LIQUID LENS: AN ADVANCEMENT IN OPTICAL COMMUNICATIONS

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Abstract:

"Liquid lens" technologies promise significant advancements in machine vision and optical communications systems. Utilizing two isodensity liquids with differing electrical characteristics to focus, liquid lenses require no moving parts for operation. Liquid lenses also offer lower power consumption and smaller package sizes than their electromechanical counterparts. Liquid lenses are quickly becoming a viable alternative to conventional lens technologies for a wide variety of applications. Notable variations of liquid lens technology are discussed. A machine vision student project utilizing this technology will be discussed in detail. An adaptation of the machine vision project, for use in human vision correction, and independent research in optical communications are also used to exemplify the versatile nature of this technology.

Keywords: *cliquid lens, electrowetting, machine vision, electrostatic deflection, electrostatic defraction, fiber optics, immersion lithography, speed detection, autofocus, ophthalmic lenses*

1. Introduction

An Electronics Engineering Technology senior project design, at DeVry University, is a series of three sequential, project management and development courses which are requirements for graduation. These courses demonstrate the technical skills and knowledge that an Electronics Engineering Technology student has acquired throughout their entire course of study. The program requires students to plan the project in great detail, according to realistic requirements, with a limited budget and finite amount of time. During the project planning stage, great care must be taken to select a project which is feasible. Usually several potential projects are considered during the planning process. One potential project, the Automatic Speed Detection System, a machine vision application, was implemented during the Summer 2006 trimester.

2. Speed detection

Originally, the Automatic Speed Detection System was based on microwave radar which would be used to detect the speed of passing objects such as motor vehicles. The radar would be used in conjunction with a camera system to collect data on a particular object, in this case, the license plate of the motor-vehicle. Early experiments involved inexpensive cameras with poor frame rates and manually focused conventional lenses. These cameras yielded a surprising result.

An object which was moving quickly would become distorted due to the low frame rate of the camera. The more distorted the object, the quicker it was moving. Through the use of pattern recognition algorithms and calibration images, the camera served the purpose of a conventional microwave radar. The camera also offered lower power consumption than conventional radar, and simplified the design of the project. Speed detection was possible through the use of a camera. Further research [1] supported the project team's conclusion.

It was now necessary to reconsider several aspects of the design. Though the current camera configuration was suitable for detecting the speed of a moving object, the camera was not capable of capturing a recognizable image of the passing object. Software enhancement of the images proved to be highly inaccurate, time consuming, and required significant hardware resources. Another solution was needed to ensure accuracy, reliability, and practicality of the project. A new camera would be necessary, one with a high frame rate, variable focus and other advantageous features, while still remaining within the confines of the project's limited budget.

The updated project consists of a custom image processor, camera, and an end-user interface, implemented on a Field Programmable Grid Array (FPGA) in conjunction with a Texas Instruments Digital Signal Processor (DSP). The system was prototyped and programmed using National Instruments LabView Vision software. To prototype the system with LabView, images were passed into a desktop computer using a generic PCI Televison-Tuner card. After being properly formatted, the images can be used as data acquisition samples by LabView. These samples are passed into customized subroutines which included pattern recognition and optical character recognition algorithms. Some of these samples were used as calibration measurements for speed detection pattern recognition algorithms. Other acquired images were used to build a database of samples for use as a reference for optical character recognition algorithms. A key component of the system is a modified NTSC video camera. A single camera would be used for both speed detection and object recognition. This camera would detect the speed, and, after reconfiguring focal length and frame rate to compensate for the object's speed, would capture a recognizable image of the object.

3. Camera

The camera was originally designed with a quarter inch Sony ICX206AK Super-Hole Accumulation Diode (Super-HAD) Color Video Camera Charged Coupled Device (CCD) packaged in a 14-pin plastic dual in-line package (p-DIP) with 900 mV typical sensitivity. The CCD has 510 (horizontal) by 492 (vertical) effective pixels resulting in a horizontal resolution of 420 lines. This particular family of Sony CCD image sensor is sensitive to the infrared spectrum, making it optimal for use in an application with little or no ambient lighting.

