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Fast Focus Mechanism Using a Pair of Convergent and Divergent Lenses Differentially for Three-dimensional Imaging

Akira Ishii
Ritsumeikan University
1-1-1 Noji-higashi, Kusatsu, Shiga 525-8577, Japan
aishii@se.ritsumei.ac.jp

Abstract

Telecentric optics with a fast focus mechanism at constant magnification was devised to achieve perfect perspective and parallel projections for a real-time system of three-dimensional close-up imaging and range measurement based on focus by differentially using a pair of convergent and divergent lenses. This was successfully used to keep the parallel and perspective projection systems in focus with a focusing precision (σ) of 0.92 μm for the former and a focusing precision (σ) of 0.25 mm for the latter. Furthermore, images that were entirely in focus were generated at a video rate of 30 Hz for a moving object within a desk top space.

1. Introduction

Models of three-dimensional (3-D) machine vision systems can be described with two types of projection schemes. The first is a perspective projection system, on which stereo vision is based. This has been used within the depth of field under fixed-focus conditions in practice. However, this is not appropriate for close-up imaging at large magnifications because of its shallow depth of field. Moreover, close-range stereo vision has encountered difficulties with matching stereo pairs of differently distorted images due to parallax. The shape-from-focus method [1] seems to have advantages over stereo vision based on triangulation in measuring the 3-D shapes of close-range objects. However, this approach needs a focus mechanism that can retain perspective projection [2-3]. Such a focus mechanism would also ensure the formation of a 3-D image that is entirely in focus at every point on the object and it would improve the precision with which 3-D shapes were measured. The second model of machine vision is a parallel projection system with constant magnification. An object-space telecentric imaging system, which is often used in industry, achieves this within the depth of field and is excellent for stably measuring the profile of an object. However, it is necessary to translate the stage carrying the object along the optical axis for focusing to form a good-quality image of a complicated 3-D object surface. This mechanical translation limits the image acquisition rate and causes fluctuations in object illumination. The focus mechanism moving the objective lens is also a factor limiting the depth scan rate due to lens inertia. A fast focus mechanism with constant magnification is useful for building a system for measuring close-range 3-D shapes based on focusing and this is the key to preserving a perspective projection system as well as a parallel projection system during focusing. The constant magnification focus mechanism itself is the perfect parallel projection system. A perfect perspective projection system can be built to combine an image-taking lens with image-space telecentricity and the constant-magnification focus mechanism. This paper describes a fast constant-magnification focus mechanism using a varifocal lens. Liquid lenses have been investigated as a compact varifocal device in the fields of compact cameras and adaptive optics research [4-5]. Here a differential pair of tiny convergent and divergent lenses is presented as a faster device with the depth scan frequency of more than 30 Hz. The divergent lens was translated with a piezoelectric positioner to focus on the object. This paper explains the underlying operating principles and presents the experimental results.

2. Constant Magnification Focusing

2.1. Operating principles

A conventional system of constant magnification involves an infinity-corrected optics that consists of an objective lens, whose front focal plane is an object plane, and an imaging lens, whose rear focal plane is an image plane. Focusing is done by moving the objective lens, which is usually a microscope objective. This consists of multiple lenses to accomplish high-quality imaging. Therefore, the focusing range is restricted within about 100 μm at a high frequency of more than 30 Hz because of its large mass. Thus, a varifocal lens was added to the infinity-corrected system with telecentricity to carry out focusing without moving the objective lens, as shown in Figure 1. The fixed objective lens and the varifocal lens, whose front principal point, H_V, is fixed at the rear focal point of the objective lens, create a specific compound lens. The definite focal length, f_V, of the varifocal lens produces a shift, q, in the front principal point, H_C, of the compound lens by f^2/f_V from the front principal point, H, of the objective lens while keeping the focal length of the compound lens equal to the focal length, f, of the objective lens. This can be derived using Gaussian optics.

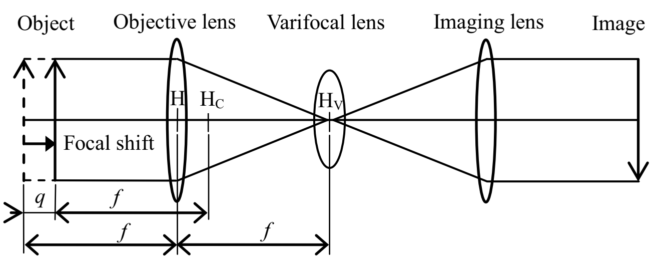

Figure 1. Constant-magnification focus by varifocal lens.

Thus, the same constant-magnification focusing as that with a conventional infinity-corrected system is obtained.

2.2. Experimental system for fast constant-magnification focus by differential pair of convergent and divergent lenses

A differential structure made up of a pair of convergent and divergent lenses (“differential lens”) was devised as a new varifocal lens and was applied to building an experimental system for a fast focus mechanism at constant magnification. Figure 2 shows the configuration for the prototype of the “differential lens,” which consists of a plano-convex lens (lens A) with a focal length, f_d, of 30 mm and a plano-concave lens (lens B) with a focal length, $-f_d$, of −30 mm. These are separated by a variable spacing, g. The H_A and H'_A correspond to the front and rear principal points of lens A. The H_B and H'_B are those of lens B. The H_V and H'_V are the front and rear principal points of the differential lens, whose focal length is f_d^2/g based on Gaussian optics. Figure 3 outlines the experimental system for the focus mechanism with the differential lens used as a varifocal lens. The H_1 and H'_1 correspond to the front and rear principal points of the objective lens with focal length f. The H_2 and H'_2 are also those of the imaging lens with focal length f. The compound lens consisting of the objective lens and the differential lens has front principal point H_C at distance $(f/f_d)^2g$ from point H_1, which produces focal shift q. The piezoelectric positioner, which translates movable lens B of the differential lens, has not been shown in Figures 2 and 3, but is described in Table 1, which summarizes the system’s specifications, together with two types of black and white cameras that were used to acquire high resolution images and evaluate focus, and to generate images that were entirely in focus at the video frame rate.

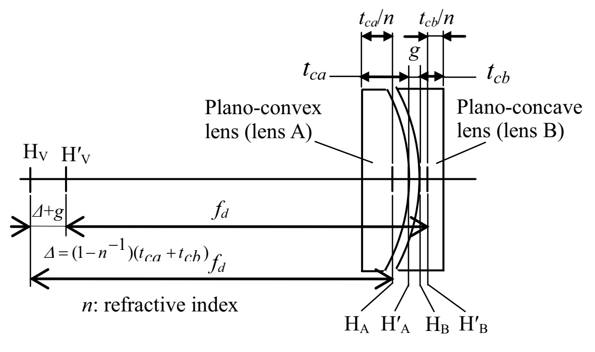

Figure 2. “Differential lens”.

2.3. Experimental results for constant magnification focus

A linear relation between focal shift q and lens spacing g with a standard deviation (σ) of 0.92 μm was experimentally verified, as shown in Figure 4. The target measured was a diffusive aluminum plate illuminated by white light from a halogen lamp. It was placed vertically to the optical axis of the objective lens and was moved along the optical axis at a pitch of 50 μm. One hundred and one defocused images were acquired at each target position by a CCD camera while varying lens spacing g at a pitch of 3 μm. The lens spacing that produced the maximum value for the focus measure was detected at every target position. A modified Laplacian [1] was used to calculate the focus measure. Constant magnification was simultaneously confirmed. The measured magnifications were 0.997±0.001 in a focus range of 1 mm. A marginal resolution of 100 lp/mm was obtained at the central part of the image plane to ensure image quality, as shown in Figure 5, but the resolution in the peripheral region was slightly lower. Optical distortion was below 0.2%. This superior optical performance of the focus mechanism was derived from its differential lens structure and the transmission of a parallel pencil of rays through the structure. Further, the moving plano-concave

Table 1. System unit specifications.

Units		Specifications and symbols
Objective and imaging lenses		• F number: F4 • Focal length f: 50 mm • Front & rear principal points: H_1, H_2, H'_1, H'_2
Differential lens	Plano-convex lens	• Focal length f_d: 30 mm • Front & rear principal points: H_A, H'_A
	Plano-concave lens	• Focal length $-f_d$: −30 mm • Front & rear principal points: H_B, H'_B
Piezoelectric positioner		PI GmbH & Co. KG, P-625.1CL • Positioning range: 0 – 500 μm /0 – 10 V
Camera and processor	High resolution images acquisition and focus evaluation	JAI 1/2-inch CCD camera: • Frame rate: 16 fps • Image size: 6.4 x 4.8 mm (1380 x 1035 pixels) Processor: Dell Precision 8250 2.4 GHz, 1.0 GB
	Entirely-in-focus images generation at video rate	Photron CMOS high-speed camera: • Maximum frame rate: 1000 fps • Image size: 6.14 x 6.14 mm (512 x 512 pixels) Processor: Focuscope FV-100 • 30 fps@30frames integration in depth

