Image Acquisition Module With All Plastic Optics

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Abstract

The quality requirements of lenses used in digital camera image acquisition are very stringent due to the enlargement required from the small image on the sensor to ultimately a hard copy of the image. CCD sensors capture color information more accurately if the light striking the sensor is close to perpendicular or the lens design is nearly telecentric. To meet optical quality requirements, glass optics are typically utilized in digital cameras. Plastic optics are more cost effective at higher camera volumes and have design flexibility with aspherical surfaces to reduce the number of lens elements required. Lens/shutter/sensor modules utilized in digital cameras sometimes use several actuators that can add cost and package volume to the module. This paper describes the patent pending technology that Polaroid Corporation employs in an image acquisition module for digital cameras that utilize a plastic lens design with a single actuator system resulting in a very compact module suitable for high volume manufacturing. The technology described is applied to a fixed focal length lens system, but can also be extended to modules with zoom lenses.

Introduction and General Requirements

The resolution of CCD sensors employed in digital cameras, the number of cameras in use and the variety of compact digital camera configurations available are all increasing with time. Requirements for Image Acquisition Modules that are consistent with these trends are high quality, suitability for high volume low cost manufacturing and compact size. Although this paper directly refers to a CCD based system, the Image Acquisition Module that will be described is designed to work with an 8.5 mm diagonal sensor that uses CCD, CMOS, or other technology.

1. Quality Requirements

Typically, digital sensors are in the order of 1/4 the size of 35mm film or smaller. Since images will be substantially enlarged for hard copy or screen display, the quality requirement of the optical system is much higher than for typical camera optics. The specific optical requirements will be described in the next section, including telecentricity requirements for more faithful color reproduction. Glass optics can typically produce the level of quality required and sometimes have aspherical surfaces, but as digital cameras become more popular and camera volumes increase, there is an increasing need for cost effective plastic lens systems that meet the quality requirements. Plastic lens systems can be molded with many aspherical surfaces that give the lens designer additional flexibility to meet quality goals and maintain low cost.

The Image Acquisition Module has a requirement for a mechanical shutter to terminate exposure and light seal the system while the image data is transferred. Since silicon area is not required to store pixel data, the mechanical shutter capability allows the use of CCDs with increased light sensitivity. Increased sensitivity improves photographic performance due to lower noise. Since the shutter passes between lens elements, an additional challenge in the lens housing and the optical design is to provide precision mounting for the lens elements as well as space for the shutter.

Another quality requirement is the ability to use two F-numbers with the module. This allows for optimized aperture and exposure programs at different light levels and subject distances. The requirement for a close up lens in the optical path allows the module to capture images with high quality from 2 feet to infinity. A typical requirement for acquisition modules is to have an anti-aliasing and visible pass filter in the light path.

The CCD package has a dust sealing requirement, so after the module is assembled in a clean room, environmental dust will not settle on the glass covering the CCD. This is particularly important at higher F-numbers where a dust particle must be small relative to the light "spot" on the CCD cover glass. The CCD must be adjusted to align with the image produced by the optics. To provide sufficient quality of this alignment, both axial and tilt adjustment about two orthogonal axes are required.

Finally, quality requirements must be maintained not only during manufacture but over environmental conditions, including temperature, humidity, shock, and vibration.

2. High Volume Manufacturing Requirements

Requirements for high volume low cost manufacturing are ease of assembly and use of all tooled vs. fabricated parts with a minimum number of parts and adjustments. Injection molded lenses can have mounting features in addition to the optical surfaces. These mounting features can allow the lenses to drop into an injection molded housing, creating an optical assembly with straightforward lens retention methods. To achieve system quality, a mechanical shutter, F-number selection and close up lens insertion is required. A requirement for high volume manufacturing is to accomplish these functions with a single actuator. The CCD position adjustment must be implemented in a 1-2-3 sequence, without having to re-adjust.

3. Compact Size Requirement

Digital cameras are becoming more compact and arranged in creative configurations, even as additional features such as memory cards are being added. A more compact Image Acquisition Module will play a role in achieving this goal, allowing space allocation for other components. Fewer number(s) of parts and actuators reduces module size. With the use of plastic aspherical elements, the lens designer has degrees of freedom to reduce the number of lenses required, resulting in a more compact lens design.

