CHARACTERISATION OF VARIABLE FOCUS LIQUID LENS CAMERA SYSTEM FOR DEPTH ESTIMATION OF A MOVING OBJECT

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I would like to dedicate this thesis to my family. My mom Choi Lian and sister Estee, for your encouragement and support to pursue my PhD.

For my wife Peniel and baby boy Elzedek who have joined me in my journey. Thanks for your love and patience.

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ABSTRACT

Depth estimation of an object or a scene are used for the purpose of motion detection, obstacle detection, positioning, depth mapping, or 3D shape recovery. These capabilities can be applied in home, industry, medical, education and other areas of applications. There are different types of depth sensor based on different technology, which suit different kinds of applications. Depth sensors can be divided into active sensor that emits out energy signal and passive sensor that does not require emission of energy signal. Camera-based depth sensor such as stereo camera and monocular camera are passive sensor. Hence, they do not have external or mutual interference problem, no emission hazard, better object detectability, while having the advantage of visual information. Compared to monocular camera, depth sensing with stereo camera vision has longer depth range. However, stereo camera faces challenges from occlusion, radiometric distortion, depth discontinuity, homogenous regions, false boundary problem, and reflection issues. Depth estimation with monocular camera uses images acquired at different focus settings. This can be achieved by varying the lens' position or the lens' optical power. Past works on depth sensing with variable focus mechanically actuates the lens position. The moving of the lens position results in change of field of view or magnification in the images, a phenomenon known as lens breathing. Image stacks acquired with linear actuator lens needs to be aligned before being processed, which adds on the complexity of image alignment, processing time, and dependence on the accuracy of image alignment. The developed liquid lens monocular camera system for depth estimation showed successful depth estimation with depth from focus technique without the need for image alignment. Lens breathing is avoided by varying the thickness of the lens to change the focal length without affecting the field of view. This research characterises the liquid lens monocular camera for depth estimation of a moving object that utilizes liquid lens to eliminate lens breathing. The response time of the liquid lens monocular camera system to complete a successful image acquisition at each lens' voltage change was

0.274 s. A function describing the relationship between the liquid lens' voltage, liquid lens' temperature and object distance is presented, based on experimental setup for object at 1 m to 8 m distance. In the second research studies, an object-based focus measure method based on the mean of sum of modified Laplacian (SML) of the edge and texture features of an object image area is presented. In the third research work, an automated depth estimation using liquid lens camera system is proposed. Based on the experiment for object distance range of 1 m to 8 m with depth resolution of 1 m and 1.5 m, the root-mean-square error (RMSE) for depth estimation of static object was 21%. Depth estimation of moving object shows standard deviation of the steady-state error of 0.78 m and the RMSE was 1.2 m. The estimated speed of the moving object was 0.47 m/s. Based on the results, the method accurately estimated depth for static object distance of 1 m to 5 m and for moving object was 1 m to 4 m.

ABSTRAK

Anggaran kedalaman sesuatu objek atau pemandangan digunakan untuk tujuan pengesanan gerakan, pengesanan halangan, penentuan posisi, pemetaan kedalaman, atau pemulihan bentuk 3D. Keupayaan ini dapat diterapkan dalam rumah, industri, perubatan, pendidikan dan sudut aplikasi lain. Terdapat pelbagai jenis sensor kedalaman berdasarkan teknologi yang berbeza untuk jenis aplikasi yang berlainan. Sensor kedalaman boleh dibahagikan kepada sensor aktif yang mengeluarkan isyarat tenaga dan sensor pasif yang tidak memerlukan pancaran isyarat tenaga. Sensor kedalaman yang berasaskan kamera seperti kamera stereo dan kamera monokular merupakan sensor pasif. Oleh itu, mereka tidak mempunyai masalah gangguan luaran atau bersama, tidak ada pancaran berbahaya, pengesanan objek yang lebih baik, sementara mempunyai kelebihan maklumat visual. Pengesanan kedalaman dengan visi kamera stereo mempunyai jarak kedalaman yang lebih panjang berbanding dengan kamera monokular. Walau bagaimanapun, kamera stereo menghadapi cabaran dari halangan, herotan radiometrik, ketakselanjaran kedalaman, sudut homogen, masalah sempadan palsu serta masalah pantulan. Anggaran kedalaman dengan kamera monokular menggunakan imej yang diperoleh pada tetapan fokus yang berbeza. Ini dapat dicapai dengan mengubah kedudukan lensa atau kekuasaan optik lensa. Kajian yang terdahulu dalam pengesanan kedalaman dengan fokus berubah secara mekanikal menggerakkan kedudukan lensa. Pergerakan kedudukan lensa mengakibatkan perubahan sudut pandangan atau pembesaran pada imej adalah fenomena yang dikenali sebagai *lens breathing*. Tumpukan imej yang diperoleh dengan lensa penggerak linear perlu diselaraskan sebelum diproses. Ini menambah kerumitan penjajaran imej, masa pemprosesan, dan pergantungan pada ketepatan penjajaran imej. Sistem kamera monokular lensa cecair yang dikembangkan untuk anggaran kedalaman menunjukkan anggaran kedalaman yang berjaya dengan kedalaman dari teknik fokus tanpa memerlukan penjajaran imej. *Lens breathing* dielakkan dengan mengubah ketebalan lensa untuk mengubah panjang fokus tanpa menjejaskan sudut pandangan. Penyelidikan ini mencirikan kamera monokular lensa cecair untuk anggaran kedalaman objek bergerak yang menggunakan lensa cecair untuk mengelakkan *lens breathing*. Masa tindak balas sistem kamera monokular lensa cecair untuk melengkapkan pemerolehan imej yang berjaya pada setiap perubahan voltan lensa adalah 0.274 s. Fungsi yang menggambarkan hubungan antara voltan lensa cecair, suhu lensa cecair dan jarak objek dibentangkan adalah berdasarkan persediaan eksperimen untuk objek pada jarak 1 m hingga 8 m. Dalam kajian penyelidikan kedua, kaedah pengukuran fokus berasaskan objek berdasarkan purata keseluruhan Laplacian yang diubahsuai (SML) atas ciri-ciri tepi dan tekstur dari sudut imej objek ditunjukkan. Dalam karya penyelidikan ketiga, anggaran kedalaman automatik menggunakan sistem kamera lensa cecair dicadangkan. Berdasarkan eksperimen untuk jarak objek 1 m hingga 8 m dengan resolusi kedalaman 1 m dan 1.5 m, punca min ralat kuasa dua (RMSE) untuk anggaran kedalaman objek statik adalah 21%. Anggaran kedalaman objek bergerak menunjukkan sisihan piawai ralat keadaan mantap 0.78 m dan RMSE adalah 1.2 m. Anggaran kelajuan objek bergerak adalah 0.47 m / s. Berdasarkan hasilnya, kaedah mengira kedalaman dengan tepat untuk jarak objek statik 1 m hingga 5 m dan untuk objek bergerak adalah 1 m hingga 4 m.