The design also included many necessary components for proper operation of the CCD. A matching chip, a Sony CXA2096N Digital Camera Head Amplifier IC provided several useful functions including correlated double sampling, Automatic Gain Control (AGC) for the CCD signal, analog-to-digital (A/D) sample and hold, blanking, A/D voltage reference, and an output driver. The IC was packaged in a plastic, 7.8 by 5.6 mm 24-pin Shrink Small-Outline Package (SSOP), with a 3.3 V supply.

A Sony CXD3142R Signal Processor LSI, for Single-Chip CCD Color Cameras, provided basic signal processing functions. This IC generated necessary timing pulses to drive the CCD, A/D converter, D/A converter for analog composite output, digital output, as well as sync functions for the CCD on-chip and from external sources. The CXD3142R supports either NTSC or PAL standards. The IC also includes a micro-controller (MCU) with control functions as well as serial (3-wire bus) and peripheral communications. This signal processor has a relatively small footprint; only14mm² in an 80-pin plastic Leaded Quad Flat Pack (LQFP). The chip has relatively low operating voltages from 3 V to 5 V. Additional instructions for the MCU were included on a small serial EEPROM.

The camera featured electronic iris control and variable electronic shutter speeds. With variable shutter speeds from 1/60th of a second to one 1/100000th of a second, this particular configuration is suited for high speed photography. A regulated 12V power supply provided suitable power for the camera power supply as well as twenty infrared light emitting diodes (LEDs). The LEDs are controlled by a cadmium sulfide (CDs) photo-resistor, and can provide illumination for black-and-white images up to 45ft in complete darkness, depending on reflection and other environmental conditions.

The camera's original lens was a 3.6 mm conventional lens, with a fixed focal length. Lens modules, for use in automatic focus and telephoto/zoom lens applications, would be necessary to replace this fixed lens. There exist two basic types of automatic focusing lenses, passive and active. Through the analysis of the sharpness of the captured image, a passive autofocus system adjusts according to the contrast of lines in the image. In an active autofocus system, typically infrared radiation or ultrasound emitters and detectors are used to determine desirable focal length. These lens modules rely on several ground and polished glass or polycarbonate lenses, or molded plastic lenses, with an adjustable collar for fine tuning the focal length. Several precision motors, gears, drivers, and control electronics would be required for movement of the lenses. Feedback and braking mechanisms would be necessary for accurate control of the lenses.

4. Drawbacks of conventional lenses

There are several drawbacks to consider when implementing a design with a conventional adjustable focus lens. Slow response due to time necessary to induce magnetism in the coils of control motors and mechanical inertia when starting and stopping are problems inherent with electromechanical lens modules. Feedback and braking control mechanisms will also slow down response time and consume valuable hardware resources.

Electromechanical components in a system are subject to degradation and failure due to friction between components and material imperfections present during manufacture. More importantly, the initial cost of components, as well as high recurring costs for replacement parts, maintenance, and downtime, make an electromechanical lens solution impractical for many applications. For a high-performance design similar to the Automatic Speed Detection System, the use of electromechanical lens modules would be impractical, especially for long term, repetitive use, due to the limitations of a mechanical system.

5. Liquid lens technologies

To overcome the obstacles posed by conventional electromechanical lens modules, an alternative solution was needed for use in the Automatic Speed Detection System. There were several viable alternatives to conventional lenses. Several types of lenses, some of which used voice-coil-based electromagnetic system or the piezoelectric effect [4], as opposed to motors and gears. These systems could be used to induce a focal change using conventional lenses. However, these types of lens systems have limitations and drawbacks similar to motor-driven electromechanical lens modules. The most noteworthy alternatives were liquid lens systems.