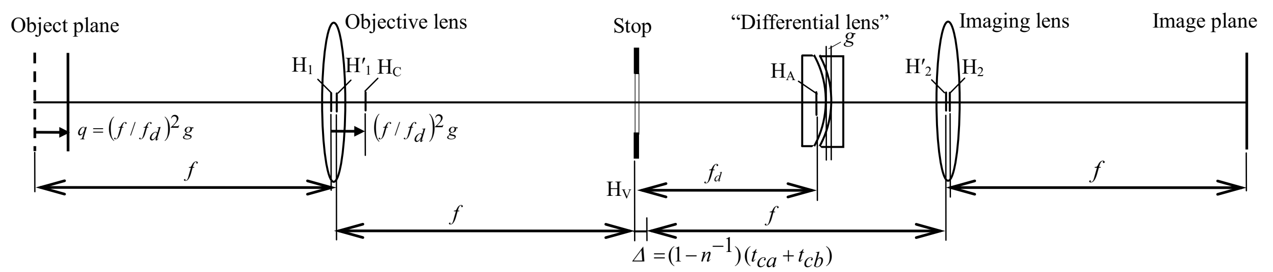

Figure 3. Experimental system for constant-magnification focus mechanism with “differential lens” used as varifocal lens.

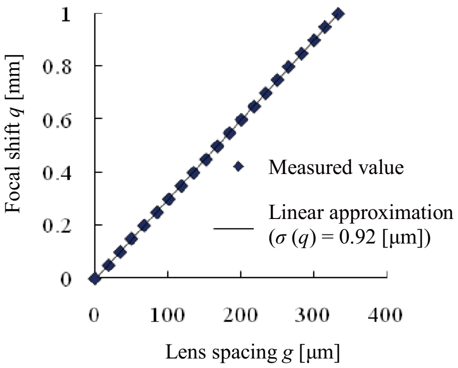

Figure 4. Focal shift vs. lens spacing characteristics.

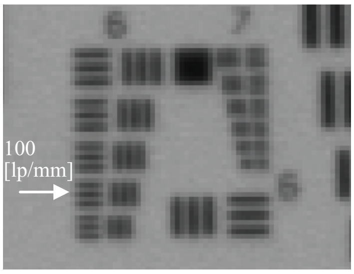

Figure 5. Image of USAF test pattern.

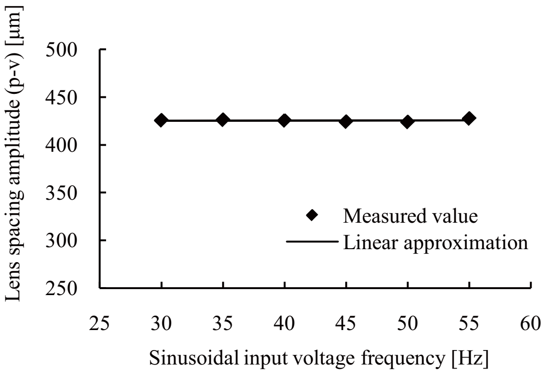

Figure 6. Frequency response of "differential lens."

lens only weighed 5 grams including its holder. This small mass contributed to the high frequency response of the differential lens up to 55 Hz, as shown in Figure 6.

3. Perfect Perspective Projection System

3.1. System configuration

A perfect perspective imaging system with the center of projection fixed during focusing could be built by placing an image-space telecentric lens in front of the constant magnification focus mechanism, i.e., the parallel projection system previously described. Figure 7 shows the configuration for the perspective imaging system with the fast focus mechanism. The image-taking lens is an image-space telecentric type and has a focal length of f_p. Its entrance pupil is at front focal point F and is conjugate to the stop of the focus mechanism. The distance, p, from focal point F to the focused object plane, where the object is indicated by the solid arrow, is $f_p{}^2/q$, where q is the image distance from rear focal point F′ to an intermediate image indicated by the dashed

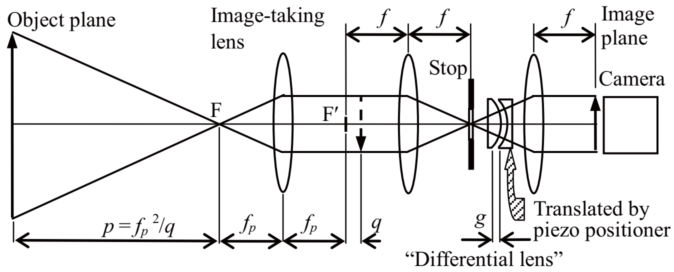

Figure 7. Perspective projection system including "differential lens."

