OpenLH: Open Liquid-Handling System for Creative Experimentation with Biology

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ABSTRACT

The biological prototyping revolution is in motion, and new tools are needed to empower HCI researchers, designers, makers, and bio-enthusiasts to experiment with live organisms. We present OpenLH, a liquid handling system that empowers users to conduct accurate and repetitive experiments with live biology in a sterile, open, and affordable way. OpenLH integrates a commercially available robotic arm with custom 3D printed parts, a modified pipette, and a visual block-based programming interface. The system is as accurate as commercial liquid handlers, capable of repetitive tasks in micro-scale accuracy, easy to operate, and supports multi-materials including biomaterials, microorganisms and cell cultures. We describe the system's technical implementation and two custom interfaces. We demonstrate the system's impact for the HCI community with two use cases that include experimentation with live biology in non-traditional fields: visual design using pigment-expressing E.coli, and beer brewing experiment using serial dilution in home context.

CCS Concepts

•Human-centered computing → **Interactive systems and tools;** **•General and reference** → *Design;* **•Applied computing** → *Computer-aided manufacturing;*

Author Keywords

Liquid-Handling; Open Source; Biology; Prototyping; Experimentation; Democratization.

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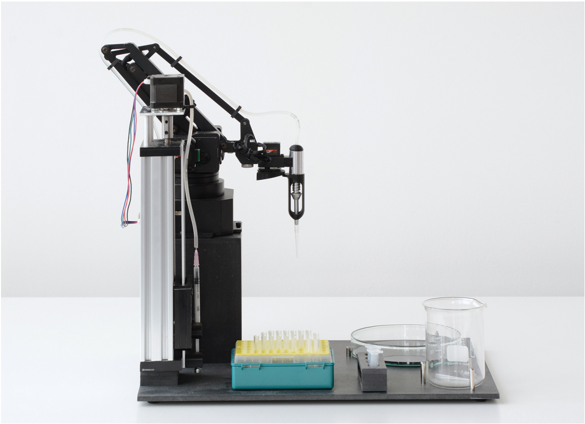


Figure 1. Open LH: an open liquid-handling system for accurate, safe, flexible, and affordable biological experimentation.

INTRODUCTION

In recent years, advancements in biology research such as streamlining of DNA sequencing and synthesizing [7, 46] led to the introduction of new tools that move biology-related technologies out of research labs and into the hands of engineers and biohackers [19, 34, 43, 45]. The next wave of more accessible tools for biology exploration has the potential to reach new audiences beyond engineers and technically-minded biohackers [33]. Simpler DIYbio tools can engage a larger community of bio-enthusiasts such as designers, artists, educators, and HCI researchers [30][16], enabling creative exploration of biology in a variety of contexts, including education, citizen science, bio-fabrication, experimental art, smart materials prototyping, and more [28, 8, 13, 14, 44, 52, 54]. This process, if realized, may be similar to previous technological shifts from high-end industry to the general public, most notable ones are CNC milling and 3D printing for distributed production [38, 29], and the Arduino revolution that democratized electronic prototyping [47]. Existing tools that already contribute to the democratization of biological prototyping include Gaudi labs's DIY lab equipment [32]; Amino educational tools for genetic engineering [31]; Bento thermo-cycler centrifuge and gel electrophoresis [4]; Open PCR DIY thermo-cycler [41]; a DIY fluorescence microscope [10]; Foldscope foldable paper origami microscope [11]; and Paper centrifuge [5].

One of the most commonly used processes in professional biology experimentation is pipetting, or Liquid-Handling (LH). The standard pipette, found in any biology lab around the world, is a handheld tool which is used to transport measured volumes of liquid (0.1-1000 µL) while maintaining sterile conditions. In domains such as microbiology, genetics, protein engineering, and diagnostics, LH is the most basic and common technique, and must be performed by skilled biologists, in a manual process done "with an experienced hand". In some advanced labs, computer automated LH is done using high throughput digital robotic systems that are very expensive and require a technician for programming new protocols [27]. The barriers LH is posing for non-biologists are the skill needed to be acquired for manual LH, the funds, biological knowledge, and technical knowledge needed to conduct experiments with the computer automated LH systems.

We present OpenLH (see Figure 1), an open-source LH system that is accurate, affordable, and flexible, supporting experimentation and creative exploration. OpenLH enables repetitive LH tasks in micro-scale accuracy, is easy to operate, and can be programmed using a block-based interface that does not require any technical knowledge.

The system is intended to be used by a wide variety of bio-enthusiasts, with two main user groups: makers who assemble the system, and end-users who conduct experiments using the system. Makers can assemble the system at parts cost with standard fabrication tools using our free fabrication files, and then integrate it into makerspaces, after school centers, HCI labs, or their own workshops; end-users will use the system in makerspaces or schools to perform experiments and creative exploration of biology.

