimised to highlight the ALL lens effect, by opening the diaphragm (setting the f-number to 3.2)

At less extreme configurations, the lens performance is very convincing showing perfectly crisp images Fig. 5.
While the manufactured lenses more than proved the concept of the lenses, then a number of low hanging improvements are still within reach, at a very low cost.

- An analogue tuning. Currently tuning of the lens is only done in discrete steps. The size of these steps made the ±4 dioptres lens inoperable. Cascading three devices and using non-integer addressing are two ways identified as means of virtually analogue tuning.
- Chromatic aberration in digital imaging. Fig. 4. Shows for the trained eye, the typical signature of chromatic dispersion caused by different wavelength having slightly different focal distances. The speed of the ALL lenses opens for the potential of dynamic compensation of chromatic distortion, by combining the colour pixels from sequential captures, each optimised for one of the principal colours (typically Red, Green and Blue).

The software for analogue lens driving and RGB capture and recombination is currently being developed. Discussions with suppliers of LC material that have the potential of working without the need for a polariser, are ongoing. These materials are still on an experimental stage, but may be brought to production, if a market, such as the ALL lenses, is identified.
While the lenses have proven their applicability in imaging, then for human vision they are still showing a haze which is bright light conditions is compromising the use of the lenses as eyewear. Thinner cells (2 µm instead of the current 9 µm) are expected to solve this issue.
The only aspect in which the project has under-performed is in the publication of results, which has led to at least 8-month delay in publication of the initial results. This first paper, which will be followed up by another scientific paper, and several outreach events such as national television, is currently undergoing final revisions 8 Month after being sent to the first journal.

5. FUTURE PROJECT VISION

The ALL project was from the beginning aimed at developing an OEM product to be included in a wide canopy of applications. In the course of the phase I project the existing consortium has had detailed discussions how to address the next phases of the project. Various options have been discussed. 1) further mature the project together with more collaborators within a publicly funding scheme 2) team up with a financial partner and/or 3) technological partner. From a control, and IP development, point of view, the former option is clearly the most attractive.

5.1. Technology Scaling

The project may be considered to have reached a TRL level 4 in the context of digital imaging. However, this will not be an entry application, given the sheer size of that market, and hence necessary investment in manufacturing equipment to address it.
In the context of the envisaged starting applications, *i.e.* highly specialised high value market, such as for example medical endoscopes, it is the assessment that the current development has reached a TRL 3.
It will be crucial over the next 12 months to partner with a manufacturer of the end product in order to focus the development towards the specific requirements of a specific end-product.
A small number of units will be manufactured, either semi-industrially, or ordering small series from a Liquid Crystal device manufacturer. It is likely that hybrid production, where part of the production is outsourced (Chip on glass mounting), while another is kept in-house, will be the best way of protecting IP, while avoiding mayor infrastructure investments
In this phase, to miniaturise the electronic driver an application-specific integrated circuit (ASIC) driver will be developed, if an existing commercially available display driver cannot be employed.

Fig. 5. Details from images using three successive lens settings. a: ALL lens inactive –no topological charge (N_T=0); b: Minimal ALL lens focusing (-0.15 dioptres ~ N_T=-1) c: Twice minimal ALL lens focusing (-0.30 dioptres ~ N_T=-2). Notice how the image quality isn't compromised at all by the ALL lensing, while the focal plan is shifted.

The roadmap to a TRL 7 thus becomes:

- Identification of exact requirements of the end-user, and subsequent design of lenses to meet them
- Integration, and potential development of ASIC for LC driving
- Identification of part supplier (LC device manufacturer)
- Integration of lenses into final application
- Demonstration and functional characterisation

5.2. Project Synergies and Outreach

A analysis of the Attract Phase 1 funded projects has failed to find any of the European optics manufacturers, which is the main partner target, however, the potential synergy between the ALL vortex based LC lenses with the projects "Vortex lasers and sensor manufacturing" and "Single pixel thermal camera based on LC resonant structures", must be explored.
The most important partner will be the future OEM client for the ALL lenses, which will define the lens requirements in terms of focal range, polarisation dependency, physical adaptation to the instrument, and remaining working parameters (temperature, light intensity, voltage limitation, user or OAM interface etc.). It may even be possible that two, ideally complementary, OAM partners can be identified. Upon the publication of the above-mentioned article the search for OAM partner will intensify. ADT has already started informal conversations with a potential medicare supplier.
As secondary partners, two of the UPM habitual partners in European LC-based projects springs to mind.