arrow. When q is equal to the focal shift, $(f/f_d)^2 g$, of the focus mechanism, the object plane is mapped to the image plane of the camera in focus. The total magnification is f_p/p. The same magnification is also retained even during defocusing because of telecentricity. Thus, a perfect perspective projection system was able to be established. The center of projection is at front focal point F of the imaging-taking lens. Under these focus conditions, where the rear focal point of the image-taking lens coincides with the front focal point of the objective lens of the focus mechanism, the focus range is beyond the minimum distance of $(f_p f_d/f)^2/g_{max}$, where g_{max} is the maximum lens spacing. To cover the practical range in a close-up space for the shape-from-focus method under the limit of lens spacing g, it is necessary to set the focus mechanism back by a specific distance, q_0, from the rear focal point of the image-taking lens. In setting the focus mechanism back by q_0, a focus range from $f_p{}^2\{(f/f_d)^2 g_{max} + q_0\}^{-1}$ to $f_p{}^2 q_0{}^{-1}$ is obtained and can be adjusted to acquire a close-up image for measuring shapes within a desktop space.

3.2. Experiments on focus characteristics and generation of image entirely in focus

An experimental system for perfect perspective projection imaging with the focus mechanism was built by only adding an image-taking lens, an f25mm F1.4 Nikon Rayfact, to the experimental system for constant-magnification focus described in Figure 3 and in Table 1. To obtain object distance p vs. lens spacing g characteristics, a target with stripes printed on a blank sheet of paper was used because the texture of the target material's surface could not be resolved within the visual field of a desktop space. Therefore, a Sobel filter was used to calculate the focus measure for the stripe edges. Figure 8 shows perspective images of the striped targets

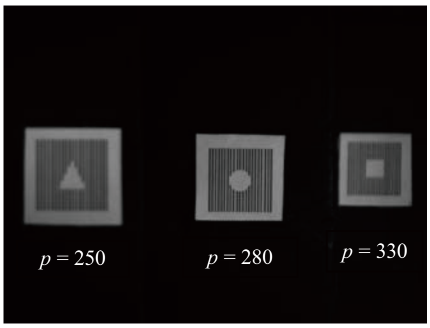

Figure 8. Perspective images of targets with triangle, circle, and square patterns against stripes. Stripe pitch is 0.5 mm and black stripe width is 0.25 pt.

placed at different distances in the visual field focused on a distance of 280 mm. The targets were illuminated by a halogen lamp. A region of black-and-white stripes at a pitch of 0.5 mm in the central target was used to evaluate focus characteristics. Accurate focus characteristics for the system of perspective projection imaging could be obtained, as shown in Figure 9. Since setting the focus mechanism back by q_0 was introduced to obtain a wide range of measurements, equivalent lens spacing $(f_d / f)^2 q_0$ was added to the amount of lens spacing directly controlled at the pitch of 3 μm by the piezoelectric positioner to obtain effective lens spacing g, as the abscissa in Figure 9 indicates. The standard deviation from a theoretical linear relation between the logarithmic values of object distance p and effective lens spacing g was 0.25 mm. This is sufficient for a robot with a tactile sensor to handle parts during assembly. Further, perfect perspective projection imaging produced a superb image that was entirely in focus, which was produced by detecting an in-focus pixel with the maximum focus measure at every pixel position in a sequence of perspective images focused on different distances in a specific depth for the same scene and by integrating all the in-focus pixels into a single image. Figure 10 shows images that are entirely in focus generated from 101 perspective images of the “triangle”, “circle”, and “square” targets taken at different focus points with the pitch of 3 μm with lens spacing g for the differential lens.

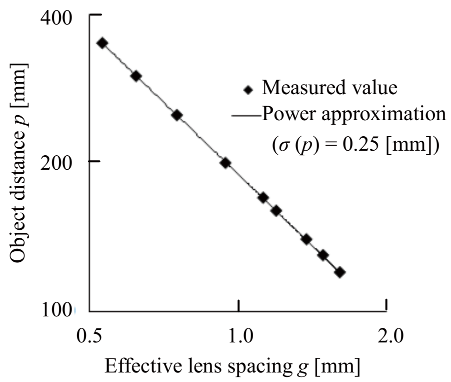

Figure 9. Focus characteristics in perspective projection imaging system.

