Computational integral imaging based on a novel miniature camera array

David Avraham[1,2*] **Guy Samuels[1]** **Jae-Hyun Jung[2]** **Eli Peli[2]** **Yitzhak Yitzhaky[1]**
[1] Department of Electro-Optical Engineering, School of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer Sheva 84105, Israel
[2] Schepens Eye Research Institute of Massachusetts Eye and Ear, Department of Ophthalmology, Harvard Medical School, Boston, MA, United States of America
*davav@post.bgu.ac.il

Abstract: A novel camera array, consisting of 3 by 7 miniature cameras, was developed for image and video capture using computational integral imaging. An object isolation algorithm was successfully demonstrated on the system's output. © 2022 The Author(s)

1 Introduction

Integral imaging (InI), initially proposed in 1908 [1], is a 3D multiscopic imaging technique in which a 2D array of microlenses or cameras and a 2D sensor array (CMOS/CCD) is used to capture the scene. Each microlens/camera captures the scene at a different angle and produces an elemental image (EI). Each EI represents one perspective of the scene, and thus integration of the EIs can represent the 3D scene. InI has the advantage of functioning in natural light conditions (incoherent light) as opposed to other active 3D imaging techniques. Therefore, the sensing in InI is said to be performed passively. The 3D scene reconstruction in InI can be performed optically or computationally. In computational integral imaging (CII), the EI array is sent to a computer, in which the 3D reconstructed image is generated. The quality of the reconstructed image is usually higher in computational reconstruction than in optical reconstruction because it avoids the effects of damaged optical components, aberration, diffraction, and the limited dynamical range of the optical components. CII-based camera array is helpful for super-resolution imaging [2]–[4] and depth-based object isolation [5], [6], which is helpful for many applications, such as prosthetic vision [7], [8]. In this study, we present a novel system for CII that includes a camera array with 3 × 7 cameras, a convenient user interface for image and video capture, and a 3D autonomic object detection and isolation algorithm for images and videos based on the data captured and stored by the system.

2 Method

2.1 Device description

The proposed system, referred to as 'INI21' (Integral Imaging 21), includes a 2D camera array comprising 21 mini cameras arranged in 3 rows with 7 cameras in each row. The mini cameras (SQ11 mini-HD camera, China) are cubical with a dimension of 23 × 23 × 23 mm. Each camera has a digital resolution of 4032 × 3024 for image capture and 1280 × 720 pixels or 1920 × 1080 pixels for video capture, a frame rate of 15 or 30 frames per second, a viewing angle of 140°, a motion sensor video recording, and night vision mode [9]. The pitch between any adjacent cameras is 21.1 mm, vertically and horizontally. The 2D camera array system consists of dedicated hardware and software. Fig. 1 presents the mini camera SQ11, its features, and an exterior view of the INI21 system hardware. The system is fully controlled through a PC-based user interface. No user controls are on the hardware side. Hardware is equipped with color LEDs for system state indication. The captured information is stored in a personal computer folder, one folder per capture event, and one file per camera. Filenames of the captured image/video are numbered according to the coordinates of each camera in the array.

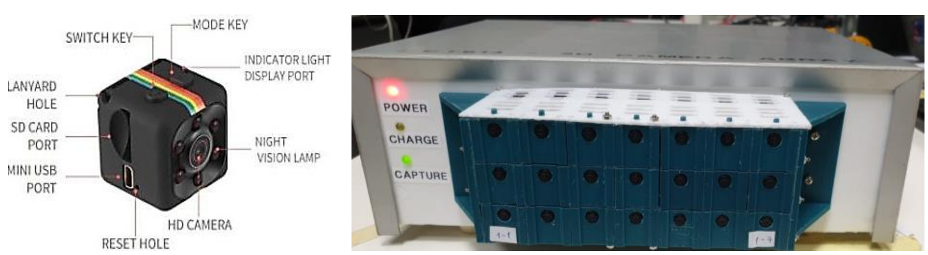

Fig. 1: (a) An illustration of the SQ11 camera and its features [9]. (b) An image of the INI21 camera array system. The system contains 3 × 7 cameras separated by 21.1 mm horizontally and vertically.

2.2 Camera Array Calibration

The proposed system is based on cheap off-the-shelf cameras that are later assembled into a camera array. This

Imaging and Applied Optics Congress 2022 (3D, AOA, COSI, ISA, pcAOP) @ Optica Publishing Group 2022

requires an intensive calibration to assure the proper functioning of the system. Calibration and rectification are needed for performing an accurate CII. Object detection from a reconstructed plane, obtained by the CII in a continuous frame grabbing, is applied for various reasons, such as scene simplification, object tracking in a 3D scene, navigation, etc.

