Auto-Focus Technology

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ABSTRACT

Several technologies that are being developed for auto-focus (AF) in miniature cell phone cameras are discussed. These include lens-motion-type AF, lens-modification-type AF, and extended depth of field AF. Len-motion-type AF includes stepper motor, voice coil, piezoelectric, electropolymer and micro-electro-mechanical-system (MEMS) technologies. In all these, precise alignment and motion control of the lens relative to the imager is important for image quality. Lens-modification-type AF includes liquid lens and solid-state electro-optical devices. Lens shape and/or refractive index changes are the key to implementing these types of AF. Extended depth of field AF use annular apodizers or wavefront coding to increase the depth of field by increasing the F# or using image processing techniques. Achieving good SNR in the presence of noise and image surrealism are the challenges in extended depth of field AF.

1. INTRODUCTION

The increased performance expectation for digital cameras in cell phones is driving the image sensor industry to develop smaller pixels that will enable the miniaturization of 2-8 Mpixel cameras to fit these mobile platforms. At the same time, optics companies are developing smaller and more precise lens barrels. Module integrators are developing more capable optical systems to take advantage of these new image sensors and lenses as they become available. These efforts need to be carefully coordinated in order to fulfill the promise of stand-alone digital still camera (DSC) quality in a cell phone.

Auto focus (AF) is commonplace for DSCs where volume and power dissipation are less critical. AF is only recently being introduced into cell phone cameras where size is very critical, and power dissipation is also of concern. Stepper motors, commonly used in DSCs, do not scale well to the requirements of the cell phone camera and different technologies have emerged. Active AF systems that use structured light or ultrasonics to determine focus are also not well suited for the size and power constraints inherent in cell phone cameras. This paper will describe the various technologies being pursued for AF and some of their advantages and disadvantages.

All technologies need to be evaluated in terms of characteristics required for cell phone cameras. These include small size (e.g. 10 x 10 x 6 mm), low cost (typically less than $2), reliability (millions of cycles), wide environmental operating range (from car dashboard in the sun to subzero freezing temps), and high shock survivability of up to 8,000-10,000Gs.

2. AUTO-FOCUS SYSTEM OVERVIEW

The AF system is composed of the image sensor, image processing, AF algorithm, driver circuit, AF actuator, and an imaging lens, as shown in Figure 2. The image sensor, image processing, and AF algorithm blocks are often integrated onto a single chip called the imager system on a chip (SOC). The lens and the image sensor must be designed to match each other for optimum performance. For example, the chief-ray angle (CRA) as a function of distance from the center of the image must be matched for the lens and image sensor. Mismatch in CRA can lead to pixel crosstalk and color artifacts. The optical resolution and imager resolution must be matched to maximize picture sharpness and avoid image artifacts caused by under-sampling.

There are various technologies available for the AF actuator. The AF actuator is responsible for modifying either the position of the imaging lens with respect to the imager or the optical properties of the imaging lens. To pick the best AF actuator for a cell phone camera, it is important to consider its effects on image quality, size, reliability, and power consumption.

Several technologies being developed for AF in miniature cell phone cameras include lens-motion-type AF, lens-modification-type AF, and computational-type AF. Lens-motion-type AF includes stepper motor, voice coil, piezoelectric, electropolymer and micro-electro-mechanical-system (MEMS) technologies. In all these, precise alignment and motion control of the lens relative to the imager is important for image quality. Lens-modification-type AF includes liquid lens and solid-state electro-optical devices. Lens shape and/or refractive index changes are the key to implementing these types of AF. Computational-type AF use wavefront coding to cause predetermined "blurring" of the image that can be removed using image processing techniques. Achieving good SNR in the presence of noise and numerical rounding, and image surrealism are the challenges in computational-type AF.