The system is "open" in several ways: makers can download the fabrication files for building the system's custom syringe pump, pipette shaft attachment, and pipette tip ejector (see Figure 2); the code is available for free use and modification; the off-the-shelf commercial parts are available for purchase from third parties in significantly lower costs than systems of comparable performance; end-users can code the system with a simple block-based language; experiments performed with the system are "open" for manipulation as the whole system design encourage intervention; finally, the system is expandable with custom interfaces, new software, and new hardware features.

This process of makers making DIY tools more accessible to the community happened before, for example with low cost FDM 3D printers.

In this work we contextualize and differentiate OpenLH from prior work, describe the system implementation, report on its technical performance and present proof-of-concept use cases of creative experimentation with live biology. Clearly a user study is needed to evaluate how makers and bio-enthusiasts use this new tool, future work will asses that.

RELATED WORK

Our work was inspired by a collection of works within the HCI field that bring DIYbio closer to novices, for creative exploration or science education. Our work also differs from professional lab-grade liquid handlers, recent advancements in XYZ gantry liquid handlers, professional bioprinters, and innovative prototypes for smart material deposition.

DIYbio in HCI

Our work was inspired by the mission of creating "low-cost tools for performing biology work in non-professional settings", as expressed by Kuznetsov and collaborators when studying DIYbio from a design and HCI perspective [30], and manifested in their design for an incubator using low-cost materials and off-the-shelf components [16]. Another inspiration came from Bioart and specifically agar art, a community culturing art with agar plates, including an annual contest conducted by the American Society for Microbiology. A recent study with high-school students showed how students creatively "painted" with bacteria and antibiotic substances [28]. Kafai and collaborators introduced the BioMakerLab in high-school classrooms [24], a wet lab starter kit for synthetic biology, utilized by students to create logo designs using microorganisms they manipulated to produce different colored pigments. Riedel-Kruse and collaborators have created novel interactive experiences and tools for Human Biology Interaction (HBI): LudusScope is a smartphone-based microscope for life-science education [25]; Trap it [35, 36] and BioGraphr [18] are interactive system enabling users to interact with living cells by drawing on a touchscreen using Euglena, a microorganism with photo-tactic properties. In addition, Bioty [53] is a JavaScript-based web toolkit that allows to remotely program protocols to manipulate Euglena cells. OpenLH contributes to this emerging effort within the HCI community with an accessible and affordable LH tool.

Figure 2. 1. The custom-made liquid handling attachment. 2. the uArm Swift Pro robotic arm. 3. The linear actuator-syringe pump.

Differentiation from existing liquid-handlers and bioprinters

Commercial liquid handlers from companies such as Tecan [48]and Biotek [6] are made for professional biology labs use and run mostly predefined protocols that support standard kits for experiments. These commercial LH systems are estimated at 50,000 USD and above, are made for high throughput research, and include advanced features such as climate control, mixing, and shaking. These systems are designed to conduct standard protocols, such as ELISA, bacterial growth, fluorescence measurement, incubating shaking, and more. The result is a highly accurate and professional research tool, but a very rigid one that limits creative exploration and is not accessible to many, both biologists and non-biologists, due to its high cost.

The Andrew LH robot [1], estimated at 24,000 USD, is a desktop pipetting machine that can pick up pipettes from a stand, configure volume and conduct LH without electronic pipetting. Andrew mimics the human hand, picks up standard pipettes from a rack and calibrates the pipette as a human hand would. Andrew also offers a software for standard LH protocol design. Andrew is "computer-vision-assisted " and uses a camera to analyze the motor activity as it is changing volume on the standard pipette. It's a robot customized to use a product (pipette) that was designed for the human hand and eye.

A recent commercial product designed to make automated LH more accessible to labs is sold by Opentrons, the OT-1 and OT-2 products that cost an order of magnitude less than other commercial systems (4000 USD for the OT-2 basic setup). Opentrons is a XYZ gantry based system that has a controlled thumb that handles standard pipettes (OT-1). Their second product (OT-2) solved known problems with the OT-1 version by adding electronic control instead of the previous mechanical control. Specifications for the OT-2 include 2 pipette mounts, it can fill a 96 well plate in 20 seconds, is accurate down to 384-well plates, is a medium size machine at 63 cm x 57 cm x 66 cm, and weighs 40kg. The OT App is used to conduct standard protocols with standard tubes and plates. OpenLH differs from Opentrons by allowing more creative exploration, is more affordable, and is more portable due to its size and weight.

The Lego Liquid handler [17] is able to do effective LH work using a Lego built liquid handler operated by a Lego app. