

Portable Smartphone-Integrated Incubator for Real-Time Cell Culture Monitoring

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Abstract—Incubators play a crucial role in maintaining living conditions of healthy cell cultures by adjusting the temperature, humidity and gas composition. During conventional workflows, samples are usually removed for imaging purposes, leading them to expose inappropriate conditions that may compromise experimental reliability. Therefore, we present a compact, low-cost smartphone-based incubator capable of real-time cellular monitoring. The necessity for complex computer-integrated monitoring systems is eliminated by the implementation of smartphone for both imaging purposes and control interface. The enclosed chamber preserves optimal growth conditions, ensuring cell viability throughout observation, while its portable design supports precise environmental regulation and uniform culture media distribution. With this approach, an affordable, portable and smartphone integrated solution is achieved, enabling continuous cell tracking with a wide accessibility for real-time characterization in various laboratories and field environments.

Keywords—cell analysis, confluency, incubator, image processing.

I. INTRODUCTION

For cell culture experiments, a controlled environment is required and often maintained by incubators, operating at 37°C, 5% CO₂ and high humidity [1], [2]. Changes in environment, such as temperature, gas concentration and humidity, can occur due to removal of cell cultures for imaging, which can affect the results of the experiment [3]. Since conventional setups consist of incubators and imaging systems separately, this issue is crucial for long-term or real-time monitoring. Under these circumstances, data reliability and cell health can be affected in a negative way by unnecessary exposure to external conditions, the possibility of contamination and delays in returning the samples to incubator. To solve this problem, existing commercial devices either place a microscope directly inside an incubator or use incubation chambers that enclose the microscope to integrate imaging with incubation. Although these solutions provide real-time imaging, they can be costly, increase risk of contamination, be incompatible with different sizes of incubators, and damage electronics due to high humidity CO₂, which all can be considered as downsides. Researchers tried to develop low-cost prototypes [4], [5], [6], [8]; however, their portability and accessibility are constrained by customized optics, motorized stages, and computerized image acquisition. Smartphones are strong candidates for micro-imaging [9], [10] and integrating them

eliminates the need for complex optical systems or specialized computers, enabling real-time imaging. Nevertheless, there isn't an existing system, consisting of an integrated smartphone for imaging and a small-sized incubator for continuous cell monitoring. In this work, a low-cost portable platform with an integrated incubator and a smartphone for imaging is introduced for cell culture, proliferation and continuous monitoring, as demonstrated in Figure 1 [11]. The aim of design is sustaining environmental stability, high-quality image capturing, transferring outcomes directly with a smartphone application, removing the requirement of computerized bulky microscopes [12]. Its portability and compatibility with existing incubators enable sample imaging in an appropriate environment, eliminating the possibility of contamination, and increasing the reliability of experimental outcomes. Owing to low-cost production, incubator-based imaging can be adopted by a wider range, ensuring reliable experiments across various laboratory systems.

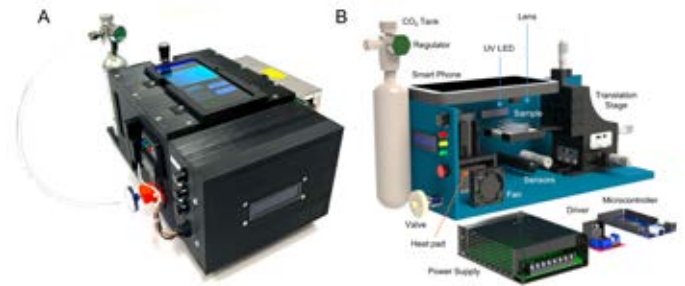


Fig. 1: Portable, low-cost incubator system: (A) photograph and (B) schematic diagram.

II. METHODOLOGY

A. System Architecture

A portable incubator has been developed by coupling a smartphone-based imaging module with an environmental control system for real-time cell observation and monitoring without bulky and computer-based microscopes. The incubator contains a small chamber that maintains intact cell growth under defined stable conditions. Additionally, it can ensure environmental homogeneity since the chamber has a small internal volume. Samples are illuminated by an LED array

beneath the chamber, and images are captured through a low-cost focusing lens mounted in front of the smartphone camera. A micrometric XYZ stage adjusts sample–lens distance for optimal focus. Environmental regulation consists of an Arduino control unit that controls the LED light source, heat pad, Thermal–Humidity (TH) and CO₂ sensors, and safety valve solenoid. The control unit energizes a heat pad to maintain the chamber at 37°C. The temperature is continuously monitored by the TH sensor. Humidity is maintained (>80%) generated from a water container above the heat pad, with the TH sensor sending alerts for refill downstream of 81% relative humidity. CO₂ concentration is maintained at 5% from a tank with a regulator and a sensor–valve system with feedback to limit overshoot. All environmental parameters are monitored during the run and reported in real time by an internal LCD.