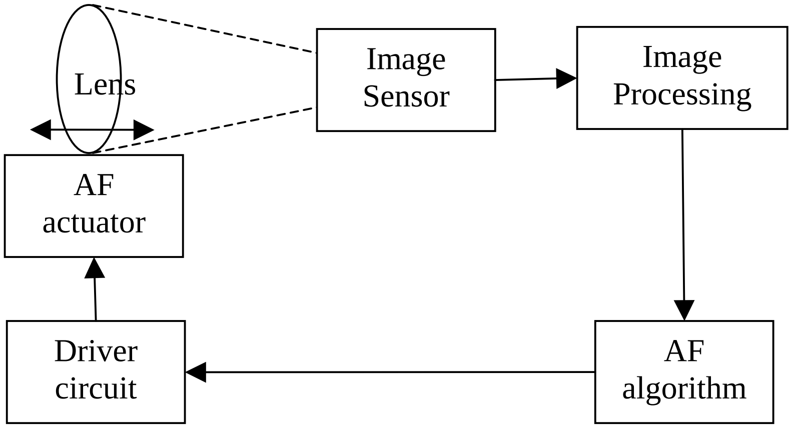

Figure 1. Block diagram illustrating the system level operation of an AF system.

For lens-motion-type and lens-modification-type AF, the control loop requires the capture of an image, processing of the image to evaluate focus, moving or modifying the lens to a next value, capturing another image, calculating a new focus score, etc., until some optimum focus position has been passed through. The lens is then set to the condition of best focus. The lens position or shape, etc., must return to the same value it had when the best focus score was achieved. The presence of hysteresis (not returning to the same position) can result in an out of focus image, or a need to redo the loop leading to latency, or a need for position sensing. The latter adds cost, size and additional complexity to the design and should be avoided. Computational focus is either deterministic and does not require a focus-score feedback, or the feedback takes place completely in the computational domain.

The AF process must take place in the shortest possible amount of time. This is to avoid user frustration over "missed photo opportunities" associated with latency. Continuous focus is a possible solution but it requires more power.

3. AF USING MOTION OF AN OPTICAL ELEMENT

When moving an entire lens barrel, it is important that the lens barrel is properly positioned with respect to the imager in all but one degree of freedom. The position of the lens barrel along the optical axis (z-axis) affects focus, so it is important to have the ability to place the lens barrel with better than 10 micrometer precision. Position in the x and y axes affects the chief-ray-angle (CRA) matching of the optics and imager, as well as the relative illumination and distortion, so it is important to place the lens barrel optical axis with the imager active area center with better than 50 micron accuracy. The position of the lens barrel in pitch and yaw affects the optical resolution as shown in Figure 2. The vertical axis is the modulus of the optical transfer function (from 0 to 1) and the horizontal axis is the spatial resolution on the horizontal axis (from 0 to 125 cycles/mm). The graph on the left is for a lens barrel that is properly aligned, while the graph on the right is for a lens barrel that is misaligned in pitch by 2 degrees. Whereas a properly aligned lens barrel has > 30% MTF at 125 cycles/mm, a misaligned lens barrel has some portions of the image with < 30% MTF at about 30 cycles/mm. As a result, it is important to place the lens barrel with a pitch and yaw accuracy of < 0.3 degrees.

Lens-motion-type AF then has two key requirements. First, the motion must be controlled with optical precision. Second, the actuator must use low power and occupy small space. Thus, stepper motors that use a rotary electromagnetic actuator and gears to convert the rotary motion into linear motion are not suitable due to their relatively large size, larger cost, and low shock survivability. Although stepper motors were used in DSCs in the first autofocus cameras, they are largely not being applied to the cell phone camera market.

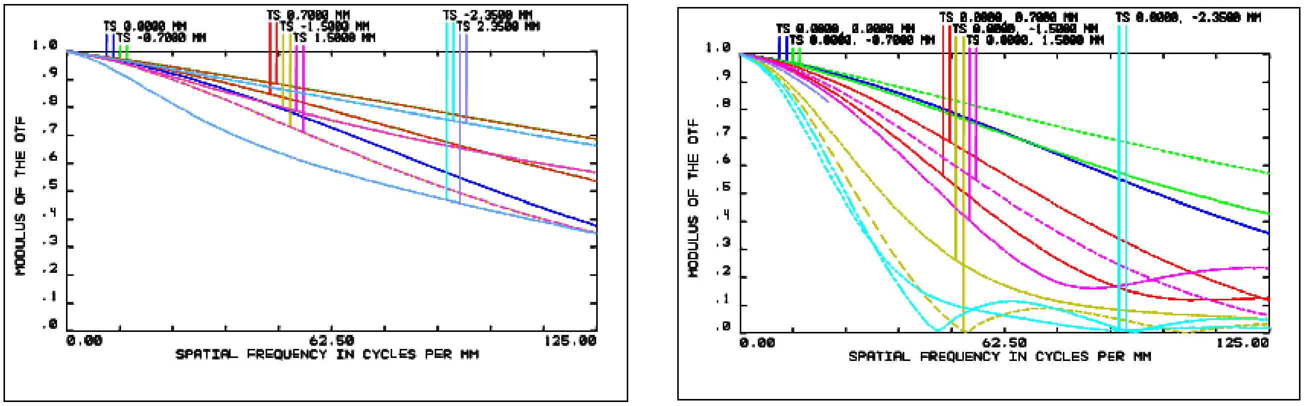

Figure 2. Plots showing the MTF as a function of the spatial frequency for a properly aligned lens barrel (left) and a lens barrel with a misalignment of 2 degrees in pitch (right). The various curves are for different positions on the imager.

MEMS technology, which uses photolithography and etching of silicon wafers to enable moving mechanical structures with less than 1 micron tolerance, ensure that the lens is optimally positioned with respect to the imager for AF [1]. This, in turn, ensures a high quality picture. A photograph of a MEMS AF digital camera and the MEMS components that make this type of camera possible are shown in Figure 3.

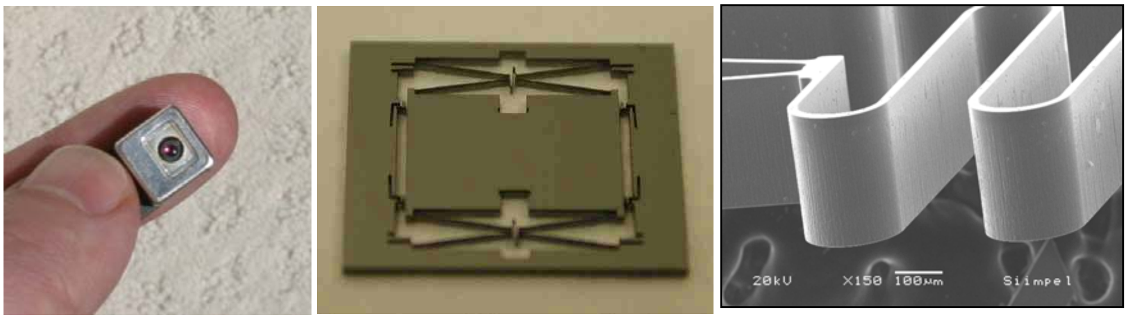

Figure 3. Photograph of a MEMS digital camera for use in cell phone (left), photograph of the MEMS stage used for AF (center), and scanning electron microscope photograph of a portion of the MEMS stage (right).

The voice-coil motor (VCM) and the MEMS actuator both use linear electromagnetic actuation, which use interaction between a permanent magnet and the magnetic field generated by the current flowing through a coil. However, the motion control for each of these two technologies has widely different tolerances and only the MEMS actuator ensures the proper lens positioning previously specified. For example, Figure 4 shows measurements of the position accuracy for a MEMS and VCM actuator. This data was taken using a laser metrology system of the lens position (y-axis from 0 to 350 microns) vs. the code given to a 10 bit current mode digital to analog converter (x-axis from 0 to 1024 corresponding to 0 to 100 mA). The plot on the left shows the data for the MEMS actuator, whereas the plot on the right shows the data for a VCM from a cell phone. The VCM has considerable hysteresis. As a result of the improved positioning accuracy, MEMS provides improved imaging quality. In addition, MEMS has advantages in size and environmental robustness, as a result of the machining precision of silicon micromachining and the strength of silicon.