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LIST OF SYMBOLS

μ	-	Mean
μ_f	-	Coefficient of friction
D	-	Dioptre
d	-	Distance
f	-	Focal length
g	-	Gravity of Earth
t	-	Time
v	-	velocity
V	-	Voltage

LIST OF ABBREVIATIONS

AF	-	Auto-focus
CCD	-	Charge coupled devices
CMOS	-	Complementary metal–oxide–semiconductor
CPU	-	Central processing unit
DC	-	Direct current
DFF	-	Depth from focus
DFD	-	Depth from defocus
FM	-	Focus measure
FOV	-	Field of view
FPS	-	Frames per second
GPU	-	Graphics processing unit
IR	-	Infrared
Lidar	-	Light detection and ranging
NS	-	Not specified
NTC	-	Negative temperature coefficient
PSF	-	Point spread function
PWM	-	Pulse width modulation
radar	-	Radio detection and ranging
RGB	-	Red Green Blue
RMSE	-	Root-mean-square error
ROI	-	Region of interest
SFD	-	Shape from defocus
SFF	-	Shape from focus
SML	-	Sum of modified Laplacian
USB	-	Universal Serial Bus

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CHAPTER 1

INTRODUCTION

1.1 Background

Depth estimation is the estimation of depth of an object or a scene for the purpose of motion detection, obstacle detection [1], positioning [2], depth mapping [3], or 3D shape recovery [4]. These capabilities can be applied in automated home appliances, measuring tools, robotic application, human-computer interaction [5], manufacturing industry, entertainment, education, automotive [6], and others. There are different types of depth sensor based on different technology, which suit different kinds of applications. Applications can be categorized into different distance range such as short, mid or long range. Many short-range applications are indoors, and often having close contacts with human. It can be a single point depth sensor used for simple automated task such as dispensing water, lighting control, automotive parking system, indoor robot and others. It can also be used for depth measurement or 3D scanning application in industrial design, digitization of objects, medical, computer-aided design, and indoor robotic mapping [7]. Mid-range and long-range depth estimation applications are mostly including outdoor robot [8], terrain mapping [9], automotive [6], aviation [10], marine traffic surveillance [11] and others.

Depth sensors for depth estimation can be divided into active or passive sensors [12]. Active sensor emits out self-generated energy and the object reflects back the signal to the sensor. The sensor determines the object distance by analysing the reflected signal. Infrared, ultrasound, radar and Lidar are examples of an active sensor. On the other hand, passive sensor does not require to emit out any form of energy. Camera-based depth sensor such as stereo camera and monocular camera are passive sensor. For this reason, camera-based depth sensor does not have the problem of being susceptible to interference of similar energy sources or pose health concern due to the emission of energy. Unlike other active sensor, camera-based depth sensor has the highest data density. The acquired monochrome or colour image data by the camera can also be used for object recognition [13] besides being used for depth estimation. This is not possible for other active depth sensors without the fusion of camera.

Many short-range applications are used indoor and often having close contacts with human. Examples of such applications are phones [18] [19], mobile devices [20], wearable computer for interface [21] [22], assistive wearable computer [23], computing ecology [24] [25], assistive robots [26] [27] [28] [29] and others. Such trend may increase in the future, as computer vision, machine learning and computing technology improves. Depth estimation with non-emitting solution will become an important option for such applications. Camera-based depth sensor provides such solution as it does not rely on emission of energy for depth sensing [30] [17]. Camera-based depth estimation using stereo camera or monocular camera does not rely on self-emitting energy signal, does not have external or mutual interference problem like an active sensor, and is similar to human's visual modality.

Camera-based depth estimation can be achieved using stereo camera and monocular camera. Compared to monocular camera, depth sensing with stereo camera vision has longer depth range [31]. However, by matching two images to obtain depth causes stereo camera to face challenge from occlusion [32] where some object area is not visible by either side of the camera. Research work is still being done to improve the occlusion solution [33] [34] [35]. The depth range in a stereo vision is proportional to the baseline distance of the two cameras and the focal length of the camera lens. However, increasing the baseline distance will increase the missing parts problem and decreasing the field of view [36]. Other challenges in stereo vision are radiometric distortion, depth discontinuity, homogenous regions [37], false boundary problem, and reflection issues [38]. On the other hand, depth sensing with monocular camera uses only one camera, avoiding occlusion problems and the correspondence matching problem that are faced in stereo camera [39].

Depth estimation with monocular camera is achieved by varying focus setting of a scene or object to determine the depth by analysing the change in focus value [40] [41]. Depth can be estimated by comparing the sharpness in the images [41] or calculating the degree of blurring with the known camera parameters [40]. Images with different focus settings can be acquired with monocular camera by varying the lens' position [40] [41] or the lens' optical power [42] [43]. Current conventional type of lens used in monocular camera is the linear positioning lens or the lens-motion-type, where the lens' position is adjusted with an actuator for focusing. Several disadvantages of the linear positioning lens are the deterioration from mechanical movement, noise during operation, challenges in mass production, and design requiring several solid lenses to control wider focal length range [44]. With the increasing development of small portable devices and robots, the scalability of lens becomes an important challenge. Shrinking of linear positioning lens would limit the performance, complicate the process, and reducing the lifetime of the lens [44] [45]. On the other hand, the liquid lens is highly adaptable and scalable [45]. Due to the concept and design, liquid lenses are inexpensive, durable, quiet during operation, vibration insensitivity, high optical quality, and more suitable for the mass production and device packaging while exhibiting tunable focal lengths [44]. Another disadvantage of the linear positioning lens is the lens breathing [46]. Lens breathing occurs due to change in field view as the lens position is moved. The images acquired needs to be aligned before being processed.

1.2 Problem statement

Past works on depth sensing with variable focus are done by mechanically moving the lens position. The lens is made of solid transparent material such as glass, crystal or plastic. An example of a mechanically moving lens is the voice-coil-motor (VCM). The moving of the lens results in change of field of view or magnification in the image [18] [47]. This phenomenon is also known as lens breathing [46]. In DFF or DFD, image stacks acquired with linear actuator lens needs to be aligned before being processed. Several methods of pre-processing the images are scaling and translating [48], similarity transform [49], Optical flow [18], global homography-based alignment [47] and others. This pre-processing adds on the complexity of image alignment, processing time, and dependence on the accuracy of image alignment.

