# Focus Control Using Flexible Lens

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## Abstract

Traditional focusing system usually uses multi-lenses by moving two concentric lenses towards or away from each other. However, the small and compact implementation using multiple-lenses is difficult to achieve since a certain distance between two- lenses is required for different focal length. To overcome this problem, in this paper, a new focusing system based on flexible lens is introduced. The flexible lens is made from natural rubber membrane and water, which is used as the optical medium. In the proposed system, focusing is achieved by the change of volume of water inside the lens. A passive control algorithm for auto-focusing has been employed using LabVIEW, a graphical programming language. The experiments show that the proposed flexible lens is capable of projecting colored images onto the CCD sensor for objects lying at a distance of 100 mm to 7000 mm from the camera.

## 1. Introduction

Focusing using multiple lenses has long been used extensively in many engineering applications such as cameras, microscopes and telescopes. Focusing by multiple lenses is achieved by moving two concentric lenses towards and away from each other. As a result, a certain distance is required for different focal lengths. Therefore, small and compact implementation of multiple lenses is hard to achieve. On the other hand, focusing using flexible lens only requires change of curvature of the lens and thus occupies less space. A flexible lens with focus control capability is a demand of today’s technology. These lenses could be used in micro cameras, medical and surgical devices, and military surveillance devices.

It is a well-known fact, that focus of a lens changes with the change in curvature of the lens surfaces. But to date, there are very few works available using this principle in controlling focuses of lenses. In 2002 Jassim and Al-Jumaily [1] have attempted to use piezoelectric material with optical transparency to produce flexible lenses. But lack of sufficient transparency of piezoelectric materials has hindered the progress to go further. Hendriks et. al [2] of Philips came out with a liquid lens at the beginning of this year (2005) which is the only example of dynamic flexible lens system that uses this basic principle. It is made of two liquids of identical densities with different index of refraction. Both the fluids are contained in a transparent plastic container and actuated by charges of electricity. Electro-wetting is the underlying technology in realizing Philips liquid lens.

As it seems, very little work have been done on flexible lens. This paper presents a result of research work is carried out with the objective of developing a fluid-actuated flexible-membrane optical lens, which is capable of projecting clear images of objects lying at varying distances onto the CCD of a digital camera. The system is controlled using a software and algorithm, which enables it to focus on images interactively with the help of the user. In the proposed system, findings of the focal length obtained in the actual experiments and the focal length obtained from the approximate mathematical model of the lens are presented.

## 2. Hardware development

### 2.1 Lens construction

The proposed flexible lens is shown in Fig. 1. As shown in Fig. 1, the proposed lens is made of an opaque PVC tube sandwiched between rigid transparent acrylic plate at the bottom and a transparent flexible membrane at the top. The PVC tube is 22 mm in diameter and 5 mm in height. A hole made in the PVC tube allows fluid to be pumped in and out of the lens using a small syringe pump. The chosen diameter was good enough to minimize the gravity effect of the fluid upon the flexible membrane. Water is used as the optical medium. Fig. 2 shows the flexible membrane of the lens in its outward deflected shape to form a plano-convex lens. As the fluid is withdrawn from the lens the membrane becomes flat (Fig. 2).

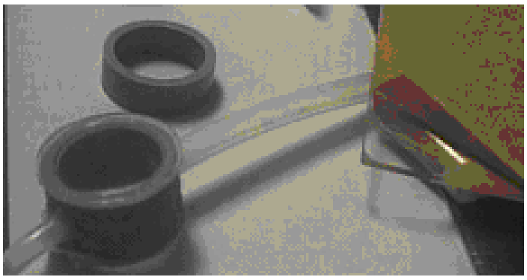


Fig. 1: Picture of the flexible lens and its main components.