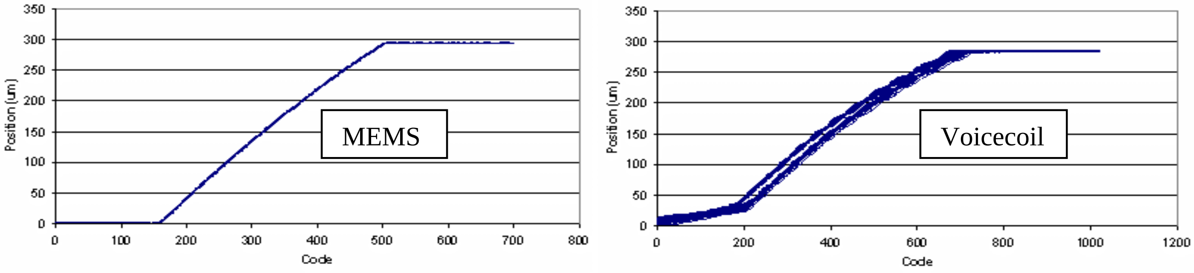

Figure 4. Plot comparing positioning accuracy along optical axis for MEMS (left) and voicecoil (right) AF actuators.

Many solutions have been implemented using piezoelectric actuation. For example piezoelectric actuators from Limited 1 and New Scale Technologies are shown in Figure 5. The Limited 1 actuator is unique in that it achieves mechanical motion amplification by making a coil of piezoelectric material. The Squiggle motor from New Scale Technologies uses piezo actuators to turn a screw and achieve large motion through thousands of small steps. The main disadvantage of piezoelectric actuators is that they require position sensing due to their large hysteresis and poor positioning repeatability. The position sensor requirement combined with the limited strength of piezo materials translate into disadvantages in size and environmental robustness.

Figure 5. Piezoelectric AF actuators from Limited 1 (left) and New Scale Technologies (right).

Artificial Muscle uses electropolymers for AF actuation. Although electropolymers have the advantage of large actuation energy density, their dependence on water in the polymer raises significant problems in environmental robustness. In addition, the electropolymers would have the same limitations as piezoelectric materials in terms of hysteresis, poor motion control, and environmental robustness.

4. AF USING MODIFICATION OF AN OPTICAL ELEMENT

When modifying the optical properties of an optical element to adjust focus, it is important that the optical element does not introduce additional aberrations and does not absorb any light. The optical aberrations are carefully controlled in the design of an imaging lens system by using aspheric surfaces and selecting materials with specific values of index and Abbe numbers (optical dispersion). Liquid lens from Varioptic is the most published approach [3] that uses the modification of the optical properties of a lens to achieve focus control. A liquid lens varies the radius of curvature of the surface joining two liquids with different index of refraction to change optical properties. Because the optical surface created by these two liquids is spherical (as opposed to aspheric), this technology has significant limitations in terms of optical performance. Figure 6 shows a photograph of the liquid lens from Varioptic and a camera using the liquid lens for AF.

Figure 6. Photograph of a camera (left) using liquid lens from Varioptic (right).