This study develops and characterizes the liquid lens camera system for short-range depth estimation of object. After which, a depth estimation with liquid lens camera system for a moving object can be developed. The performance of the liquid lens camera system will be analysed.

1.3 Aim and objectives

The aim of this research is to characterise liquid lens monocular camera for depth estimation of a moving object that utilizes liquid lens to eliminate lens breathing. The objectives of the research are:

i. To characterize the properties of the liquid lens for a camera system in depth estimation.
ii. To investigate the focus measure algorithms in processing time and modify it for object depth estimation application.
iii. To develop an automated depth estimation using liquid lens camera system for static and moving object in short-range.

1.4 Scopes

This research concentrates on short-range depth estimation of a moving object with a variable focus liquid lens camera system. The depth estimation system is targeted for short range indoor application below 8 m. The depth resolution is limited to 1 m. The targeted object used in the experiments is a checkerboard object with edge features, and black and white colour. The experiments are carried out in an indoor and in a well-lighted scene. The camera and targeted object are placed on a flat surface. The targeted object is placed perpendicular to the ground. The temperature of the scene during the experiment are not controlled. The temperature readings are from heat generated by the equipment and from the surrounding temperature. The hardware used are commercially available webcam and laptop products. The liquid lens and the Arduino board are development and evaluation kits. The programs are carried out using MATLAB or C++.

The DFF and DFD methods for the comparison study are selected from the publicly available source code. The study is carried out on the same laptop. The study focuses on comparing the processing time as the aim is for an object-based focus measure of a moving object. In this research, the region of interest of the object image is manually fixed but it can be further developed to incorporate object detection and image segmentation.

For the depth estimation system using liquid lens camera system, the test on static and moving object is limited to object that is directly in front of the camera. The object is set approximately at the centre of the image. The tests were carried out in indoor and in a well-lighted scene.

1.5 Contribution and novelty

The contributions of this research are as follows:

i. The response time starting from sending out a liquid lens command signal to a stable image acquisition is identified to ensure accurate image acquisition every time the lens' focus setting changes. The steps to obtain the response time for liquid lens camera system are provided.
ii. A function of relationship between the lens' voltage, lens' temperature and object distance is presented. This contributes to the implementation of liquid lens monocular camera to estimate object depth based on focus analysis and temperature of the lens.
iii. A methodology for the estimation of depth based on object-based focus measure method and hill-climbing search was proposed. This method implemented the characterised liquid lens monocular camera system to estimate depth by varying focal length through changing the optical power of the lens. The experiment to estimate depth on static and moving object was implemented and evaluated.

Novelty of this research:

i. This research presents a novel characterisation of liquid lens monocular camera system. The response time starting from sending out a liquid lens command signal to a stable image acquisition is identified to ensure accurate image acquisition every time the lens' focus setting changes. A function of relationship between the lens' voltage, lens' temperature and object distance is also presented.

Innovation of this research:

i. A method to obtain focus measure of an object is presented. The object-based focus measure computes the mean of SML of the edge and texture features of an object image area.

ii. A methodology for estimation of depth of an object based on object-based focus measure method and hill-climbing search is proposed. This method was able to estimate depth on static and moving object in short range application.

1.6 Thesis outline

This thesis consists of five chapters. Chapter 1 covers the background, problems, objectives, scopes and contributions of the research work.

Chapter 2 presents the overview of the importance of depth estimation and the challenges in short range application. Different types of depth sensors are reviewed. Comparison of stereo camera and monocular camera in depth sensing is presented. Here, the advantage of depth sensing with monocular camera is identified. The different types of lens focusing technique used in monocular camera depth sensing are reviewed. A comparison of linear positioning lens and liquid lens is made. The problems in linear positioning lens are pointed out. Following is the review of different depth from focusing techniques. Finally, search algorithms are reviewed for continuous and quick search in the depth estimation with varying focus application.

Chapter 3 presents the methodology of the research. The hardware assembly of the liquid lens camera system is described. The characterisation method for the liquid lens monocular camera system for depth estimation is presented. The method for compute focus measure on an object is also presented. Lastly, a methodology for depth estimation with liquid lens monocular camera system is described, along with the experiments for testing on static and moving object.

Chapter 4 shows the results and discusses the observation of the experiments described in Chapter 3. The result of the calibration of temperature sensor on the liquid lens module is shown. Next, the response time of the liquid lens monocular camera is determined through the experiments. The response time includes sending signal to the liquid lens until successful image acquisition of the desired image focus. In the characterisation of liquid lens camera system, the function of the relationship

REFERENCES

1. J. Hernandez-Aceituno, R. Arnay, J. Toledo and L. Acosta, "Using kinect on an autonomous vehicle for outdoors obstacle detection," *IEEE Sensors Journal,* vol. 16, no. 10, pp. 3603-3610, 2016.
2. T. Gaspar and P. Oliveira, "New Depth From Focus Filters in Active Monocular Vision Systems for Indoor 3-D Tracking," *IEEE Transactions on Control Systems Technology,* vol. 23, no. 5, pp. 1827-1839, 2015.
3. W. Smith, K. Lam, D. Collins and J. Tarvainen, "Estimation of Depth Map Using Image Focus: A Scale-Space Approach for Shape Recovery," in *Emerging Trends in Computing, Informatics, Systems Sciences, and Engineering*, 2013.
4. F. Mahmood, J. Mahmood, A. Zeb and J. Iqbal, "3D shape recovery from image focus using Gabor features," in *Tenth International Conference on Machine Vision (ICMV 2017)*, 2018.
5. Z. Ren, J. Meng and J. Yuan, "Depth camera based hand gesture recognition and its applications in human-computer-interaction," in *2011 8th International Conference on Information, Communications \& Signal Processing*, 2011.
6. Smartmicro, UMRR Automotive Type 153 Data Sheet, Smartmicro, 2019.
7. G. Sansoni, M. Trebeschi and F. Docchio, "State-of-the-art and applications of 3D imaging sensors in industry, cultural heritage, medicine, and criminal investigation," *Sensors*, vol. 9, no. 1, pp. 568-601, 2009.
8. B. Yamauchi, "Fusing ultra-wideband radar and lidar for small UGV navigation in all-weather conditions," in *Unmanned Systems Technology XII*, 2010.
9. C. Hug, A. Ullrich and A. Grimm, "Litemapper-5600-a waveform-digitizing LiDAR terrain and vegetation mapping system," *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences,* vol. 36, no.

Part 8, p. W2, 2004.

10. L. Thobois, J. P. Cariou and I. Gultepe, “Review of lidar-based applications for aviation weather,” *Pure and Applied Geophysics*, vol. 176, no. 5, pp. 1959-1976, 2019.

11. H. Greidanus and N. Kourti, “Findings of the DECLIMS projectâ€”Detection and classification of marine traffic from space,” *Proc. Advances in SAR Oceanography from Envisat and ERS Missions*, 2006.

12. A. Discant, A. Rogozan, C. Rusu and A. Bensrhair, “Sensors for obstacle detection-a survey,” in *2007 30th International Spring Seminar on Electronics Technology (ISSE)*, 2007.

13. M. Hirz and B. Walzel, “Sensor and object recognition technologies for self-driving cars,” *Computer-aided design and applications*, vol. 15, no. 4, pp. 501-508, 2018.

14. J. Wenger, “Automotive radar-status and perspectives,” in *IEEE Compound Semiconductor Integrated Circuit Symposium, 2005. CSIC'05.*, 2005.

15. A. N. Catapang and M. Ramos, “Obstacle detection using a 2D LIDAR system for an Autonomous Vehicle,” in *2016 6th IEEE International Conference on Control System, Computing and Engineering (ICCSCE)*, 2016.

16. C. Bouvier and Y. Ni, “Logarithmic image sensor for wide dynamic range stereo vision system,” *Procedia Computer Science*, vol. 39, pp. 146-149, 2014.

17. G. Surya and M. Subbarao, “Depth from defocus by changing camera aperture: A spatial domain approach,” in *Proceedings of IEEE Conference on Computer Vision and Pattern Recognition*, 1993.

18. S. Suwajanakorn, C. Hernandez and S. M. Seitz, “Depth from focus with your mobile phone,” in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2015.

19. A. Dey, G. Jarvis, C. Sandor and G. Reitmayr, “Tablet versus phone: Depth perception in handheld augmented reality,” in *2012 IEEE international symposium on mixed and augmented reality (ISMAR)*, 2012.

20. R. Roberto, J. P. Lima, T. Araujo and V. Teichrieb, “Evaluation of motion tracking and depth sensing accuracy of the tango tablet,” in *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*,

2016.

21. C. Harrison, H. Benko and A. D. Wilson, “OmniTouch: wearable multitouch interaction everywhere,” in *Proceedings of the 24th annual ACM symposium on User interface software and technology*, 2011.
22. S. Sridhar, A. Markussen, A. Oulasvirta, C. Theobalt and S. Boring, “Watchsense: On-and above-skin input sensing through a wearable depth sensor,” in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 2017.
23. A. Perez-Yus, G. Lopez-Nicolas and J. J. Guerrero, “Detection and modelling of staircases using a wearable depth sensor,” in *European Conference on Computer Vision*, 2014.
24. C.-J. Wu, S. Houben and N. Marquardt, “Eaglesense: Tracking people and devices in interactive spaces using real-time top-view depth-sensing,” in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 2017.
25. M. Rofouei, A. Wilson, A. Brush and S. Tansley, “Your phone or mine? Fusing body, touch and device sensing for multi-user device-display interaction,” in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2012.
26. K. M. Hasan, K. J. Reza and others, “Path planning algorithm development for autonomous vacuum cleaner robots,” in *2014 International Conference on Informatics, Electronics \& Vision (ICIEV)*, 2014.
27. M. Guettari, I. Gharbi and S. Hamza, “UVC disinfection robot,” *Environmental Science and Pollution Research*, pp. 1-6, 2020.
28. M. Tee Kit Tsun, B. T. Lau and H. Siswoyo Jo, “An improved indoor robot human-following navigation model using depth camera, active ir marker and proximity sensors fusion,” *Robotics*, vol. 7, no. 1, p. 4, 2018.
29. D. Seita, N. Jamali, M. Laskey, R. Berenstein, A. K. Tanwani, P. Baskaran, S. Iba, J. Canny and K. Goldberg, “Robot bed-making: Deep transfer learning using depth sensing of deformable fabric,” *arXiv preprint arXiv:1809.09810,* vol. 26, 2018.
30. N. Lazaros, G. C. Sirakoulis and A. Gasteratos, “Review of stereo vision

algorithms: from software to hardware," *International Journal of Optomechatronics*, vol. 2, no. 4, pp. 435-462, 2008.

31. Stereolabs, ZED Camera and SDK Overview, Stereolabs, 2018.
32. Q. Wei, "Converting 2d to 3d: A survey," 2005.
33. T. Yan, Y. Gan, Z. Xia and Q. Zhao, "Segment-based disparity refinement with occlusion handling for stereo matching," *IEEE Transactions on Image Processing*, vol. 28, no. 8, pp. 3885-3897, 2019.
34. J. Wang and T. Zickler, "Local Detection of Stereo Occlusion Boundaries," in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2019.
35. T.-C. Wang, A. A. Efros and R. Ramamoorthi, "Occlusion-aware depth estimation using light-field cameras," in *Proceedings of the IEEE International Conference on Computer Vision*, 2015.
36. R. A. Jarvis, "A perspective on range finding techniques for computer vision," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, no. 2, pp. 122-139, 1983.
37. K. Y. Kok and P. Rajendran, "A Review on Stereo Vision Algorithms: Challenges and Solutions," *ECTI Transactions on Computer and Information Technology (ECTI-CIT)*, vol. 13, no. 2, pp. 134-151, 2019.
38. A. O Riordan, T. Newe, G. Dooly and D. Toal, "Stereo Vision Sensing: Review of existing systems," in *2018 12th International Conference on Sensing Technology (ICST)*, 2018.
39. J. Ens and P. Lawrence, "An investigation of methods for determining depth from focus," *IEEE Transactions on pattern analysis and machine intelligence*, vol. 15, no. 2, pp. 97-108, 1993.
40. T. Gaspar and P. Oliveira, "New dynamic estimation of depth from focus in active vision systems," in *Preprints of the 18th IFAC World Congress Milano (Italy) August*, 2011.
41. S. Emberger, L. Alacoque, A. Dupret, G. Sicard, J. L. d. B. de la Tocnaye and others, "A near pixel Depth From Focus architecture for video rate depth estimation," *Electronic Imaging*, vol. 2018, no. 11, pp. 447-1, 2018.

42. J. N. Martel, L. K. Muller, S. J. Carey and P. Dudek, “High-speed depth from focus on a programmable vision chip using a focus tunable lens,” in *2017 IEEE International Symposium on Circuits and Systems (ISCAS)*, 2017.