Optical Requirements

Optical requirements for a consumer product are always difficult to specify. Requirements should be set to meet or exceed customer expectations; but if they are set too high, the product becomes unnecessarily expensive. For a digital product, the first decision is what will be the primary output of the device. Many images will be viewed on a monitor directly or sent to a friend to view over the Web. Other images will be printed on devices with extremely high image quality at large magnifications or included in letters with modest image quality and smaller magnifications. The basis used for determination of the Modulation Transfer Function (MTF) of the imaging system was that the system output would be a print approximately 4" by 6". Since output devices using inks and papers can be characterized and optimized for "Photographic Quality", the assumption was that in the low frequency range (under 5c/mm on the print) the MTF of the printing step would be loss less or provide an MTF of 100%. This is possible because clipping the higher frequency harmonics effectively increases edge contrast, which would enhance the lower frequencies. The low frequency response has been shown to be important in consumer imaging systems by the work of Granger and Cupery[1] in the development of Subject Image Quality (SQF), which is essentially the normalized integral of the system log MTF curve between 1/2 and 2 cycles per mm on the print. At the sensor, this frequency range is scaled by the magnification of the print approximately 20 times. Thus the decision was made to evaluate, specify and tolerance the optical system at 40 cycles per mm.

Polaroid has also developed a unique additive color reproduction filter system using stripes rather than a two-dimensional filter pattern. This effectively eliminates the need for an anti-aliasing filter in the direction along a color stripe providing a more cost effective lens/filter system and a cost-effective sensor. The color reproduction quality of this approach has been verified in the award winning Polaroid PDC-2000/3000 cameras. The direction orthogonal to the color stripes still requires an anti-aliasing filter to eliminate high frequency input above the Nyquist frequency. Since all filters applied to silicon based sensors are separated by a small but important distance from the photosensitive region, rays entering from extreme angles can pass through the neighboring filter and expose the wrong color pixel. One solution is to constrain the chief ray entry angle to the sensor to be "near" perpendicular. This places a constraint on our optical design and increases the size of the optical system. In the system described, the optimum angle was determined to be 8 degrees from telecentricity orthogonal to the color stripes or approximately 10 degrees from telecentricity at the tip corner.

Finally, the system specification for the module must account for manufacturing variations and environmental effects. During the design, particular attention was paid to desensitizing the design for expected manufacturing variations. The final design does require state of the art molding practices to achieve a consistently high quality imaging system. Environmental effects are also included in the analysis over the expected range of temperature and humidity changes during normal operations. The design is balanced, having negative and positive elements of materials with divergent thermal and hydrophilic properties. These, along with the mount design, tend to reduce focus variations to an acceptable level and maintain overall image quality. All of these factors were included in the overall system modeling to achieve an image quality which would be acceptable for a consumer digital camera system.

Lens Design

1. The Starting Point

It is usually assumed that for a given lens requirement, the manufacturing cost varies directly with the number of lens elements. Accordingly, lens designs progress from singlet to doublet, and then to the classical triplet. But the classical triplet is not easy to manufacture, even with the addition of aspherical surfaces. The basic design form has just enough surfaces and air-spaces to obtain a reasonable aberration correction, but any attempt to reduce manufacturing sensitivity also reduces performance. If the lens design is then restricted to plastic elements, the effects of the low index of refraction, and poor match of index between the positive and negative elements further exacerbates the manufacturing tolerance problem.

The design approach we selected was to assume that all surfaces could be aspherical if necessary, and use the extra aspherical surfaces to reduce manufacturing sensitivity. To do this it is first necessary to select the correct Gaussian optics configuration. The classical triplet has its aperture stop near the center of the lens, and obtains all of the correction for spherical aberration, axial color, and field curvature from the single negative element at the center. This overworked lens element is the source of the sensitivity problem, so we needed to provide another lens element for at least some of the aberration correction. The inverse triplet, Figure 1, has a leading negative element followed by a positive element, followed by another negative element. In addition the stop is placed near the front of the lens, ideal for our requirement. The plan was to use the aspherical surfaces to correct the positive and negative elements individually for the aberrations that cause trouble if a lens is not fabricated perfectly. The chromatic aberration, field curvature, and the camera constraints would be handled by the correct choice of optical powers. The assumption was that there had to be many combinations of aspherical surfaces to satisfy the basic requirement, and so at least some of those combinations would also correct for distortion and astigmatism.

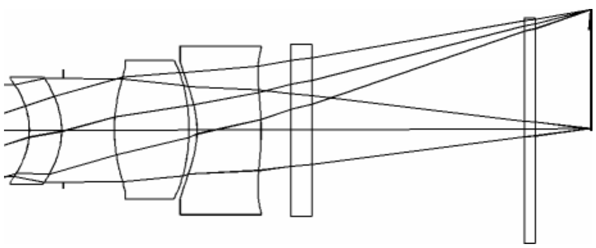


Figure 1.

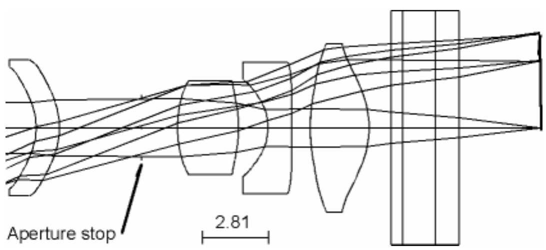


Figure 2.

2. Modifications for the Camera Requirements

It turns out that the inverse triplet satisfies all of the imaging requirements. It outperforms an ordinary triplet and is much easier to manufacture, but it does not have the extended exit pupil position required by the image sensor. By adding a simple positive element in the space near the sensor, the exit pupil requirement is satisfied; but the additional requirements for filters in the image space forced that element to be near the negative element. The design at this stage began to look somewhat like the final design shown in Figure 2. The MTF performance for the early version of the design was very high, but the manufacturing tolerances were much too difficult for today's technology. We were ready to test the assumption that by using more aspherical surfaces than necessary to correct aberrations, we would be able to reduce manufacturing sensitivity.

3. Desensitization

By treating various manufacturing deviations, and groups of deviations, as individual zoom positions, the lens was simultaneously optimized over what we defined as the manufacturing space. This space is delimited by the tolerance deviation that can be achieved according to a particular mechanical design and the associated process-engineering requirement. Of course, the limits of the space—the region of insensitivity—can be increased to further reduce manufacturing cost, but the first requirement is to be certain that there are no tolerances beyond the manufacturing capability.

We started with a set thickness, tilt and decentration tolerances, and optimized the performance over that space. The resulting performance is assessed using the through-focus MTF. This calculation determines the depth and shape of the image surface for a particular spatial frequency (40 cycles/mm) at a defined threshold value. The calculation is particularly useful because the optical sensitivities are indicated as a mechanical dimension, the longitudinal depth-of-focus. By calculating for an entire image diagonal, the image tilt angle is determined separately. Those effects are removed from the tolerance budget because the sensor must be adjusted for both position and tilt during assembly. Although the lens design is optimized over the defined manufacturing space, the actual tolerances must be determined and assessed at each stage of the design. By changing the selection of the mounting surface for a particular lens element, not only would all of the tolerances change, but the entire lens design would change as well. While this procedure is time consuming, any progress achieved in the design process will lead to a more manufacturable lens.

4. Desensitization: Results

After several repetitions of the process outlined above we were able to achieve manufacturability—not one tolerance would be beyond the manufacturing capability and the combination of tolerances would be sufficient such that the final manufacturing cost would be within the target value. Analysis of the surface contributions of the aberrations confirms that we were able to balance and minimize the aberrations in each lens element so that those aberrations that change over the entire aperture of the lens element would not provide correction for aberrations from a different element.[2] The final MTF data for the plane of best focus are shown in Figure 3.

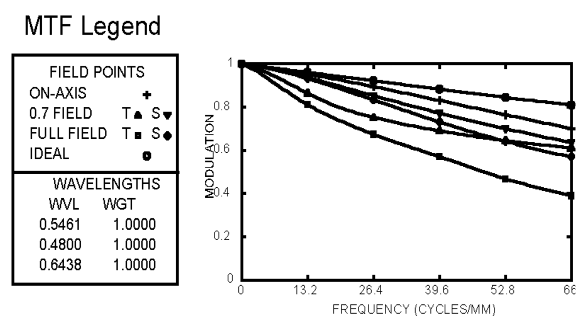


Figure 3.

Some samples of through-focus MTF data for various tolerance deviations are shown in Figure 4. Please note these have a reduced field angle more appropriate for system tolerancing.