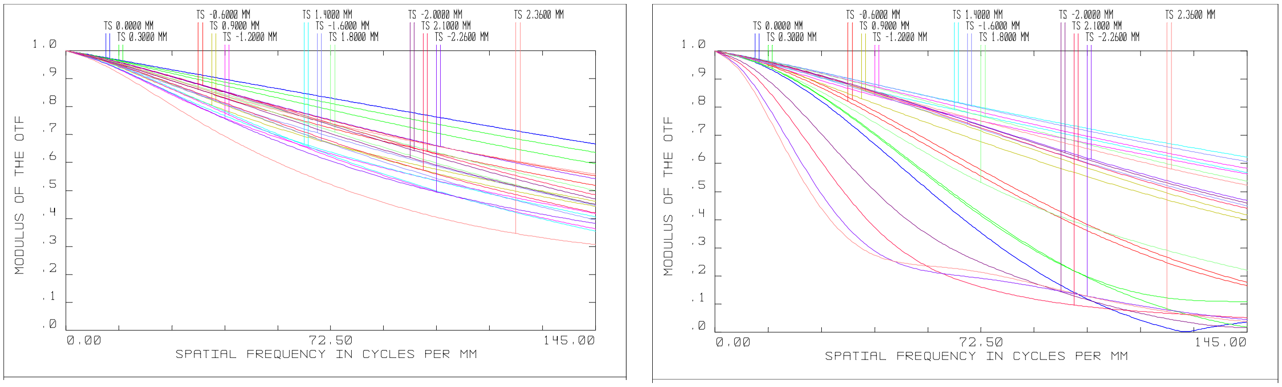

Figure 7. Optical performance comparison between an AF based on moving a lens barrel (left) and liquid lens (right) for F# 2.5. The horizontal axis is the spatial frequency on the imager surface, and the vertical axis is the modulus of the optical transfer function (MTF). Plots show modeling results at 10 cm focus.

In order to quantify the effect that liquid lens has on the image quality, we modeled the MTF of an imaging system with F# 2.5 when focusing on an object at 10 cm both using a liquid lens and moving the lens barrel. This is shown in Figure 7. In the plots, the vertical axis is the modulus of the optical transfer function (from 0 to 1) and the horizontal axis is the spatial resolution on the horizontal axis (from 0 to 145 cycles/mm). The graph on the left is for moving a lens barrel, while the graph on the right is for liquid lens. Whereas a properly aligned lens barrel has > 30% MTF at 145 cycles/mm, a liquid lens has some portions of the image with < 30% MTF at about 30 cycles/mm. This modeling was done assuming a perfect alignment of the liquid lens, so additional issues are possible if the optical axis of the liquid lens and/or barrel is not aligned with the rest of the imaging system. In addition to the reduced resolution, additional disadvantages of the liquid lens are increased thickness of the camera, and reliability that depends on proper sealing, separation, and stability of two fluids.

5. EXTENDED DEPTH OF FIELD

Finally, there is also a separate group of technologies being applied to achieve extended depth of field in order to eliminate the need for AF in cell phone cameras. Although these approaches may eliminate the need for AF, they do so at the expense of image realism, as the human brain is not used to seeing objects at different distances all in focus.

The standard approach to increase the depth of field is to reduce the entrance pupil diameter by placing a spatial filter that only allows light in the center of the lens to pass through the optical system. This increases the F# of the lens and, as a result, increases the depth of focus. A camera using this approach is often referred to as a “pinhole” camera. The advantages of this approach are that the lens becomes very simple to design and manufacture, and that objects from 10 cm to infinity can be at the same focus position of the lens. The disadvantages are lower resolution and bad low light performance.

A new approach to increase the depth of field is to reduce the effective entrance pupil diameter by placing a spatial filter that only allows light in the center of the lens to pass through the optical system without phase disruption. Since light from the entire aperture falls on the imager, image processing is used to reconstruct the image using knowledge of the phase disruption at the entrance pupil plane. This approach is also known as computational AF. Although this approach does not directly increase the F# of the lens, it effectively increases the F# of the imaging system (after image reconstruction) and, as a result, increases the depth of focus. The advantages of this approach are that the lens becomes very simple to design and manufacture, and that objects from 10 cm to infinity can be at the same focus position of the lens. Compared to the "pinhole" camera, this approach has the advantage that the amount of light falling on the imager is increased, and this can be used for the low frequency components of the image. The disadvantages are lower resolution, bad low light performance, increased image processing requirements, additional optical element, and higher power consumption.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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