My First Biolab: a System for Hands-On Biology Experiments

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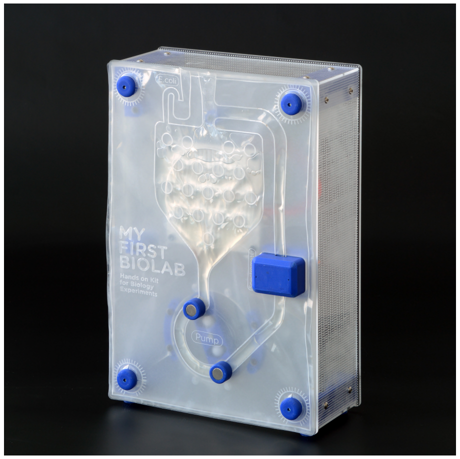

Figure 1: My First Biolab (MFB)
A lab in a box and experiment in a bag.

ABSTRACT

Biology labs routinely conduct direct experimentation with living organisms. However, most high-schools are not able to engage students in such experimentation due to multiple factors: sterility, cost of equipment, cost of skilled lab assistants, and difficulty measuring micro-scale processes. We present the design and implementation of My First Biolab (MFB), a lab in a box with a novel disposable fluidic vessel (experiment in a bag) using two sheets of Polyacrylamide-Polyethylene channeling liquids via paths created with a laser-cutter. The system implementation includes a 2D magnetic peristaltic pump, a spectral sensor, and a heat transfer plate. MFB is an affordable, safe, and sterile system for hands-on experimentation with live microorganisms. Our system supports temperature control, liquid circulation, measurement of optical density, and a web interface for remote control and monitoring. Our first experiment demonstrates the three phases of bacterial growth: initial lag phase, the rapid-growth log phase, and the stationary phase.

KEYWORDS

Macrofluidics; Education; Biology; Human Biology Interaction (HBI); Design;

INTRODUCTION

Research in life sciences often involves the study of living organisms using direct experimentation. Scientists need tools for conducting experiments and for measuring the effect of various parameters. Without such tools, research and discovery are unachievable. Microbial cell culturing is a fundamental scientific practice when introducing students to the field of biology [11]. This practice is still confined to professional research labs and not available for K-12 education [3].

In physics and chemistry, high schools are able to provide students with tools for direct experience, empowering students to conduct experiments and experience scientific discovery [7]. Due to advancements in life sciences, there is a growing need for tools that will enable teachers to provide students with direct experience [12]. However, high schools are not able to provide students a direct experience with live microorganisms. The barriers for microbiology experimentation in classrooms include: strict regulations, safety, sterility, long experiments duration (far longer than a class), lack in funds for equipment that can maintain temperature control and liquid circulation, difficulties in visualizing processes that happen in micro-scale, and the personnel with the skills required to operate relevant equipment. We present My First Biolab (MFB) (See Figure 1), a microbiology teaching kit designed specifically for direct, hands-on experimentation with live organisms and cell cultures. MFB allows students to work in a safe and sterile way, with temperature and circulation control, and with the ability to monitor bacterial growth remotely.

Regulation in Classrooms
Biosafety Level 1 (BSL1) is a set of precautions required for work involving well-characterized agents not known to consistently cause disease in healthy individuals, and present minimal potential hazard to laboratory personnel and the environment. BSL1 requires primary barriers and personal protective equipment [2]. In high schools, main safety measures include: personal protection, standard laboratory procedures, and the need for trained personnel [3].

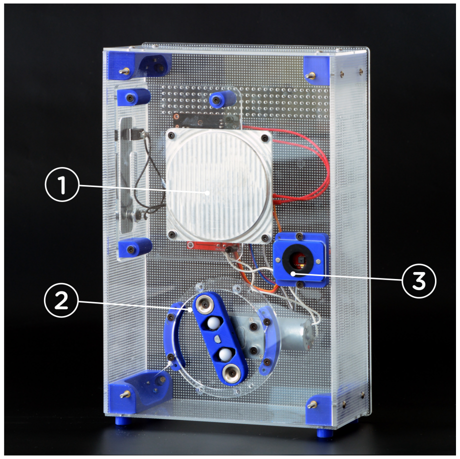

Figure 2: The MFBbox
1. heat transfer plate. 2. magnetic peristaltic pump. 3. Spectral Sensor.

Digital Interfaces Simulating Biology
Simulating biological processes using digital and tangible interfaces rather than conducting experiment with live organisms is one approach to introduce biology to students. Such methods include video games, augmented reality, and tangible interfaces. BacPac is a digital museum experience that introduce synthetic biology [10]. BacToMars is an educational video game that engage school children in a microbiology activity [9]. SynFlo is a tangible museum exhibit for exploring microbiology biodesign [13]. Advantages of such approaches include the ability to speedup growth processes, avoid regulatory barriers, and an addition of digital feedback.