43. A. B. T. Soon, K. S. Tee, M. I. M. Awad and C. F. Soon, “Oncoming Vehicle Detection with Variable-Focus Liquid Lens,” *International Journal of Integrated Engineering,* vol. 10, no. 8, 2018.

44. C.-P. Chiu, T.-J. Chiang, J.-K. Chen, F.-C. Chang, F.-H. Ko, C.-W. Chu, S.-W. Kuo and S.-K. Fan, “Liquid lenses and driving mechanisms: a review,” *Journal of Adhesion Science and Technology,* vol. 26, no. 12-17, pp. 1773-1788, 2012.

45. G.-P. Zhu, J.-F. Yao, S.-H. Wu and X.-D. Zhang, “Actuation of adaptive liquid microlens droplet in microfluidic devices: A review,” *Electrophoresis,* vol. 40, no. 8, pp. 1148-1159, 2019.

46. K. Tanaka, “Zoom lens without focus-breathing phenomena,” in *Zoom Lenses III*, 2001.

47. J. Surh, H.-G. Jeon, Y. Park, S. Im, H. Ha and I. S. Kweon, “Noise Robust Depth from Focus using a Ring Difference Filter,” in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2017.

48. T. Darrell and K. Wohn, “Pyramid based depth from focus,” in *Computer Vision and Pattern Recognition, 1988. Proceedings CVPR'88., Computer Society Conference on*, 1988.

49. R. Ben-Ari, “A unified approach for registration and depth in depth from defocus,” *IEEE transactions on pattern analysis and machine intelligence,* vol. 36, no. 6, pp. 1041-1055, 2014.

50. M. Parashar, R. Patil, S. Singh, V. VedMohan and K. Rekha, “Water level monitoring system in water dispensers using IoT,” *International Research Journal of Engineering and Technology (IRJET)*, vol. 5, no. 04, pp. 2395-0056, 2018.

51. A. Fernandez-Montes, L. Gonzalez-Abril, J. A. Ortega and F. V. Morente, “A study on saving energy in artificial lighting by making smart use of wireless sensor networks and actuators,” *IEEE network,* vol. 23, no. 6, pp. 16-20, 2009.

52. K. O. Iyapo, O. Fasunla, S. Egbuwalo, A. Akinbobola and O. Oni, “Design and Implementation of Motion Detection Alarm and Security System,” *International*

Journal of Engineering and Advanced Technology Studies, vol. 6, no. 1, pp. 26-38, 2018.

53. A. A. Algitta, S. Mustafa, F. Ibrahim, N. Abdalruof and M. Yousef, “Automated packaging machine using PLC,” *International Journal of Innovative Science, Engineering \& Technology*, vol. 2, no. 5, pp. 282-288, 2015.
54. M. Jacob, C. Cange, R. Packer and J. P. Wachs, “Intention, context and gesture recognition for sterile MRI navigation in the operating room,” in *Iberoamerican Congress on Pattern Recognition*, 2012.
55. D. Charles, K. Pedlow, S. McDonough, K. Shek and T. Charles, “Close range depth sensing cameras for virtual reality based hand rehabilitation,” *Journal of Assistive Technologies*, 2014.
56. A. Jevtic, A. F. Valle, G. Alenya, G. Chance, P. Caleb-Solly, S. Dogramadzi and C. Torras, “Personalized robot assistant for support in dressing,” *IEEE transactions on cognitive and developmental systems*, vol. 11, no. 3, pp. 363-374, 2018.
57. A. V. Le, A. A. Hayat, M. R. Elara, N. H. K. Nhan and K. Prathap, “Reconfigurable pavement sweeping robot and pedestrian cohabitant framework by vision techniques,” *IEEE Access*, vol. 7, pp. 159402-159414, 2019.
58. J. Oberhammer, N. Somjit, U. Shah and Z. Baghchehsaraei, “RF MEMS for automotive radar sensors,” Elsevier, 2013, pp. 106-136.
59. J. C. Becker and A. Simon, “Sensor and navigation data fusion for an autonomous vehicle,” in *Proceedings of the IEEE Intelligent Vehicles Symposium 2000 (Cat. No. 00TH8511)*, 2000.
60. M. R. Andersen, T. Jensen, P. Lisouski, A. K. Mortensen, M. K. Hansen, T. Gregersen and P. Ahrendt, “Kinect depth sensor evaluation for computer vision applications,” *Technical Report Electronics and Computer Engineering*, vol. 1, no. 6, 2012.
61. International Commission on Non-Ionizing Radiation Protection and others, “ICNIRP guidelines on limits of exposure to incoherent visible and infrared radiation,” *Health Physics*, vol. 105, no. 1, pp. 74-96, 2013.
62. V. Zhmud, N. Kondratiev, K. Kuznetsov, V. Trubin and L. Dimitrov, “Application of ultrasonic sensor for measuring distances in robotics,” in

Journal of Physics: Conference Series, 2018.

63. M. Zhao, A. Mammeri and A. Boukerche, “Distance measurement system for smart vehicles,” in *2015 7th International Conference on New Technologies, Mobility and Security (NTMS)*, 2015.
64. APG, IRU-3430 Ultrasonic Level Sensor, APG, 2015.
65. A. E. Onoja, A. M. Oluwadamilola and L. Ajao, “Embedded system based radio detection and ranging (RADAR) system using Arduino and ultra-sonic sensor,” *American Journal of Embedded Systems and Applications*, vol. 5, no. 1, pp. 7-12, 2017.
66. Z. Hong, Y. Petillot and S. Wang, “RadarSLAM: Radar based Large-Scale SLAM in All Weathers,” *arXiv preprint arXiv:2005.02198*, 2020.
67. M. Goppelt, H.-L. Blocher and W. Menzel, “Automotive radar-investigation of mutual interference mechanisms.,” *Advances in Radio Science*, vol. 8, 2010.
68. G. M. Brooker, “Mutual interference of millimeter-wave radar systems,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 49, no. 1, pp. 170-181, 2007.
69. S. Alland, W. Stark, M. Ali and M. Hegde, “Interference in automotive radar systems: Characteristics, mitigation techniques, and current and future research,” *IEEE Signal Processing Magazine*, vol. 36, no. 5, pp. 45-59, 2019.
70. K. L. Ryan, J. A. D'Andrea, J. R. Jauchem and P. A. Mason, “Radio frequency radiation of millimeter wave length: potential occupational safety issues relating to surface heating.,” *Health physics*, vol. 78, no. 2, pp. 170-181, 2000.
71. B. Jerneic, A. Vidovic and I. Bogovic, “Non-Ionization Pollution in Transport System,” in *12th International Symposium on Electronics in Traffic" Harmonization of Transport Systems in the European Union*, 2004.
72. M. Kojima, M. Hanazawa, Y. Yamashiro, H. Sasaki, S. Watanabe, M. Taki, Y. Suzuki, A. Hirata, Y. Kamimura and K. Sasaki, “Acute ocular injuries caused by 60-GHz millimeter-wave exposure,” *Health physics*, vol. 97, no. 3, pp. 212-218, 2009.
73. M. Kojima, Y. Suzuki, K. Sasaki, M. Taki, K. Wake, S. Watanabe, M. Mizuno, T. Tasaki and H. Sasaki, “Ocular Effects of Exposure to 40, 75, and 95 GHz Millimeter Waves,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol.