5. Choice of Materials

A frequently expressed concern about plastic optics is that because there are few materials available, perhaps three, there would be a limited number of optical designs that would perform satisfactorily. Without the use of aspherical surfaces, that may be true, but with aspherical surfaces, chromatic aberration is not a problem. The plot of focal shift vs wavelength, shown in Figure 5, is based on the catalog values of the plastics as computed by OSLO. Those data provided to OSLO were probably the result of various measurements and may not be very accurate. However, based on those values, the color correction is quite adequate.

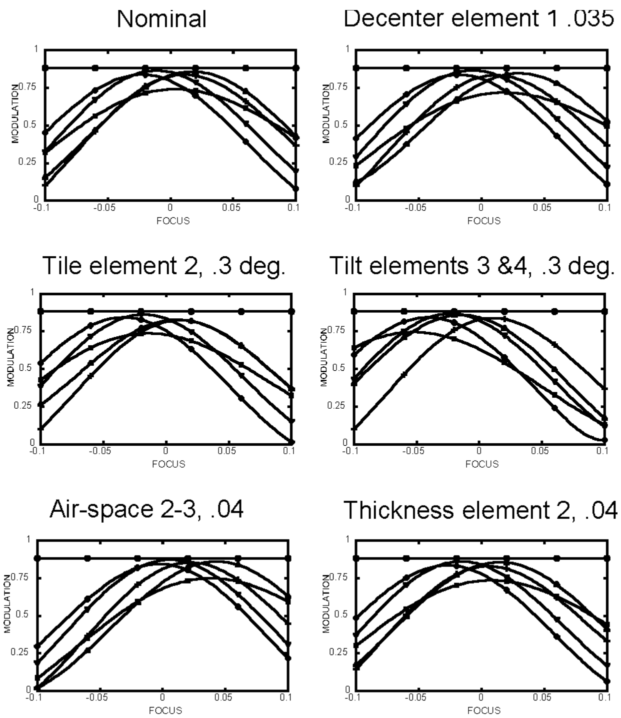


Figure 4.

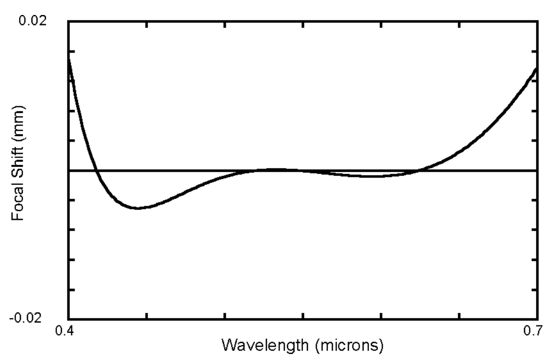


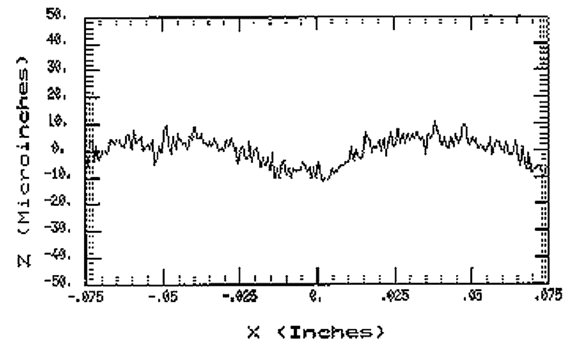
Figure 5.

Lens Manufacturing Considerations

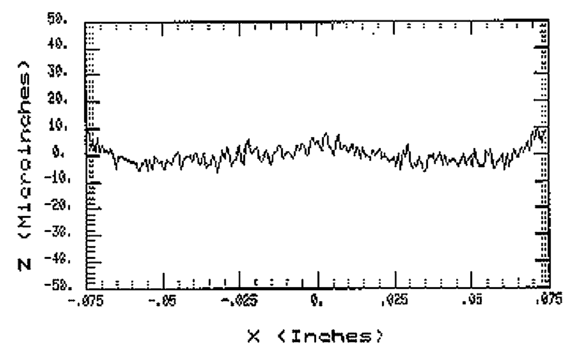
The process involved with the design of the lens system was iterative between optical design, mechanical design and manufacturing. At the onset of the design process, all disciplines were constrained by the ultimate performance requirements and maximum volume requirements of the module.

The design process required multiple iterations and numerous tolerance analyses until all requirements were achieved. The resultant design was a four element plastic lens system with all surfaces being aspherical. This design took advantage of the added degrees of freedom for a design utilizing aspherical surfaces and of Polaroid's manufacturing capabilities to manufacture and measure precision aspherical surfaces.

