Looking at liquid lenses

Liquid lenses can be used to maximize imaging system flexibility and functionality in machine vision systems

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The landscape of the machine vision world is one of rapid changes, with new technologies emerging constantly, and new tools coming to market incredibly fast to make tackling automation problems easier. In the past decade alone, the machine vision market has seen the introduction of more advanced sensors in terms of both smaller pixels and larger sensors, software platforms which continue to become more accurate, and lighting which is growing brighter and becoming more efficient. Additionally, the optics which are responsible for relaying the information from the object under inspection to the focal plane array also continue to evolve to produce higher contrast and better measurement accuracy.

One of the most exciting optical developments that has matured over the last few years has been the introduction of liquid lenses. Capable of focusing and refocusing on the order of milliseconds, these lenses cannot be underestimated in today's world of rapid automation, where speed and throughput are directly proportional to efficiency and cash flow.

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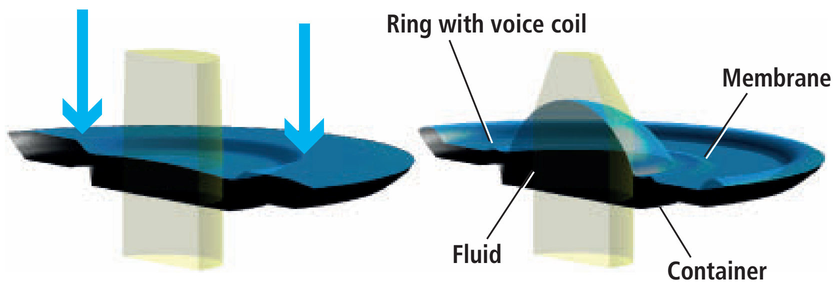

Figure 1: Working principle of a typical liquid lens. A voice coil actuator applies a force to a membrane, forcing fluid into the clear aperture of the lens, changing its curvature and increasing optical power

Liquid lenses offer several advantages in machine vision applications that could previously only be achieved with motorized lenses - if they were solvable at all. Liquid lenses allow the user to change the plane of focus of the lens system in milliseconds, which is useful for applications that require focusing at multiple distances, such as barcode reading, where the objects under inspection are often different sizes or at different distances away from the lens.

Before liquid lenses, the only options for solving applications such as these were either bulky motorized lenses, moving around the camera (or the object) or using a lens with a large depth of field, which often means increasing the f/# and thus making compromises in resolution or choosing a lens with a small focal length and obtaining a less than optimal angular field of view.

Furthermore, unlike most mechanical systems, liquid lenses can perform billions of cycles without any wear and tear. Figure 1 demonstrates the operating principles of a typical liquid lens, where a voice coil actuator applies a force to a membrane, imparting curvature (optical power) into the lens.

Retrofitting lenses

One of the ways that liquid lenses can be integrated into the optics of machine vision systems is through retrofitting existing fixed focal length lenses. While this modification may take a little more trial and error to "tune in" to the best configuration as compared to using an objective designed with an integrated liquid lens, it is a practical solution demonstrating the flexibility of this innovative lens design.

To achieve the ideal solution from such a modification and obtain the optimal image quality, several different considerations need to be taken into account, including placement of the liquid lens and focal length of the objective.

When retrofitting an off-the-shelf objective, the only two possible places to insert the liquid lens is either in front (closest to the object) or behind (closest to the sensor) the objective. Liquid lenses that are available today are still somewhat limited with respect to their diameter; most common apertures of electrically tunable lenses are currently limited to 10 mm or smaller.

This works well when liquid lenses are positioned in front of micro-video (M12 threaded) lenses but most machine vision lenses' front optic diameter is larger than 10 mm, which means that vignetting (blocking of rays through the optical system) can occur. The large diameter of the front lens element make it appear as though it is advantageous to place the liquid lens behind the objective. However, this is often not the case, as placing the liquid lens behind the objective disrupts the back flange distance such that the lens may be unable to focus.

Good results without vignetting can be achieved, however, when the back focal length is significantly longer than the distance introduced by the liquid lens between camera and objective. In such a configuration, the liquid lens works like a distance ring that brings the focus plane closer to the camera. An example of each system is shown in Figure 2, with the 25 mm lens best optimized for use with the liquid lens in front of it and the high magnification objective best optimized with the liquid lens behind the optics.