B. Control Electronics

CO₂ levels were monitored using a nondispersive infrared (NDIR) sensor (0–100,000 ppm, UART output), while temperature and humidity were measured with a waterproof I²C sensor (–40 to 125 °C, 0–100% RH). To minimize random fluctuations, each reading was averaged across three consecutive measurements. Two independent relay channels delivered 12 V to the heating pad and the CO₂ valve. Optocoupler isolation was included to protect the microcontroller against current surges. An I²C LCD module displayed the measured values in real time. The chamber illumination consisted of parallel LEDs that incorporated an array of 1 W white LEDs. These LEDs were powered directly by the 3 V output on the Arduino. The L298N driver regulated current to the valve and heating element circuits. The primary power supply was a 12 V switched-mode power supply. A common cooling fan that also operated on 12 V was added and placed to homogenize the heat, humidity, and CO₂. Near-UV SMD LED UV-C (265 to 275 nm) was also mounted inside the chamber, and was periodically turned on as a microbial sterilization design feature.

C. PID-Based Regulation

PID feedback is obtained via the TH sensor with a setpoint of 38°C to regulate temperature control, accomplishing a consistent 37°C. The Peltier element power is switched between 0–190 PWM by Arduino for prevention of overheating. The reversion of current flow is triggered by surpassing of the target, initiating the controlled cooling. To avoid continual depletion cycles, CO₂ regulation utilizes a familiar PID logic, operating only in the incrementing direction. The valve opens for a maximum of 2 s per cycle, regulated by CO₂ sensor readings, to restore the 5% target concentration. Based on the CO₂ sensor readings, the valve opens (for up to 2 seconds per cycle) to restore the target concentration of 5%.

D. Image Processing Workflow

Cell confluency is calculated with an OpenCV-based pipeline to analyze images taken in BGR format. After de-noising the image with a median filter, the image is converted

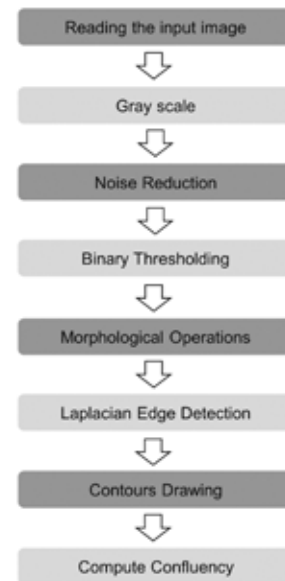


Fig. 2: Workflow diagram of the image processing method used for confluency estimation.

to a grayscale image and then a binary mask is created using adaptive Gaussian thresholding. Morphological opening and closing are used to remove artifacts and topologically fill small holes. Cell edges are measured using the Laplacian operator. This approach allows for providing accurate spatial mapping of cell coverage and for determining a quantitative parameter for assessing culture (Figure 2).

III. RESULTS

A. Incubator Performance

Environmental stability was accomplished by implementation of a microcontroller-based relay control system with sensor input. The regulation of CO₂ was held at 5.0% with $\pm 0.1\%$ variation by triggering valves for each 0.2s when the concentration was below 4.7% (94% of the set point). The loop maintains the setpoint without overshoot while counteracting the gradual return toward ambient conditions. Temperature control held the chamber at 37°C within $\pm 0.2^\circ\text{C}$, switching heaters continuously when below 90% of the target or in 0.5 s pulses when near the setpoint. The humidity was maintained at 82% in 8 to 10 minutes. When it goes down below 81%, minor manual refilling was required (Figure 3). Optocoupler isolation was utilized to protect separate relay channels, powering the heating pad and valve.

B. Confluency Analysis

The cell culturation of MCF-7 breast cancer cells seeded at 50,000 cells/mL took 2 and 3 days. The outputs of the image processing algorithm showed confluency levels of 54% and 67% respectively, demonstrating the ability of distinguishment of growth stages. Cluster regions were quantitatively marked by images processed by the algorithm, indicating the method offers spatial mapping alongside quantitative assessment.

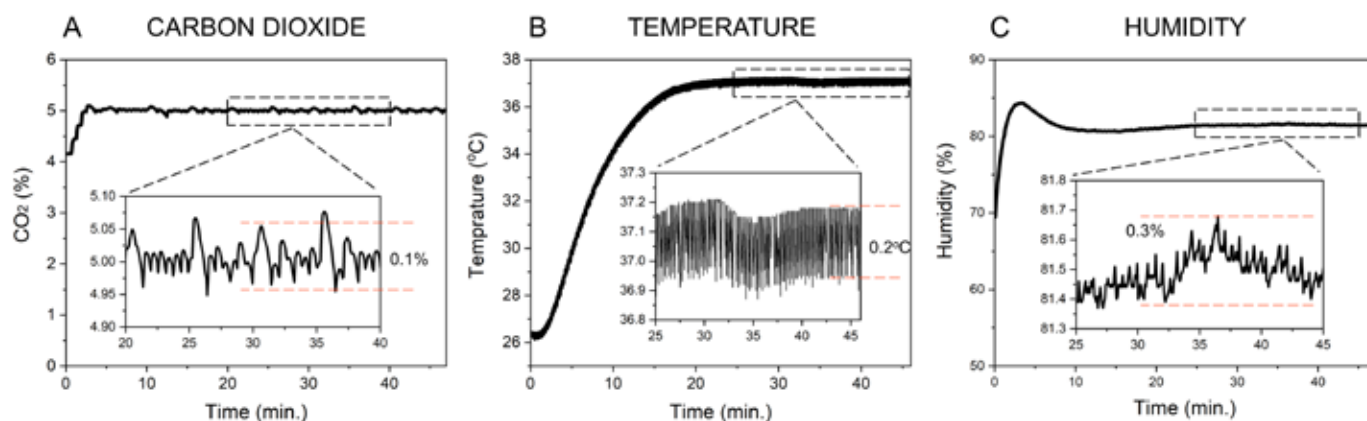


Fig. 3: Performance of the incubator in sustaining CO₂ at 5%, temperature at 37 °C, and humidity for cell culture. (A) CO₂ regulation via sensor–valve feedback. (B) Temperature control using sensor–heating pad feedback. (C) Humidity stabilization with the heating pad.

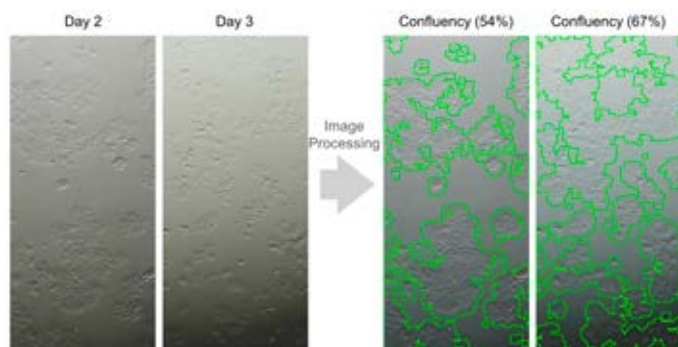


Fig. 4: MCF7 cell images captured on the second and third day of incubation.

C. Mobile Application

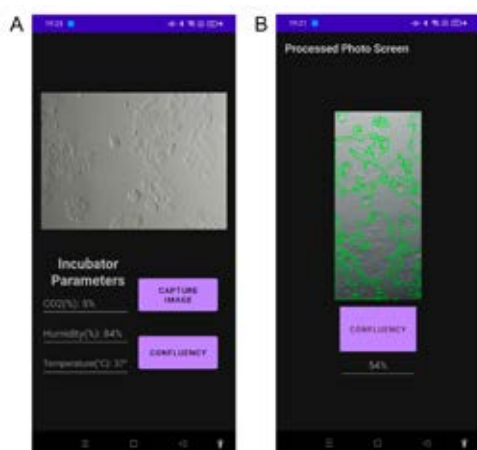


Fig. 5: Mobile application.

A Java-based application is developed with Android Studio for real-time monitoring of the incubator's CO₂, temperature and humidity sensor via USB connection. Instantaneous

analysis is achieved through integration of image processing algorithm to device, eliminating the requirement of additional computing, enabling a portable workflow for real-time cell imaging.

IV. CONCLUSION

To conclude, we introduced a compact smartphone-based solution with incubator system for live cell tracking. A lens assembly is integrated into smartphone to capture petri dish images, while the CO₂ and temperature sensors are controlled by a microcontroller. The system is enclosed in a 3D-printed case, merging environmental control and imaging in a portable, cost-effective platform as a practical solution for real-time cell imaging.

REFERENCES

- [1] Y. K. Jawale, U. Rapol, and C. A. Athale, "3D-printed focussing mechanism for cellphone-based cellular microscopy," *J. Microsc.*, vol. 273, pp. 105–114, 2019.
- [2] V. Müller, J. M. Sousa, H. C. Koydemir, M. Veli, D. Tseng, L. Cerqueira, A. Ozcan, N. F. Azevedo, and F. Westerlund, "Identification of pathogenic bacteria in complex samples using a smartphone based fluorescence microscope," *RSC Adv.*, vol. 8, pp. 36493–36502, 2018.
- [3] A. Orth, E. R. Wilson, J. G. Thompson, and B. C. Gibson, "A dual-mode mobile phone microscope using the onboard camera flash and ambient light," *Sci. Rep.*, vol. 8, p. 3298, 2018.
- [4] N. A. Switz, M. V. D'Ambrosio, and D. A. Fletcher, "Low-cost mobile phone microscopy with a reversed mobile phone camera lens," *PLoS One*, vol. 9, p. e95330, 2014.
- [5] H. Zhu, I. Sencan, J. Wong, S. Dimitrov, D. Tseng, K. Nagashima, and A. Ozcan, "Cost-effective and rapid blood analysis on a cell-phone," *Lab Chip*, vol. 13, pp. 1282–1288, 2013.
- [6] M. P. Walzik, V. Vollmar, T. Lachnit, H. Dietz, S. Haug, H. Bachmann, M. Fath, D. Aschenbrenner, S. A. Mofrad, O. Friedrich, and D. F. Gilbert, "A portable low-cost long-term live cell imaging platform for biomedical research and education," *Biosens. Bioelectron.*, vol. 64, pp. 639–649, 2015.
- [7] Q. Wei, H. Qi, W. Luo, D. Tseng, S. J. Ki, Z. Wan, Z. Göröcs, L. A. Bentolila, T. Wu, R. Sun, and A. Ozcan, "Fluorescent imaging of single nanoparticles and viruses on a smart phone," *ACS Nano*, vol. 7, pp. 9147–9155, 2013.



- [8] D. K. Rajan, J. Kreutzer, H. Välimäki, M. Pekkanen-Mattila, A. Ahola, A. Skogberg, K. Aalto-Setälä, H. Ihalainen, P. Kallio, and J. Lekkala, "A portable live-cell imaging system with an invert-upright-convertible architecture and a mini-bioreactor for long-term simultaneous cell imaging, chemical sensing and electrophysiological recording," *IEEE Access*, vol. 6, pp. 11063–11075, 2018.
- [9] K. Su, Y. Pan, Z. Wan, L. Zhong, J. Fang, Q. Zou, and H. Li, "Smartphone-based portable biosensing system using cell viability biosensor for okadaic acid detection," *Sens. Actuators B Chem.*, vol. 251, pp. 134–143, 2017.
- [10] K. Yang, J. Wu, H. Peretz-Soroka, L. Zhu, Z. Li, Y. Sang, J. Hipolito, M. Zhang, S. Santos, C. Hillier, R. L. de Faria, Y. Liu, and F. Lin, "Mkit: A cell migration assay based on microfluidic device and smartphone," *Biosens. Bioelectron.*, vol. 99, pp. 259–267, 2018.
- [11] A. E. Cetin, "A portable and low-cost incubator system enabling real-time cell imaging based on a smartphone," *Turkish Journal of Physics*, vol. 47, no. 5, pp. 279–296, 2023.
- [12] M. B. Avci, S. D. Yasar, and A. E. Cetin, "An optofluidic platform for cell-counting applications," *Analytical Methods*, vol. 15, no. 18, pp. 2244–2252, 2023.