The resultant design, which was agreed to by manufacturing, had requirements which stretched manufacturing's typical capabilities. To achieve both the optical and mechanical requirements of the lens assembly, new manufacturing methods needed to be developed to produce the ultimate system performance characteristics.



(a)



(b)

Figure 6. Profilometer measurement of (a) steel asphere surface and (b) plastic molded asphere surface. The steel and plastic measurements are expected to be and are mirror images of each other.

As indicated previously, the precision requirements for high resolution digital photographic systems is much greater than those required for conventional photographic systems. The specific requirements which demanded improvement above our "standard" manufacturing techniques were improvements with respect to optical centration which included surface-to-surface within a lens and lens to lens throughout the assembly. A number of techniques were developed to provide for centration requirements of the optical design. With respect to surfaces within a lens, a proprietary cavity set interlock design was developed to hold tolerances to within 0.0002". To maintain the design centration and air spaces between individual elements, several techniques were developed to meet the 0.001" requirements. Integral flange designs with interlocking features were generated with precision diamond machining techniques in conjunction with placement of features on one side of the mold to negate any cross parting line variations. The most critical elements were designed with these interlocking features.

In addition to the increased mechanical precision developed for the lens' flanges, there was a requirement to control the lens housing to mechanical dimensions for lens placement of less than 0.0005". A special machining technique was developed to control housing dimensions to within 0.0001".

With respect to aspherical optical surface replication, new diamond turning techniques in conjunction with advanced process technology techniques produced optical surfaces that met the design requirements. The ability to assess the optical replication, confirmed by a Polaroid designed and built profilometry measurement equipment with accuracies to 2 to 3 millionths of an inch RMS, indicated that the lens surfaces met all design requirements. See Figure 6 for molding replication. The molding process for lens elements was determined by varying different process parameters and finding the process that resulted in the best surfaces. Once molded, the lenses were coated with $MgFl_2$ on both surfaces.

Photographic System Tradeoffs

The Image Acquisition Module has the functionality of selecting from two F-numbers, introducing a close up lens and mechanical shutter capability. An aperture disk driven by a single stepper motor implements all of these functions.

1. F-Number Selection

The f/4 lens in the Image Acquisition Module is fast enough to achieve a desirable strobe range indoors and capture sufficient ambient light in low level outdoor scenes to produce a natural appearing image with a shutter speed that eliminates camera motion. The gain of the sensor can be increased in lieu of a low F-number lens, but sensor noise increases and image quality is compromised. Having high F-number capability in addition to the f/4 aperture improves depth of field in photographic situations where additional light is not needed. The scenes that will benefit the most are high light level ambient pictures and close in strobe pictures. Diffraction limits the value of the high F-number, which for the Image Acquisition Module is f/11. The F-number selection is implemented by utilizing an aperture disk, shown in Figure 7. In the Figure, the layout of the module is shown, including the lens housing, lenses, stepper motor, and aperture disk. The aperture disk is driven by a stepper motor that rotates the disk to the appropriate aperture, either f/4 or f/11.

2. Close-up Lens

The minimum focus distance for the Image Acquisition Module is 2 feet. This requires a close up lens to produce the desired sharpness at an f/4 aperture. The close up lens is implemented by securing a weak focusing element to the aperture disk, shown in Figure 7. The stepper motor aperture disk has a position where the close up lens is aligned with the fixed f/4 aperture.