There are several liquid lens implementations which could be used to adjust focal length. A rudimentary use of liquid as a lens resulted from the semiconductor industry's push to extend the useful life of 193 nm immersion lithography equipment [5]. An innovation on the 'step-and-repeat' lithography process makes use of a transparent liquid as a lens element to fill the gap between the lens projecting the design and the surface of the unexposed wafer [5]. This offers semiconductor designers higher resolutions, as the lens offers numerical apertures higher than 1 and greater control over the distribution of light [5,7]. An adaptation of this technique uses a liquid contained within two transparent plates. One plate is fixed and the other is adjustable. By adjusting the plate, the pressure exerted on the liquid changes, thus adjusting the focal length. This solution offers quicker response times, smaller packaging, and fewer moving parts when compared with conventional lens systems utilizing motors and solid lenses.

A different liquid lens technology was born from an improvement in the manufacturing of conventional lenses and relies on no moving parts for operation. Instead, this technology uses an electrically conductive polymer which is separated from another conductor by a dielectric material [6,7]. This assembly is mounted on an insulating layer of glass [6,7]. As a voltage is applied across the device, the polymer changes shape. Depending on the voltage applied, the focal length of the lens can be adjusted by reshaping the polymer. Spherical geometries can be fabricated more precisely utilizing this method, as opposed to grinding and polishing or molding the lens material. This technique has been successfully used to shape lenses comprised of an Ultraviolet (UV) curable polymer. After the lens is shaped it is exposed to a UV light source and then solidify. Unless the polymer is exposed to UV light and solidifies, the properties of the lens can be adjusted.

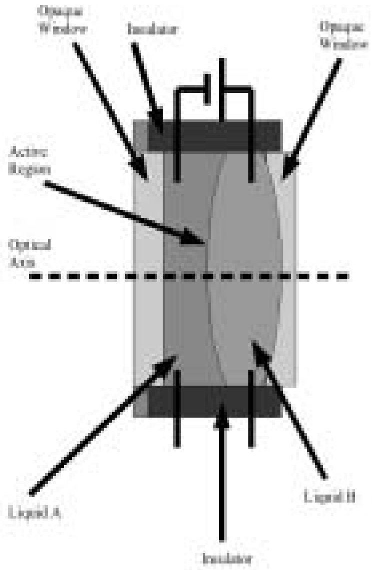
6. Liquid zoom lens

There was another liquid lens solution, one which also required no moving parts, that proved to be the most suitable replacement for conventional lenses. Based on a phenomenon known as electrowetting, these types of lenses use two isodensity liquids suspended between two transparent windows with electrodes at opposite ends, to adjust focal length (please see figure). The liquids are immiscible, yet have similar densities [2,3,10,12]. The liquids also have unique individual electrical characteristics; one liquid acts as an insulator while the other functions as a conductor [2,3,10,12]. The lenses operate on the principles of electrostatic deflection and electrostatic defraction, to manipulate light passing through the lens element. When a high voltage is applied across the liquids, the meniscus, or curvatures, formed by tension between the liquids changes. The conductive liquid distends (flattens). This adjustment in the curvature of the liquids changes the focal length of the lens. This method completely removes mechanical components from the lens system, and greatly reduces power consumption, size and cost [2,3,10,12].

The lens module chosen for the speed detection project is manufactured by Sunex Digital Imaging Optics, Inc. exclusively for the manufacturer of the liquid lens, a French company, Varioptic SA. The lens module emulates an electromechanical auto-focus/zoom lens by incorporating two liquid lenses and a conventional fixed lens, which corrects for aberrations. The lens is capable of producing adjustable effective focal ranges from 5 cm to the horizon (∞) [3].This lens system can adjust focal length faster, consumes 1/10th of the power, and occupies half of the volume of conventional electromechanical lens systems [2].

7. Lens control

To operate the Varioptic lens, an specialized integrated circuit (IC) driver is necessary. The IC, the DUREL LL3 driver, manufactured by the DUREL Division of the Rogers Corporation, was designed to perform perfectly with Varioptic liquid lens. The driver is packaged in a 4 mm², 16-pin, lead-less quad flat pack (QFP). The circuit is similar to that which drives electroluminescent lamps. A Direct Current (DC) input, ranging from 2.8 V to 5.5 V, is boosted to a higher DC voltage, then, this is converted to Alternating Current (AC). The output is 60VRMS, which is capable of driving capacitive loads up to 500 pF, in this case the lens. [3]