RELATED WORK

Biology labs that enable scientific microbiology experimentation exists in universities and selected high schools, but is out of reach for most high schools and after-school centers [1]. Such labs require a qualified lab technician and expensive equipment (over 3000 USD in the minimal case) including an autoclave (for sterilization), an incubator (for temperature control and circulation), and a spectrophotometer (for measuring bacterial growth). In addition, working with microorganisms requires active safety measures to obtain a BSL-1 biosafety permit (see Sidebar on previous page). Safety measures include non-porous (vinyl) covers for biology work surfaces, biohazard waste bins, a waste-pickup procedure for biological materials, and a labeled fridge for organic materials and reagents [7].

In recent years, tools and platforms were developed to support microbiology experimentation in schools, and can be classified to two approaches: simulation tools (see Sidebar) and live biology experimentation (detailed below). Academic projects for children that enable interaction with live biology include Biobits, an affordable molecular biology educational kit based on freeze-dried, cell-free reactions that engage the senses [4], and the Ludusscope smartphone-based microscope, enabling students to interact with very small live organisms (single-celled algae) [6]. Projects that enable cell culturing include Biorealize [5], a fabrication tool for synthetic biology activities in K-12 education, used by students to create logos on petri dishes with live bacteria that were genetically modified to express pigments; and Bioart workshop [8] that utilized antibiotics to enable students to paint and erase with microorganisms that were grown on agar plates. These pioneering works enable experimentation with microbial cells and cell culturing, our contribution is the added sterility, safety, controlled conditions, and real-time measurement and visualization of bacterial growth.

Industry platforms for schools aimed at cell culturing include DNA playground (395 USD) and BioExplorer (1695 USD) for cultivating genetically modified microorganisms, allowing students to modify live bacteria by introducing new genes and plate them on solid or liquid media. Beside the cost, these systems pose challenges with sterility and lack of real-time measurement.

Our work differs by enabling a controlled cell culturing process, in an affordable cost and with appropriate safety measures. The MFB kit provide cell culturing conditions that are similar to professional biology labs, including sterility, temperature and circulation control, with real-time measurement and visualization of bacterial growth through liquid optical density, and with remote control and remote monitoring.

DESIGN AND IMPLEMENTATION

The MFB system has three main components: a Lab in a box (MFBbox), an Experiment in a bag (MFBbag) and a User Interface (MFBUI). The MFBbox is comprised of a 2D magnetic peristaltic pump, a spectral sensor, and a heat transfer plate (See Figures 1 and 2). The MFBbag is a sterile custom

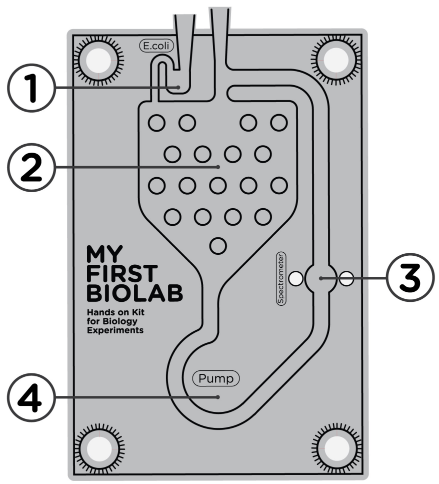

Figure 3: The MFBbag
1. Inoculation chamber. 2. Cultivation area. 3. Spectral sensing area. 4. Pump channel.

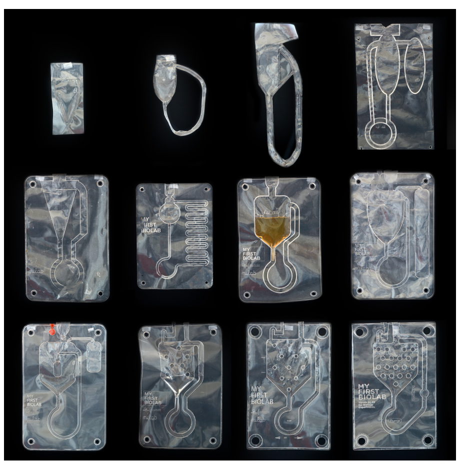

Figure 4: Bag Design Iteration Process

designed nylon bag, which includes all biological materials and fluidic structures required for a single experiment. The MFBUI allows for remote operation and continuous monitoring of the experiment (See Figures 5 and 6). The system was designed to comply with BSL-1 regulations, but did not go through regulatory process yet.

The MFBbag

The MFBbag (See Figure 3) is a novel solution enabling a full experiment setup in one container. The MFBbag is created using two sheets of Polyacrylamide-Polyethylene (PAPE), which is often used in the food industry for vacuum packaging and heat sealing. The two layers are welded together using a laser cutter, allowing accurate formation of "Macrofluidics", channeling the liquids via paths formed using different geometries. This technique offers several advantages: flexibility and accuracy in the Macrofluidics path design; transparency that reveals the biological experiment processes and the system mechanisms; safety and sterility; liquid manipulation by users; annotation of experiment details on the bag; and safe disposal. MFBbags are designed using standard vector design tools (Adobe Illustrator). Laser cutting allows for flexible, accurate and low-cost iterations of the design (See Figure 4). In this paper we present the first MFBbag, designed for bacterial growth curve experiment. The Macrofluidics geometry enables a cultivation area, an inoculation chamber, a pump, and a spectral sensing area. The inoculation chamber is designed as a "swan neck" shape, to keep the bacteria separated from the media until the user will manually move it to start the cultivation process.

The MFBbox

The MFBbox plastic case holds a D1 mini board (an ESP-8266EX, Arduino compatible board with built-in Wi-Fi) that controls the 2D magnetic peristaltic pump, spectral sensor, and heat transfer plate. The case is constructed from laser cut acrylic sheets with 3D printed custom connectors. The MFBbag is designed to be placed on top of the MFBbox (See Figure 2).

"2D" Magnetic Peristaltic Pump. Professional bioreactors cultivate microorganisms by mixing the biological materials in various ways. Mixing is critical to distribute the bacteria evenly in the liquid. We designed a peristaltic pump that enables continuous mixing using a DC motor and two magnets placed over the MFBbag, keeping the experiment sterile at all time (See Figure 2, 2).

Temperature Control. Temperature is one of the most influential elements on biological reaction rate. We fabricated an aluminum-based heat transfer plate using a CNC milling machine (See Figure 1, 1), and fitted it to the acrylic case. The plate can be heated using a 12V, 40W ceramic heating element with an aluminum thermal core, controlled by the D1 mini board. We installed a DS18B20 temperature sensor on the heat transfer plate, allowing proportional-integral-derivative (PID) control. We added a wired environment temperature sensor and calibrated the system to overcome the temperature

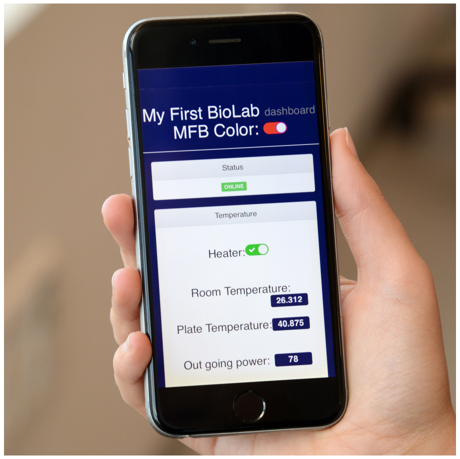

Figure 5: The MFBUI
The web based interface has the ability to control multiple systems, set temperature, pump direction and speed, and start or stop the spectral measurement.

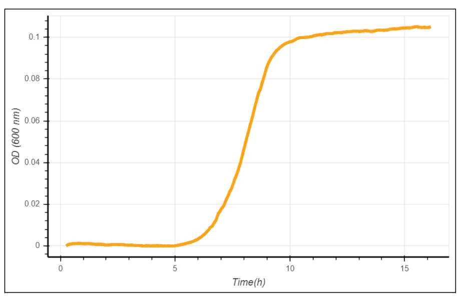

Figure 6: Microbial growth curve
Data from the spectral sensor is visualized on a graph showing OD600 readings, representing bacterial growth over time. Users can access the data at all times through the MFBUI.

difference between the liquid (inside the MFBbag) and the heating plate, so that the temperature defined by the user in the MFBUI would correlate with the desired liquid temperature.

Spectral Sensor Data Visualization: Estimating Bacterial Growth. In professional biology labs, estimation of liquid-based bacterial growth is done by collecting liquid samples, and then measuring the liquid Optical Density (OD) in 600nm wavelength (OD600) using a spectrophotometer. Spectral sensor measure how much light passes through liquid in time "X" relativity to time "0" (-log(OD(X)/OD(0)), and the result is defined as the OD. We implemented an affordable version of a Spectrophotometer using an LED and a Spectral Sensor (Sparkfun AS7262 Visible Breakout), and achieved OD600 as a means to estimate bacterial concentration in liquid. The sensor is located inside the MFBbox, and the LED is mounted over the MFBbag using magnets (See Figure 1). The magnets also conduct electricity for powering the LED, which illuminates through the liquid to the sensor (See Figure 2, 3). The sensor measures the light passing, allowing continuous, sterile, and remote measurement without interfering.

The MFBUI

The MFBUI is an online interface accessible by web, allowing the control of system parameters and the remote monitoring of bacterial growth over time (See Figures 5 and 6).

RESULTS AND DISCUSSION

We presented the MFB prototype, a safe, sterile, and affordable system for microbiological experiments. MFB's novel Macrofluidics design using common laser cutter enables easy production of different types of "experiments in a bag". Our first MFBbag design is relevant for microbial growth, a standard biology lab process. Our system's built-in sensor produced continuous OD600 data, showing the different phases of bacterial growth: initial lag phase, the rapid-growth log phase, and the stationary phase. We hope our system can overcome the barriers limiting high-school students from direct experimentation with live biology. The current system is semi-modular and can support more experiment by cutting a new acrylic front for the MFBbox and designing a new macrofluidic circuit for the MFBbag.

LIMITATIONS AND FUTURE WORK

This initial work will be followed by a user study with high-school students. One of the systems limitations comes from the sterility of the MFBbag, preventing students from adding or extracting biological materials from the bag.

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