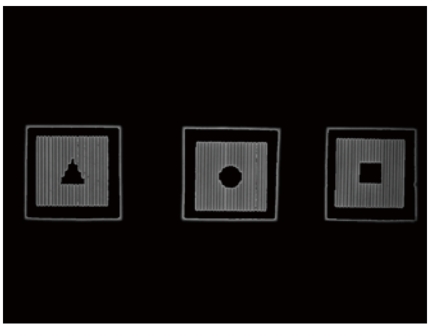

Figure 10. Images entirely in focus of Sobel filter outputs displayed at the same magnification.

3.3. Generation of video frame rate for images entirely in focus

A real-time system to generate images that were entirely in focus was built using a high-speed camera and an image processor, the Focuscope FV-100 of Photron, Ltd. whose specifications are listed in Table 1. The Focuscope FV-100 is a microscope developed for observing the behaviors of germs in images that are entirely in focus. The depth of scanning done by the microscope objective was limited to 100 μm in parallel projection. This was increased to 1 mm in parallel projection and to 100 mm at a magnification of 1/10 in the desktop space in perspective projection by the differential lens. Perspective video images of an object (a plastic figure) moving back and forth on a swing during a period of around 2 s (average linear speed 150 mm/s) were synchronously taken at a throughput of 900 fps with thirty-step focusing at depths ranging from 260 to 450 mm at every 1/30 s interval done by the piezo-electric positioner, which was controlled by the FV-100. An image that was entirely in focus was formed from thirty frames at a rate of 30 Hz. Figure 11 shows the results of generating images that were entirely in focus.

(a) Distance of 340 mm (b) Distance of 280 mm

Figure 11. Images entirely in focus generated at video frame rate of 30 Hz.

4. Conclusions

A differential pair of convergent and divergent lenses with adjustable lens spacing (“differential lens”) was devised as a varifocal lens and was successfully integrated it into telecentric optics to build a constant-magnification focus mechanism, i.e., a parallel projection system. Further, a system for perfect perspective projection imaging without shifting the projection center during focusing could be built by using this focus mechanism. The focus resolution obtained in the experiments was 0.92 μm (σ) for the parallel projection system with a depth range of 1.0 mm and this was 0.25 mm (σ) for the perspective projection system with a range from 120 to 350 mm in the desktop space. This is sufficient for robotic handling during assembly in a desktop space. A marginal image resolution of 100 lp/mm was obtained with optical distortion of less than 0.2% in the parallel projection system. The differential lens could work up to a repetitive frequency of 55 Hz using the piezoelectric positioner. Therefore, images that were entirely in focus of an object moving at a speed of around 150 mm/s in depth were successfully obtained at a frame rate of 30 Hz. Applying parallel projection systems to the assembly and inspection of semiconductor devices would be useful in the future considering the successful results that have been obtained from feasibility studies on varifocal mirror-based systems with similar performance [6] and the simplicity of transmission-type systems using varifocal lenses. Applications of perspective projection systems would be those for close-range 3-D imaging and measuring shapes in a desktop space based on focus such as that from the shape-from-focus method and these would be useful for replacing stereo vision in fields that have experienced problems such as those with occlusion and errors in matching stereo-pair images, e.g., automated assembly and inspection of products with a complex of wires by robots.

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References

[1] S. K. Nayar and Y. Nakagawa: "Shape from Focus," *IEEE Trans. PAMI*, Vol. 16, No. 8, pp. 824-831, 1994.

[2] A. Ishii, "Three-dimensional imaging based on perfect projection using varifocal mirror," *Proc. SPIE*, Vol. 5202, pp. 38-49, San Diego, U.S.A., Aug., 2003.

[3] A. Ishii and R. Okada: "Perfect perspective projection using a varifocal mirror and its application to three-dimensional close-up imaging," *Proc. 17th ICPR*, Vol. 3, pp. 270-273, Aug., 2004.

[4] B. Berge: "Liquid lens technology: principle of electrowetting based lenses and applications to imaging," *Proc. of the 18th IEEE conference on Micro Electro Mechanical Systems (MEMS 2005)*, p. 227, 2005.

[5] S. Murali, K. P. Thompson, and J. P. Rolland: "Three-dimensional adaptive microscopy using embedded liquid lens," *OPTICS LETTERS*, Vol. 34, No. 2, pp. 145-147, Jan. 15, 2009.

[6] A. Ishii and J. Mitsudo: "Constant-Magnification Varifocal Mirror and Its Application to Measuring Three-Dimensional (3-D) Shape of Solder Bump," *IEICE Trans. Electron*., E90-C, 1, pp. 6-11, Jan., 2007.