There are two additional considerations to take into account when placing the liquid lens on the front of an objective: the angular field of view of the objective and the objective's aperture (f/#). The angular field of view

Figure 2: Two different systems retrofitted with liquid lenses. The system on the left is optimized with the liquid lens in front of the objective while the system on the right, co-developed by Edmund Optics and Optotune, the Dynamic Focus VZM Lens, has the liquid lens integrated behind the optics to maximize performance.

of an objective is determined by both the focal length of the objective and the sensor size of the camera that it is being used with, assuming a small percentage of distortion. The longer the focal length of the lens (and the smaller the sensor), the smaller the angular field of view. Longer focal length objectives are more advantageous when used with liquid lenses not only because their smaller fields of view make it easier for the light rays to pass through the entire lens system without vignetting, but due to the hyperfocal condition.

Hyperfocal distance

All fixed focal length objectives have a hyperfocal distance associated with them when the lens is effectively focused at infinity. The hyperfocal distance of a lens is the plane of focus beyond which all objects are within focus to some acceptable blur criteria. Generally it is associated with a resolution and contrast value important to the application where the lens is being used.

If a lens is focused at its hyperfocal distance, the depth of field can be considered to stretch from that position out to optical infinity in the direction away from the lens. Paraxially, when moving toward the lens, the lens is said to be "in focus" all the way down to half of the hyperfocal distance. When comparing the hyperfocal distances of two objectives of different focal lengths, the shorter focal length will have a shorter working distance where the hyperfocal condition is met when compared to the longer focal length objective.

What this means is that using liquid lenses with short focal length objectives can often not buy much in terms of the ability to section through different working distances, whereas longer focal length objectives give the user the ability to sharply focus on objects at a variety of working distances away from the lens, while blurring unessential portions of the field of view.

While retrofitting objectives with liquid lenses can offer wide-focusing ranges from very close working distances to infinity, it is nevertheless important to optimize the working range of the liquid lens. Liquid lenses are good at imparting a range of optical power, from acting as windows (effectively zero optical power) to bending into powerful focal lengths on the order of 50 mm (or 20 diopters). In liquid lenses, tas with standard lenses, the smaller the focal length of the lens, the larger the curvature that is imparted onto the membrane to allow the light to focus.

Aberrations and curvature

Where the optical design is not optimized,

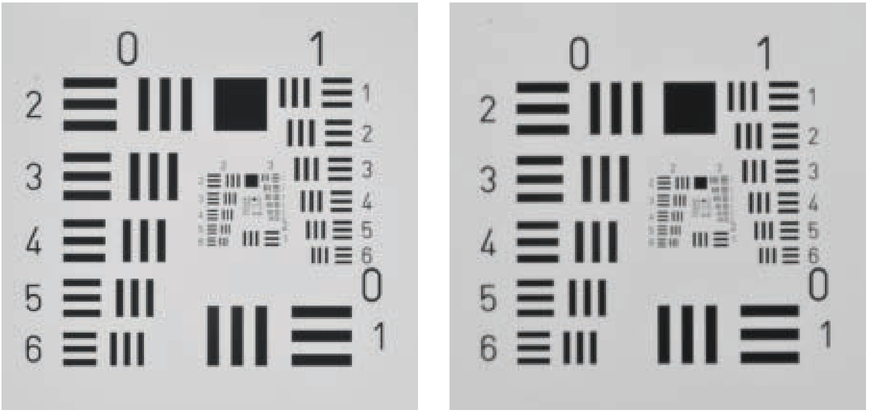

Figure 3: A properly optimized liquid lens/objective combination can produce high resolution and contrast images. Both images were taken with a 25 mm objective and a liquid lens on the front. The image on the left has the object 200 mm away from the system while the object is and 350 mm away on the right. The only refocusing was performed using the liquid lens.

higher amounts of curvature can introduce spherical aberration and field curvature. When retrofitting a liquid lens to a fixed focal length objective, minimizing the amount of necessary curvature imparted on the liquid lens while still obtaining the range of distances required is paramount to achieving optimal image quality (Figure 3).

Minimizing the necessary curvature will usually also optimize the power consumption of the liquid lens at the same time. Introducing chromatic aberrations can also be a concern, but fortunately, there are liquid lenses available with very low dispersion (Abbe number > 100) which can be combined with off-the-shelf optics without having to worry about color correction. Lastly, it is important to consider the aperture (f/#) at which the objective is running to further mitigate vignetting and to provide greater control over the depth of field.

Liquid lenses are an incredibly powerful tool to have available when facing challenging imaging applications, and have progressed far in the relatively brief time that they have been available. This technology will only continue to grow more exciting over time as larger aperture lenses become available to enable a wider range of imaging applications. Understanding how best to use liquid lenses not only on their own, but in combination with objectives, becomes key to offering state-of-the art solutions in in R&D, life sciences, high magnification inspection and automation applications.