Fig. 2: Flexible lens during full and medium inflation

### 2.2 Actuation mechanism

The mechanism used to pump fluid in and out of the flexible lens is simply made of a power drive mechanism connected to a 3 ml syringe. The syringe is filled with water which has refractive index of 1.333. A stepper motor is used to actuate the power drive mechanism to an accuracy of 0.25 mm increment. A total linear displacement of 15 mm of the syringe was required to fully inflate the flexible lens which corresponds to a 1500 mm$^3$. Fig. 3 shows the actual experimental setup of the actuation mechanism.

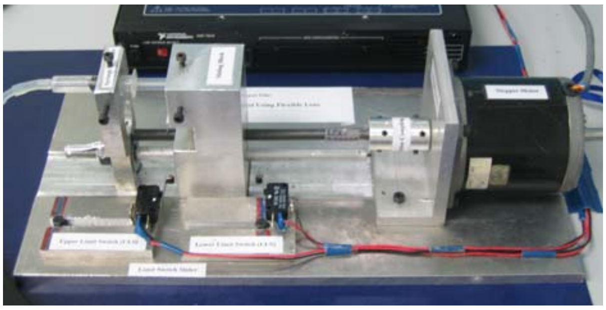


Fig. 3: Actuation mechanism of the syringe.

## 3. Lens mathematical modeling

An idealized mathematical model was developed for the flexible lens. Few assumptions where made in developing the mathematical model. First, the flexible lens is thin and second the flexible lens inflates spherically. Fig. 4 shows the schematic diagram from which the mathematical model of the flexible lens was derived. The shaded part of the diagram is what represents the lens volume, while the rest is just for derivation purposes. The relationship that is developed relates the amount of volume of fluid inside the lens with the value of focal length of the flexible lens is as follows:

$$V_L(f)=\frac{2\pi}{3}\left(f(n-1)\right)^3\left[1-\frac{\sqrt{\left(f(n-1)\right)^2-r^2}}{f(n-1)}\right]-\frac{\pi}{3}r^2\sqrt{\left(f(n-1)\right)^2-r^2} \quad (1)$$

where VL, R, n and f represent liquid volume inside the lens, radius of the sphere at any instant, lens base radius, refraction index and focal lens respectively.

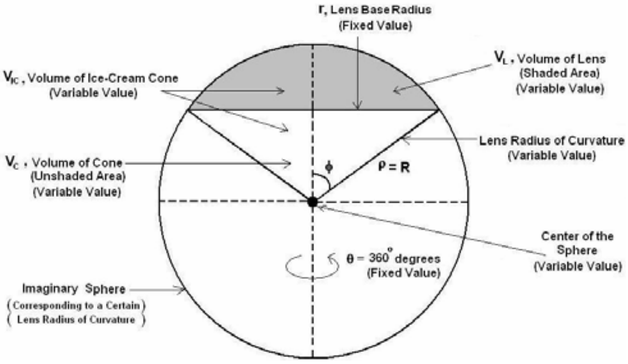


Fig. 4: The idealized model of the flexible lens.

## 4. Autofocusing system development

### 4.1 System software

The software used in running the system was developed using the Graphical Programming Language LabVIEW. Both motion control for the actuation mechanism and vision algorithm for autofocusing were developed in an integrated way in LabVIEW environment. As shown in Fig. 5, a user friendly interface displays all the important parameters such as focal length, amount of fluid inside the lens, images captured, input tools, and some support information for debugging.

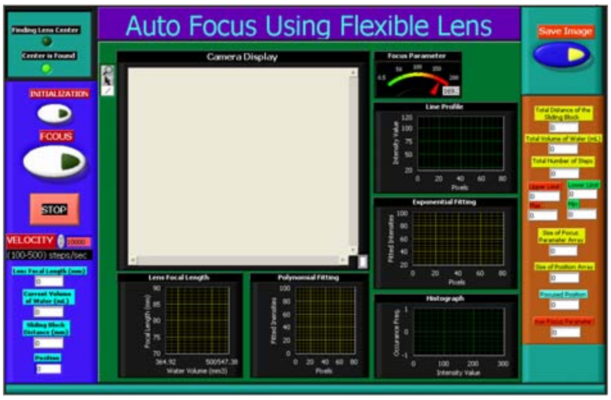


Fig. 5: User interface for the flexible lens system.

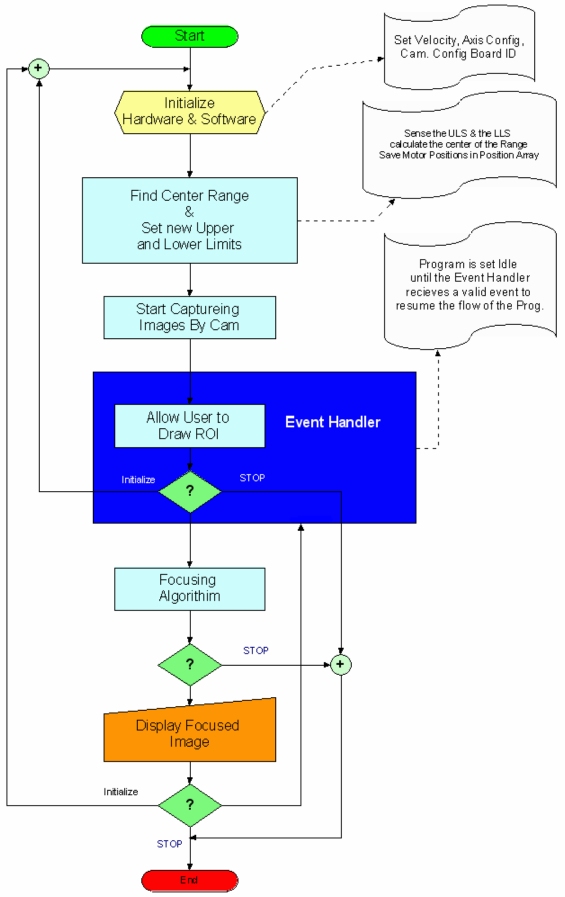


Fig. 6: Flow-chart of autofocusing process

The flexible lens attached to a camera CCD sends the captured images to a computer program. The program requires a user input in the form of a line of pixels along an edge on the image. After the input is completed the software starts an automated procedure to evaluate different images captured through the flexible lens at different inflation rates. The flowchart of the developed software is shown in Fig. 6.

### 4.2 Focusing algorithm

The autofocusing method used in this system is passive in nature. Passive autofocusing is a method which relies only on the captured images for information. Fig. 7 shows the algorithm used for focusing. the Image processing is used to extract information from the captured images. In this system the autofocusing is achieved by analyzing the contrast of one edge in the captured image. The user is instructed to draw a line of pixels along an edge in the image. Thereafter the corresponding values of pixels are stored in a database.

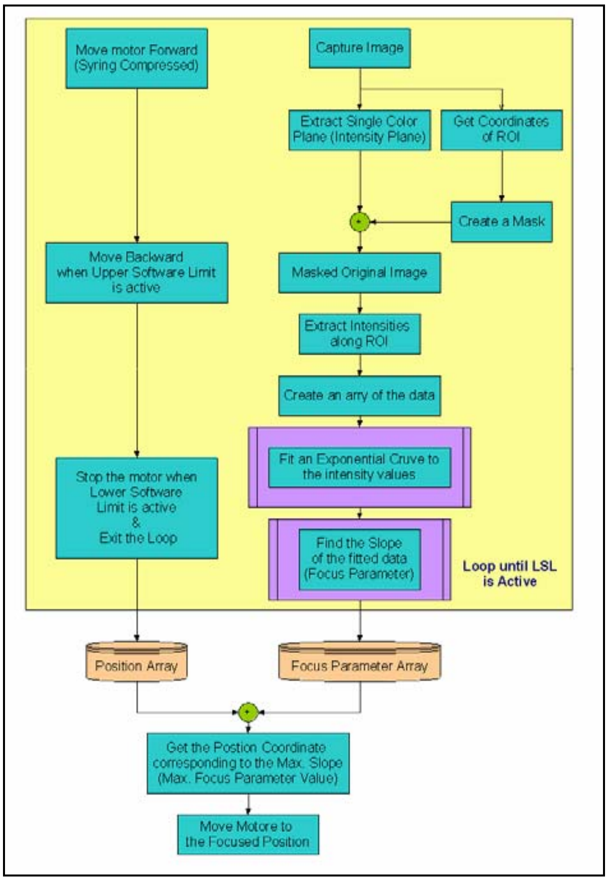
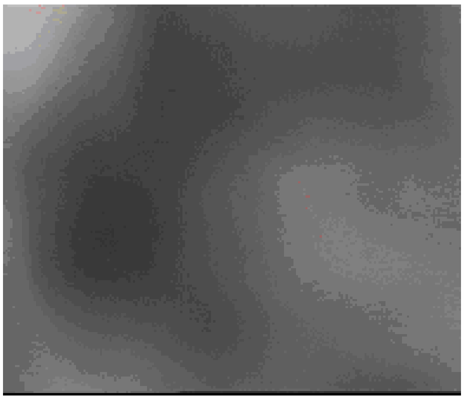