39, no. 9, pp. 912-925, 2018.

74. International Commission on Non-Ionizing Radiation Protection and others, “Guidelines for limiting exposure to Electromagnetic Fields (100 kHz to 300 GHz),” *Health Physics,* vol. 118, no. 5, pp. 483-524, 2020.

75. Infineon, Health effects of mmWave radiation, Infineon Technologies AG, 2018.

76. R. Collis, “Lidar,” *Advances in Geophysics,* vol. 13, pp. 113-139, 1969.

77. P. F. McManamon, “Lidar technologies and Systems,” in *SPIE*, 2019.

78. G. Kim, J. Eom and Y. Park, “Investigation on the occurrence of mutual interference between pulsed terrestrial LIDAR scanners,” in *2015 IEEE Intelligent Vehicles Symposium (IV)*, 2015.

79. Velodyne, Velodyne HDL-64E Resource Manual, Velodyne, 2007.

80. D. Van Norren and J. Vos, “Light damage to the retina: an historical approach,” *Eye,* vol. 30, no. 2, p. 169, 2016.

81. A. Nguyen, “mmWave Radar Sensors: Object Versus Range,” 2018.

82. A. Samman, L. Rimai, J. McBride, R. Carter, W. Weber, C. Gmachl, F. Capasso, A. Hutchinson, D. Sivco and A. Cho, “Potential use of near, mid and far infrared laser diodes in automotive LIDAR applications,” in *Vehicular Technology Conference Fall 2000. IEEE VTS Fall VTC2000. 52nd Vehicular Technology Conference (Cat. No. 00CH37152)*, 2000.

83. S. Pertuz, D. Puig and M. A. Garcia, “Analysis of focus measure operators for shape-from-focus,” *Pattern Recognition,* vol. 46, no. 5, pp. 1415-1432, 2013.

84. R. Gutierrez, E. Fossum and T. Tang, “Auto-focus technology,” in *Proc. Int. Image Sensor Workshop*, 2007.

85. F. Lemke, Y. Frey, B. P. Bruno, K. Philipp, N. Koukourakis, J. Czarske, U. Wallrabe and M. C. Wapler, “Multiphysics simulation of the aspherical deformation of piezo-glass membrane lenses including hysteresis, fabrication and nonlinear effects,” *Smart Materials and Structures,* vol. 28, no. 5, p. 055024, 2019.

86. C.-S. Liu, P.-D. Lin, P.-H. Lin, S.-S. Ke, Y.-H. Chang and J.-B. Horng, “Design and characterization of miniature auto-focusing voice coil motor actuator for

cell phone camera applications," *IEEE Transactions on Magnetics*, vol. 45, no. 1, pp. 155-159, 2009.

87. R. C. Gutierrez, T. K. Tang, R. Calvet and E. R. Fossum, "MEMS digital camera," in *Digital Photography III*, 2007.

88. H.-K. Lee, N.-J. Choi, S. Jung, K.-H. Park, H. Jung, J.-K. Shim, J.-W. Ryu and J. Kim, "Electroactive Polymer Actuator for Lens-Drive Unit in Auto-Focus Compact Camera Module," *ETRI journal*, vol. 31, no. 6, pp. 695-702, 2009.

89. J. F. Algorri Genaro, D. Zografopoulos, V. Urruchi del Pozo and J. M. Sanchez Pena, "Recent Advances in Adaptive Liquid Crystal Lenses," 2019.

90. G. Zhou, H. Yu and F. S. Chau, "Microelectromechanically-driven miniature adaptive Alvarez lens," *Optics express*, vol. 21, no. 1, pp. 1226-1233, 2013.

91. D.-K. Yang and S.-T. Wu, Fundamentals of liquid crystal devices, John Wiley \& Sons, 2014.

92. F. Schneider, J. Draheim, R. Kamberger, P. Waibel and U. Wallrabe, "Optical characterization of adaptive fluidic silicone-membrane lenses," *Optics express*, vol. 17, no. 14, pp. 11813-11821, 2009.

93. H. Ren, D. Fox, P. A. Anderson, B. Wu and S.-T. Wu, "Tunable-focus liquid lens controlled using a servo motor," *Optics express*, vol. 14, no. 18, pp. 8031-8036, 2006.

94. W. Xiao and S. Hardt, "An adaptive liquid microlens driven by a ferrofluidic transducer," *Journal of Micromechanics and Microengineering*, vol. 20, no. 5, p. 055032, 2010.

95. H. Ren and S.-T. Wu, "Adaptive lenses based on soft electroactive materials," *Applied Sciences*, vol. 8, no. 7, p. 1085, 2018.

96. B. Berge, "Liquid lens technology: principle of electrowetting based lenses and applications to imaging," in *18th IEEE International Conference on Micro Electro Mechanical Systems, 2005. MEMS 2005.*, 2005.

97. C.-C. Cheng and J. A. Yeh, "Dielectrically actuated liquid lens," *Optics Express*, vol. 15, no. 12, pp. 7140-7145, 2007.

98. varioptic, TEDS-150114-Arctic 39N0, Parrot SA, 2016.

99. G. Mercado, The Filmmaker's Eye: The Language of the Lens: The Power of

Lenses and the Expressive Cinematic Image, Taylor \& Francis, 2019, p. 35.

100. B. Berge and J. Peseux, “Variable focal lens controlled by an external voltage: An application of electrowetting,” *The European Physical Journal E,* vol. 3, no. 2, pp. 159-163, 2000.

101. varioptic, TEDS-150708-Caspian C-39N0-16, Parrot SA, 2013.

102. M. Watanabe, S. K. Nayar and M. N. Noguchi, “Real-time computation of depth from defocus,” in *Photonics East'95*,

103. M. T. Mahmood, “Shape from focus by total variation,” in *IVMSP Workshop, 2013 IEEE 11th*, 2013.

104. R. Hariharan and A. Rajagopalan, “Shape-from-focus by tensor voting,” *IEEE Transactions on image Processing,* vol. 21, no. 7, pp. 3323-3328, 2012.