The camera array captures RGB images. These images are converted to grayscale before performing the calibration process to speed the process. To use CII, the array should be rectified with minor shifting between the cameras, and these shifts and the shooting angles should be equal for all the cameras. A calibration process was applied to remove the lens distortion of each camera. The 2-D affine geometric transformation between the camera array and a reference camera can be estimated to compare scale, translation, rotation, and shearing by detecting the matching feature with each camera. This matching feature, a robust and flexible visual fiducial marker called AprilTag [10], has been detected by each camera. This fiducial marker is a 2D bar code style “tag”, allowing full 6 degrees of freedom localization of features from a single image. Then, the elemental images of the camera array were shifted accordingly, and the accuracy of the calibration process was validated.

3 Results

An object isolation algorithm, in which objects are detected and isolated according to the values of the gradient image along the depth axis in the CII reconstructed depth planes [5], was tested in our system. It was possible to isolate objects after the system calibration effectively. Results of depth-based object detection using this method are presented in Fig. 2.

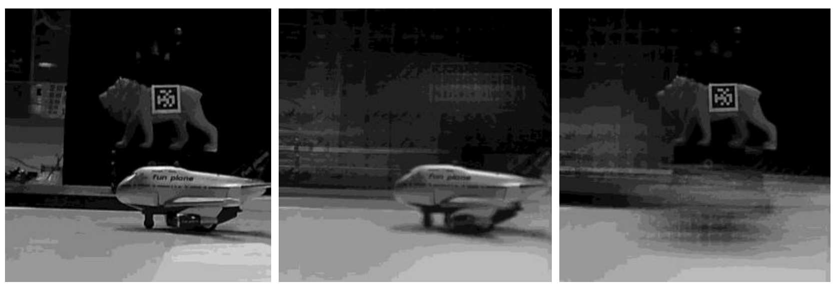

Fig. 2. Cropped reconstructed depth-plane images in the detected peaks of the average gradient magnitude of the CII reconstructed image planes. Left: original scene. Middle: reconstructed image at a depth of 280 mm from the camera. Right: reconstructed image at a depth of 600 mm from the camera. The airplane and lion toys were placed 280 and 600 mm away from the camera array, respectively.

4 Discussion and summary

A novel system with 3 by 7 cameras was developed and calibrated. An object isolation algorithm was tested on the elemental images (the system’s output) and found to work with similar effectiveness as was demonstrated with a synthetic aperture integral imaging system [5]–[8]. This system is the first step towards a glasses prototype for prosthetic vision, in which a miniature camera array is placed on the user’s glasses to achieve a higher quality prosthetic vision by performing depth-based object isolation on the input images of the prosthesis.

5 Acknowledgement

This work was supported in part by a US Department of Defense grant (W81XWH-16-1-0033), a NIH core grant P30EY003790, a gift from The Margaret and Leo Meyer and Hans M. Hirsch Foundation, and an Israel Science Foundation grant (No. 1519/20).

6 References

[1] G. Lippmann, “Épreuves Réversibles Donnant La Sensation Du Relief,” *J. Phys. Théorique Appliquée*, vol. 7, no. 1, pp. 821–825, 1908.

[2] M. A. Preciado, G. Carles, and A. R. Harvey, “Video-rate computational super-resolution and integral imaging at longwave-infrared wavelengths,” *OSA Contin.*, vol. 1, no. 1, p. 170, Sep. 2018.

[3] C. Yang, J. Wang, A. Stern, S. Gao, V. Gurev, and B. Javidi, “Three-Dimensional Super Resolution Reconstruction by Integral Imaging,” *J. Disp. Technol.*, vol. 11, no. 11, pp. 947–952, Nov. 2015.

[4] X. Li *et al.*, “Optical encryption via monospectral integral imaging,” *Opt. Express*, vol. 25, no. 25, p. 31516, Dec. 2017.

[5] D. Aloni and Y. Yitzhaky, “Automatic 3D object localization and isolation using computational integral imaging,” *Appl. Opt.*, vol. 54, no. 22, pp. 6717–6724, 2015.

[6] D. Aloni and Y. Yitzhaky, “Detection of object existence from a single reconstructed plane obtained by integral imaging,” *IEEE Photonics Technol. Lett.*, vol. 26, no. 7, pp. 726–728, 2014.

[7] D. Avraham and Y. Yitzhaky, “Effects of Depth-Based Object Isolation in Simulated Retinal Prosthetic Vision,” *Symmetry (Basel).*, vol. 13, no. 10, p. 1763, Sep. 2021.

[8] J. H. Jung, D. Aloni, Y. Yitzhaky, and E. Peli, “Active confocal imaging for visual prostheses,” *Vision Res.*, vol. 111, pp. 182–196, 2015.

[9] “SQ11 mini DV. User Guide,” pp. 9–12, 2018.

[10] E. Olson, “AprilTag: A robust and flexible visual fiducial system,” in *2011 IEEE International Conference on Robotics and Automation*, 2011, pp. 3400–3407.