Fig. 7: Flowchart of focusing algorithm

As the lens inflates and deflates in an attempt to capture the most focused image, all the pixels of the corresponding line are recorded in the database. The line profile of the pixels is analyzed for each single image captured. A line profile that has a steep transition (vertical slope) in its pixel values from one color to another would indicate a sharp edge. On the contrary, a line profile with a low transition rate (shallow slope) would indicate an unfocused image [3]. The slope of the line profile is used as the parameter of focusing. All the values of the parameter of focusing are stored in the database. The focusing parameters for all the pictures are retrieved later on for comparison. The higher the value of the focusing parameter the steeper the line profile slope is and vice versa. Each focusing parameter value corresponds to a specific curvature profile of the flexible lens and each curvature profile corresponds to a specific volume of water inside the lens and eventually the focusing parameter is directly lined to the exact position of the syringe mechanism. Hence, once the optimum focusing parameter is obtained the software would instruct the motor to drive the syringe mechanism to the position where the focusing parameter was recorded in the first place.

## 5. Results and discussion

A series of experiments was conducted in order to establish correlation between the measured focal length of the flexible lens and the theoretical results obtained from the mathematical model. The capability of the flexible lens system on focusing images is shown in Fig. 8. Fig. 8(a) shows image of unfocused lens while Fig. 8(b) depicts that of focused lens.



(a) Before focusing

(b) Focusing result

Fig. 8: Illustration of image focusing: (a) image before focusing; (b) image after focusing.

The mathematical model of the flexible lens serves as a reference for the measurements obtained from the experiments. Fig. 9 shows focal length versus volumetric displacement plotted from the solution of the mathematical model. The plot shows the non-linear relationship between the amount of fluid volume in the lens and the focal length. This non-linear relationship will eventually limit the accuracy of the flexible lens in focusing images. In the range of the maximum focal length of the lens, which lies between 50 mm and 70 mm, the rate of change of focal length is very sensitive to the change of fluid volume. This level of sensitivity poses difficulty in acquiring good image. A change of 250 mm$^3$ of fluid volume makes a change of 20 mm in the focal length. On the contrary, in the range of the minimum focal length, which lies between 30 mm and 50 mm, a change of 1250 mm$^3$ of fluid volume makes a change of 20 mm in the focal length. Therefore the effect of the volume variation on the focal length is relatively low within the minimum range of focal length compared to the effect of the volume variation on the focal length within the maximum range of focal length. As a result, capturing images of objects that require short focal lengths are more accurate and precise than images taken of objects that require long focal lengths. Furthermore, in the case of short focal lengths there is more tolerance for errors in the volume transferred (in and out of the lens) compared to that of long focal lengths, where the tolerance is low to the extent that images can be distorted even for the least error in volume transfer.