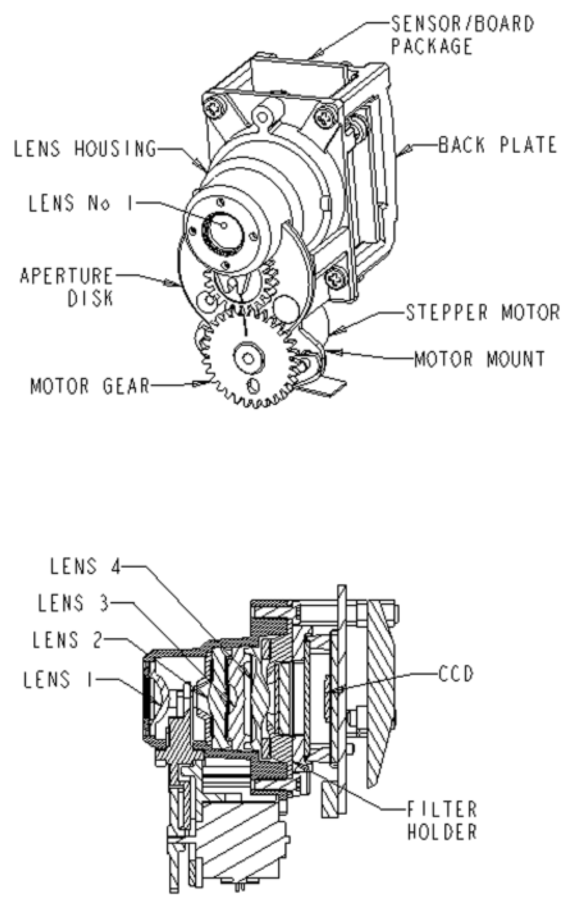


Figure 7.

3. Mechanical Shutter

The mechanical shutter in the Image Acquisition Module is implemented as follows. Since CCDs have capability of electronic exposure initiation, the shutter needs only to terminate exposure and light seal during transfer of the data between pixels. The stepper motor on command rotates the aperture disk to the space between apertures to light seal the aperture disk and terminate the exposure. The closing time of the shutter is in the order of 2 ms, which is sufficiently fast to ensure exposure precision, even at the brightest light levels. The stepper motor is controlled by electronic damping drive circuitry that provides dynamic stability to the aperture disk system.

Currently, the aperture disk utilizes two F-numbers and a close up lens for a total of 3 open positions. Testing has shown that this system has the capability to add an additional aperture or lens without increasing package size.

Module Packaging

The Image Acquisition Module packaging is composed of three subassemblies: the lens/housing, aperture disk and the CCD mounting/adjust system.

1. Lens/Housing Subassembly

The lens mounting design is shown in Figure 7. High precision is required to maintain the relative position of the optical elements. Element decenter and tilt must be minimized and axial position maintained. From Figure 7, both Lens 1 and Lens 2 are located on datum surfaces and internal diameters. The location of Lens 1 to Lens 2 is controlled by the molding precision of the lens housing. Lens 3 locates on a ring feature molded on lens 2 that defines Lens 3's plane. Its centration is controlled by the lens housing diameter. Lens 3 and 4 require the most relative precision, and for that reason, they are keyed together by molded ring features to maintain concentricity and planarity. Lens 1 is secured to the housing by a conventional adhesive approach. Lens 2, 3 and 4, plus several limiting apertures, including the fixed f/4 aperture, are mechanically secured in the lens housing by the filter holder and a compliant washer.

2. Aperture Disk Subassembly

The aperture disk drops in pivot saddles molded on the lens housing. The stepper motor mounts to the motor mount, which in turn traps the aperture disk in its pivots. The entire subassembly is secured by the motor mount screws. An assembly procedure ensures the alignment of the apertures in the aperture disk with the fixed aperture.

3. CCD Mounting/Adjust System Subassembly

The CCD mounting/adjust system must ensure that the cover glass above the CCD remains free of dust and the CCD is aligned with the image created by the lens. This is accomplished by utilizing a compliant material that both seals the CCD package to the filter holder and loads the CCD board against the three adjustment screws. The screws are arranged in an orthogonal pattern that will allow the corners of the image to be adjusted in a 1-2-3 sequence without readjustment. Different sections of the image, other than where the screws are located, can be altered by simple lever calculations applied to the rotation of the adjustment screws.

The design is suitable for high volume manufacturing, using injection molded plastic parts, a minimum number of mechanical parts including screws, a minimum number of lens elements, straightforward lens retention methods with lens mounting features molded in the lens elements, and a single actuator. These factors also contribute to the small package size of the Image Acquisition Module which is 20x30x40 mm.

Conclusions

It has been shown that high quality digital camera images are created by a four element plastic lens and lens housing system. The lens design results in faithful color reproduction due to a nearly telecentric design. It has been shown that the use of aspherical lens element surfaces has resulted in a manufacturable optical design that meets quality and packaging requirements. Manufacturing technology has been developed to injection mold the lens and lens housing to very high precision. An aperture disk driven by a single stepper motor accomplishes F-number selection, close up lens insertion, and a mechanical shutter function. The sensor adjustment allows for axial and two tilt adjustment. The packaging of the module is compact and suitable for cost effective high volume production. Due to the combined effort of design and manufacturing, we believe the technology of precision plastic molding of lenses and components for small format imaging has been advanced.

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