The driver IC is controlled via either an I²C serial interface or pulse-width modulation (PWM) interface. The circuit includes and integrated comparator which monitors the generated voltage through a resistive divider. Then the comparator compares the output to the control input, and provides feedback, which helps control the high DC voltage. Finally, the voltage is passed through an H-bridge which is connected to the lens. The H-bridge converts the high voltage DC into an AC signal. Under normal operating conditions, this particular Varioptic lens based module draws 40 mW, when focused to 5 cm, and only 20 mW when focused to ∞. With low power operation, and standby current as low as 1 µA, this system is one of the most power efficient lens systems in the world. [3] The system also offers the option of completely shutting down power to the lens, to conserve more power when the lens is not is use.

The Varioptic liquid lens module provided the most desirable results for integration into the Automatic Speed Detection System. This lens allowed the most reliable and accurate configuration for adjusting camera focus. This module provided a cost-effective solution while conserving power and greatly reducing the size and complexity of the project.

8. Additonal applications

There are several interesting alternative applications for which liquid lens technologies could be adapted. Ongoing research in the use liquids and fiber optic communications systems has already yielded promising results. "Tunable optical-fiber devices can be useful for many important operations in optical communications systems..."[8]. Typically, fiber optic devices are tuned thermally or using mechanical strain techniques [8]. These types of tuning have limitations and can place unnecessary stress on elements of the system. The use of liquid lens technology, in the form of electrowetting pumps, allows for a tunable optical filter [8]. This filter would consume less power, have quicker response time, and have lower overall production costs, than conventional optical filtering techniques [8].

Independent research has also proven the effectiveness of this technology for fabrication of microelectromechanical devices. Electrowetting could be used to drag a micromotor [11]. It could also be used to expand and contract a small capillary, and could serve the purpose of a pump or actuator [11]. Another possible application which had also been prototyped by other researchers was the use of the technology as a spatially programmable filter. Through the use of electrowetting with an additional absorbing material, and several multiplexed channels, a filter of this nature could be fabricated [11].

Liquid lens technology could serve important purposes in the medical field as well. Improvements in machine vision and diagnostic imaging for medical applications has many, potentially broad, and far reaching implications. One of the most significant advances in the medical field with regards to liquid lens technology may aid the visually impaired. A wide range of vision impairments are corrected, simply by bending light in conventional ground lenses. Liquid lenses, such as those used in the Automatic Speed Detection System, are easily fashioned into a primitive pair of programmable spectacles.

An early observation by the project team noted that, although prototyped eyeglasses may not be aesthetically pleasing, a functional pair could be produced. In this case the conventional a single liquid lens would be utilized to reduce size and weight. An MCU controlled the driver for the lens, and thus the signal across the lens, according the necessary amount of correction, while a lightweight battery provided power to the system. The glasses prototyped provided uniformly varying optical powers capable of correcting mild nearsightedness (lens power of -5) through virtually the entire spectrum of farsightedness. Many different types of specialty lenses for a wide range of visual impairments could be "programmed" in this way into a single device, greatly reducing the recurring expense and turnaround time for new lenses.

Specialty lenses and lenses with curvatures and features not possible with ground lenses are also possible, bringing hope of unimpaired vision to individuals on whom vision correction would normally not be possible or practical. Thinner, lightweight liquid lenses could replace thick ground lenses necessary in some cases of severe vision impairments. Even individuals with no significant vision impairments could use this technology as a compact pair of electronic binoculars. Many corrective lenses require governmental regulatory testing. Extensive safety and reliability testing will be required before liquid lenses are brought to market for widespread use in medical applications.

9. Conclusion

Liquid lens technologies offer many undeniably advantageous features for a wide variety of applications. The possible implementations of liquid lens technologies and fabrication techniques are almost limitless. These new forms of lenses will allow designers of machine vision, medical, and optical communications systems new and innovative opportunities to enhance performance, accuracy, throughput, reliability and overall cost of their devices. Designs, which were not feasible due to limitations and drawbacks of electromechanical lens systems, are now within the reach of systems designers. Truly, a powerful new set of tools has been added to the engineers' tool chest.

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