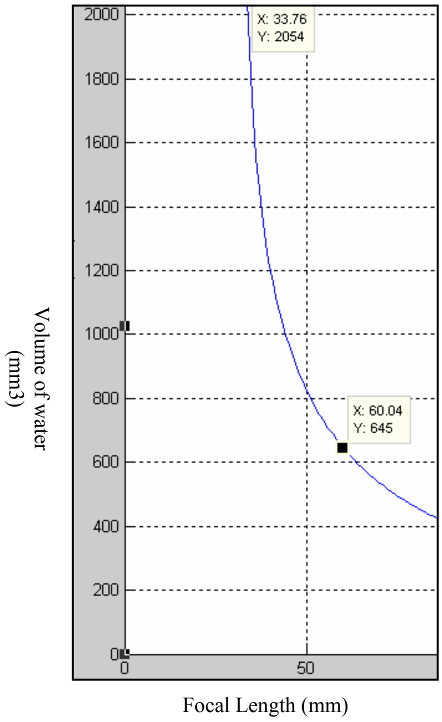


Fig. 9: Theoretical graph of volume of water vs. focal length.

Table 1 shows the comparison of results of theoretical and experimental focal lengths for images taken at different distances from the lens. The percentage of error between the theoretical and the experimental focal lengths is shown in the last column. In addition, Fig. 10 shows the trend of both the theoretical and experimental focal lengths. Comparison shows for shorter focal lengths the error is relatively low compared to that of the longer focal lengths.

Table 1. Comparison of theoretical and experimental focal lengths.

| Exp No | Object Distance (mm) | Focal length (mm) | | Error (%) |
|---|---|---|---|---|
| | | Theoretical | Experiment | |
| 1 | 215 | 46.9 | 35.8 | 30 |
| 2 | 345 | 50.0 | 38.2 | 30 |
| 3 | 1110 | 56.9 | 41.5 | 37 |
| 4 | 7500 | 61.1 | 42.7 | 43 |

The causes of larger error are expected to happen due to the following reasons:

a) Ripples and unevenness might appear on the flexible membrane during long focal length focusing due to less stretching of the membrane.

b) Gravity effect on the membrane is dominating over the membrane tension which is not taken into consideration in the mathematical model.

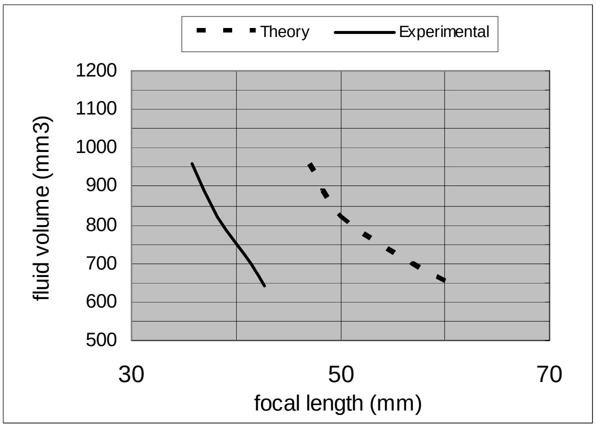


Fig. 10: Comparison of theoretical and experimental focal lengths.

## 6. Conclusion

A fully functional autofocusing system using Flexible Lens was designed and fabricated. Focusing is achieved by varying the radius of the flexible lens. A number of experiments were conducted to show the quality of pictures and also to show the relationship of the focal length between the mathematical model and that of the actual lens. In general, it was noticed that as the lens operates in the long focal length range, achieving the right focal length becomes more difficult, while operating the lens in the shorter focal length range provides better accuracy.

## References

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[2] Hendriks, B. H. W., Kuiper, S., Van As, M. A. J., Renders, C. A. and Tukker, T. W. “Electrowetting-Based Variable-Focus Lens for Miniature Systems”, Optical Review, Vol. 12, No. 3, (2005), 255–259.

[3] Jain, R., Kasturi R., Schunck B. G., Machine Vision, Singapore, Mc Graw Hill, 1995.