- IMEC Ghent (BE), is one of the few installations, private or public in Europe, that is still capable of manufacturing medium scale fully integrated LC devices. IMEC has the equipment for mounting the LC driver (ASIC) on the LC glass-substrate (Chip-on-Glass), which may be done either on the finished devices, or before the final assembly of the lens components. It is possible that IMEC may have conflicting interests, due to its involvement in Morrow Optics. Alternatively, UPM has been collaborating with Global Display Technologies (GST) (ES), which specialises in sourcing LC displays OEM components and services.
- MUT, Military University of Technology (PL). MUT is the world leading developer of LC compounds, licencing numerous LC materials to the world LC producers. MUT has already expressed interest in participating in the project, developing LCs specifically for the project. MUT, is not only developing materials, but has also facilities for upscaling to commercial production, for special applications such as the ALL lenses. To the knowledge of the proposers WAT is the only commercial supplier of LC materials synthesised in Europe, since Merck transferred all its LC production and development to Far East in 2018.

The envisioned consortium is outlined in Table 1.

Tab. 1. The planned Phase II consortium**.**

Partner	Role
UPM	Coord. Design and manufacture of lenses
ADT	OEM interface and driving electronics
MUT	Optimised LC synthesis and development
IMEC/GST	LC driver integration with lens
END(1&2)	End users (TBD). Definition of lens specifications and lens integration

Due to the delay in the publication of the initial results, then consortium has already been prematurely in contact with various national Spanish TV broadcasters. However, the authors have refused to publish their results in mainstream media prior to peer reviewed journals.
Being a truly visible application (active moving focus) that can be explained, using simple geometric arguments, accessible to any STEM inclined A-level student, makes this project attractive to news and divulgation channels. Not only as a news item, but also as an educational inspiration for future STEM students. The UPM will furthermore prepare own audio-visual material, which will be shared with the ATTRACT Consortium.
In all these contexts the funding and importance of the ATTRACT Consortium will be appropriately acknowledged.

5.3. Technology application and demonstration cases

The ALL technology aims at substituting lenses in all contexts where tuneable optical systems are currently implemented (microscopes, telescopes, image projection etc), but also in applications where they could be desirable, but not yet implemented (*e.g.* eyewear or automotive head lights).
The ALL project is applied photonics, one of the key enabling technologies, to the area of optics. This area Europe is standing strong, not only academically, but also industrially with market leaders such as Zeiss, Leica, Rodenstock, Essilor and Schott being household names.
The continuation of the ALL project will not only cement the European lead in the area of optics but will also in the area of LC development and production.
The envisaged initial commercial application of the ALL lenses is at the time of writing the Medicare sector, more specially in the context of endoscopes, which of course is oriented towards health, which in turn has a larger impact on an increasingly aging population. The medium-term applications industrial machine vision and microscopy with automatic focus are of wider scope potentially affecting several of the societal challenges.
The invention is of such a broad and basic application that, upon success it is bound to affect the day to day life of all EU citizens.

Apart from the industrial outcome that will be defined by the, yet to be defined, consortium end-users, emphasis will be made on making lens implementations with both scientific and technological relevance.
These implementations (adaptive eyeglasses, headlights, image projectors, laser handling for LIDAR) will not only be of academic interest, but will also work as showcases for the technology, and of course of the Attract funding scheme.

5.4. Technology commercialisation

Currently, the most valued option for the commercial exploitation of this technology is the creation of a specialised spin-off. Two business lines have been considered. The first is oriented towards large clients, such as camera or medical instrumentation manufacturers, which need OEM solutions for their products. In this business line, our solution is adapted to the specific need of each client.
The second business line consists of creating an own products catalogue. It is being considered, based on AD Telecom's previous experience in image processing and analysis, to develop automated visual inspection applications for production lines. The ALL lenses allow for quick focus of large parts at different heights.
Regardless of the creation of the spin-off, the UPM has already been contacted by private investors interested in buying the exploitation rights of the patent, but no formal negotiations have been undertaken.

5.5. Envisioned risks

The lenses have already reached a TRL of 4 in a generic context, and 5 in a specific context. Hence, no technological risks are foreseen. The only new technology is the chip-on-glass, for which three solutions are already identified.: 1) purchase of substrates with chip-premounted, 2) subcontracting of the substrate preparation or 3) subcontracting of the entire LC cell, filled or not with LC material.
The major risk is in the consortium formation. It is imperative to identify a producer of high-end professional equipment, such as the mentioned endoscope. However, the consortium has already contacts in the medicare industry, and by not a priori committing to only one partner, the likelihood for successful partner search is very high.

5.6. Liaison with Student Teams and Socio-Economic Study

Having reached a TRL where both adaptive eyewear, headlights and photovoltaics may be within reach, the technology becomes relevant for Socio-Economic Studies. Furthermore, due to the COVID confinement, students and professors are now used to the new norm of distance learning, which facilitates and reduces cost of student liaison. Dr. Geday, has already given 60 min. presentation of the technology for Ms. Students.
Dr. Geday will be available for both interviews and lectures during any ATTRACT Phase 2 project.

6. ACKNOWLEDGEMENT

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