105. M. T. Mahmood, A. Majid and T.-S. Choi, “Optimal depth estimation by combining focus measures using genetic programming,” *Information Sciences,* vol. 181, no. 7, pp. 1249-1263, 2011.

106. P. Favaro, S. Soatto, M. Burger and S. J. Osher, “Shape from defocus via diffusion,” *IEEE transactions on pattern analysis and machine intelligence,* vol. 30, no. 3, pp. 518-531, 2008.

107. A. N. Rajagopalan and S. Chaudhuri, “An MRF model-based approach to simultaneous recovery of depth and restoration from defocused images,” *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 21, no. 7, pp. 577-589, 1999.

108. J. M. Tenenbaum, “Accommodation in computer vision.,” 1970.

109. J. F. Schlag, A. C. Sanderson, C. P. Neuman and F. C. Wimberly, “Implementation of Automatic Focusing Algorithms for a Computer Vision System with Camera Control.,” 1983.

110. C.-Y. Tseng and S.-J. Wang, “Shape-From-Focus Depth Reconstruction With a Spatial Consistency Model,” *IEEE Transactions on Circuits and Systems for Video Technology,* vol. 24, no. 12, pp. 2063-2076, 2014.

111. S. K. Nayar and Y. Nakagawa, “Shape from focus,” *IEEE Transactions on Pattern analysis and machine intelligence,* vol. 16, no. 8, pp. 824-831, 1994.

112. A. Thelen, S. Frey, S. Hirsch and P. Hering, “Improvements in shape-from-

focus for holographic reconstructions with regard to focus operators, neighborhood-size, and height value interpolation," *IEEE Transactions on Image Processing,* vol. 18, no. 1, pp. 151-157, 2009.

113. C.-y. Tseng and S.-J. Wang, "Maximum-a-posteriori estimation for global spatial coherence recovery based on matting Laplacian," in *Image Processing (ICIP), 2012 19th IEEE International Conference on,* 2012.

114. E. P. Krotkov, Active computer vision by cooperative focus and stereo, Springer Science \& Business Media, 2012.

115. M. Moeller, M. Benning, C. Schonlieb and D. Cremers, "Variational depth from focus reconstruction," *IEEE Transactions on Image Processing,* vol. 24, no. 12, pp. 5369-5378, 2015.

116. H. Xie, W. Rong and L. Sun, "Construction and evaluation of a wavelet-based focus measure for microscopy imaging," *Microscopy research and technique,* vol. 70, no. 11, pp. 987--995, 2007.

117. E. Krotkov, "Focusing," *International Journal of Computer Vision,* vol. 1, no. 3, pp. 223-237, 1988.

118. F. Mahmood, U. Munir, F. Mehmood and J. Iqbal, "3D shape recovery from image focus using gray level co-occurrence matrix," in *Tenth International Conference on Machine Vision (ICMV 2017),* 2018.

119. M. T. Mahmood and T.-S. Choi, "Focus measure based on the energy of high-frequency components in the S transform," *Optics letters,* vol. 35, no. 8, pp. 1272-1274, 2010.

120. B. K. P. Horn, "Focusing," 1968.

121. A. Saxena, S. H. Chung and A. Y. Ng, "Learning depth from single monocular images," in *Advances in Neural Information Processing Systems,* 2005.

122. J. Shi, L. Xu and J. Jia, "Just noticeable defocus blur detection and estimation," in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition,* 2015.

123. S. Gur and L. Wolf, "Single Image Depth Estimation Trained via Depth from Defocus Cues," in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition,* 2019.

124. N. N. K. Chern, P. A. Neow and M. H. Ang, “Practical issues in pixel-based autofocusing for machine vision,” in *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, 2001.

125. A. S. Malik and T.-S. Choi, “Consideration of illumination effects and optimization of window size for accurate calculation of depth map for 3D shape recovery,” *Pattern Recognition,* vol. 40, no. 1, pp. 154--170, 2007.

126. M. Subbarao and T. Choi, “Accurate recovery of three-dimensional shape from image focus,” *IEEE Transactions on pattern analysis and machine intelligence,* vol. 17, no. 3, pp. 266-274, 1995.

127. M. Asif and T.-S. Choi, “Shape from focus using multilayer feedforward neural networks,” *IEEE Transactions on Image Processing,* vol. 10, no. 11, pp. 1670-1675, 2001.

128. M. B. Ahmad and T.-S. Choi, “A heuristic approach for finding best focused shape,” *IEEE Transactions on Circuits and Systems for Video Technology,* vol. 15, no. 4, pp. 566-574, 2005.

129. M. T. Mahmood and T.-S. Choi, “Shape from focus using kernel regression,” in *2009 16th IEEE International Conference on Image Processing (ICIP)*, 2009.

130. M. S. Muhammad and T.-S. Choi, “3D shape recovery by image focus using Lorentzian-Cauchy function,” in *2010 IEEE International Conference on Image Processing*, 2010.

131. M. S. Muhammad and T.-S. Choi, “A novel method for shape from focus in microscopy using Bezier surface approximation,” *Microscopy research and technique,* vol. 73, no. 2, pp. 140-151, 2010.

132. R. Minhas, A. A. Mohammed and Q. J. Wu, “Shape from focus using fast discrete curvelet transform,” *Pattern Recognition,* vol. 44, no. 4, pp. 839-853, 2011.

133. A. P. Pentland, “Depth of scene from depth of field,” 1982.

134. A. P. Pentland, “A new sense for depth of field,” *IEEE transactions on pattern analysis and machine intelligence,* no. 4, pp. 523-531, 1987.

135. S. Bae and F. Durand, “Defocus magnification,” in *Computer Graphics Forum,* 2007.

136. Y.-W. Tai and M. S. Brown, “Single image defocus map estimation using local contrast prior,” in *Image Processing (ICIP), 2009 16th IEEE International Conference on*, 2009.

137. C.-T. Shen, W.-L. Hwang and S.-C. Pei, “Spatially-varying out-of-focus image deblurring with L1-2 optimization and a guided blur map,” in *2012 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2012.

138. S. Zhuo and T. Sim, “Defocus map estimation from a single image,” *Pattern Recognition*, vol. 44, no. 9, pp. 1852-1858, 2011.

139. D.-J. Chen, H.-T. Chen and L.-W. Chang, “Fast defocus map estimation,” in *2016 IEEE International Conference on Image Processing (ICIP)*, 2016.

140. S. Liu, F. Zhou and Q. Liao, “Defocus map estimation from a single image based on two-parameter defocus model,” *IEEE Transactions on Image Processing*, vol. 25, no. 12, pp. 5943-5956, 2016.

141. C. Tang, C. Hou and Z. Song, “Defocus map estimation from a single image via spectrum contrast,” *Optics letters*, vol. 38, no. 10, pp. 1706--1708, 2013.

142. C. Tang, C. Hou and Z. Song, “Depth recovery and refinement from a single image using defocus cues,” *Journal of Modern Optics*, vol. 62, no. 6, pp. 441-448, 2015.

143. D. Zion, S. Wang and J. Vaillancourt, “Depth from defocus using the hermite transform,” in *Proceedings 1998 International Conference on Image Processing. ICIP98 (Cat. No. 98CB36269)*, 1998.

144. P. P. Chan, B.-Z. Jing, W. W. Ng and D. S. Yeung, “Depth estimation from a single image using defocus cues,” in *2011 International Conference on Machine Learning and Cybernetics*, 2011.

145. P. Favaro, “Recovering thin structures via nonlocal-means regularization with application to depth from defocus,” in *2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 2010.

146. W. Zhang and W.-K. Cham, “Single-image refocusing and defocusing,” *IEEE Transactions on Image Processing*, vol. 21, no. 2, pp. 873--882, 2011.

147. N. Takayama and H. Takahashi, “Foreground object extraction using variation of blurs based on camera focusing,” in *Cyberworlds (CW), 2015 International*

Conference on, 2015.

148. A. Karaali, “Spatially varying defocus blur estimation and applications,” 2017.

149. S. Pertuz, D. Puig and M. A. Garcia, “Reliability measure for shape-from-focus,” *Image and Vision Computing*, vol. 31, no. 10, pp. 725-734, 2013.

150. J. Lin, X. Ji, W. Xu and Q. Dai, “Absolute depth estimation from a single defocused image,” *IEEE Transactions on Image Processing*, vol. 22, no. 11, pp. 4545-4550, 2013.

151. N. Shroff, A. Veeraraghavan, Y. Taguchi, O. Tuzel, A. Agrawal and R. Chellappa, “Variable focus video: Reconstructing depth and video for dynamic scenes,” in *2012 IEEE International Conference on Computational Photography (ICCP)*, 2012.

152. E. Hecht, Optik, McGraw-Hill, 1987.

153. K. Tarabanis, R. Y. Tsai and D. S. Goodman, “Modeling of a computer-controlled zoom lens,” in *Proceedings 1992 IEEE International Conference on Robotics and Automation*, 1992.

154. K. Ooi, K. Izumi, M. Nozaki and I. Takeda, “An advanced autofocus system for video camera using quasi condition reasoning,” *IEEE Transactions on Consumer Electronics*, vol. 36, no. 3, pp. 526-530, 1990.

155. F. R. Boddeke, L. J. van Vliet, H. Netten and I. T. Young, “Autofocusing in microscopy based on the OTF and sampling,” *Bioimaging*, vol. 2, no. 4, pp. 193-203, 1994.

156. J. He, R. Zhou and Z. Hong, “Modified fast climbing search auto-focus algorithm with adaptive step size searching technique for digital camera,” *IEEE transactions on Consumer Electronics*, vol. 49, no. 2, pp. 257-262, 2003.

157. J. Li, “Autofocus searching algorithm considering human visual system limitations,” *Optical Engineering*, vol. 44, no. 11, p. 113201, 2005.

158. X. Xu, Y. Wang, J. Tang, X. Zhang and X. Liu, “Robust automatic focus algorithm for low contrast images using a new contrast measure,” *Sensors*, vol. 11, no. 9, pp. 8281-8294, 2011.

159. Y. Xiong and S. A. Shafer, “Depth from focusing and defocusing,” in *Proceedings of IEEE Conference on Computer Vision and Pattern Recognition*,

1993.

160. N. Kehtarnavaz and H.-J. Oh, “Development and real-time implementation of a rule-based auto-focus algorithm,” *Real-Time Imaging*, vol. 9, no. 3, pp. 197-203, 2003.

161. S. Yazdanfar, K. B. Kenny, K. Tasimi, A. D. Corwin, E. L. Dixon and R. J. Filkins, “Simple and robust image-based autofocusing for digital microscopy,” *Optics express*, vol. 16, no. 12, pp. 8670-8677, 2008.

162. Z. Wu, D. Wang and F. Zhou, “Bilateral prediction and intersection calculation autofocus method for automated microscopy,” *Journal of microscopy*, vol. 248, no. 3, pp. 271-280, 2012.

163. Y. Wang, H. Feng, Z. Xu, Q. Li, Y. Chen and M. Cen, “Fast auto-focus scheme based on optical defocus fitting model,” *Journal of Modern Optics*, vol. 65, no. 7, pp. 858-868, 2018.

164. Y. Yao, B. Abidi, N. Doggaz and M. Abidi, “Evaluation of sharpness measures and search algorithms for the auto-focusing of high-magnification images,” in *Visual Information Processing XV*, 2006.

165. Logitech, Logitech C920 HD Pro Webcam Data Sheet, Logitech International SA, 2011.

166. varioptic, MAUG - 140904 - Caspian C Com Board User Guide, Parrot SA, 2014.

167. Cytron, SN-TEMP-MOD Getting Started Guide, Cytron Technologies Sdn. Bhd., 2013.

168. Arduino, “ARDUINO UNO REV3,” 2019. [Online]. Available: https://store.arduino.cc/usa/arduino-uno-rev3. [Accessed 13 December 2019].

169. N. Zeuch, Understanding and Applying Machine Vision, Marcel Dekker, Inc., 2000.

170. I. Sobel, “An isotropic 3x3 image gradient operator,” *Machine vision for three-dimensional scenes*, pp. 376-379, 1990.

171. D. Simon, Evolutionary Optimization Algorithms, Wiley, 2013, p. 21.

172. A. Pentland, T. Darrell, M. Turk and W. Huang, “A simple, real-time range camera,” in *Computer Vision and Pattern Recognition, 1989. Proceedings*

CVPR'89., IEEE Computer Society Conference on, 1989.

173. M. Subbarao and G. Surya, “Depth from defocus: a spatial domain approach,” *International Journal of Computer Vision*, vol. 13, no. 3, pp. 271-294, 1994.

174. M. Subbarao, T.-S. Choi and A. Nikzad, “Focusing techniques,” *Optical Engineering*, vol. 32, no. 11, pp. 2824-2836, 1993.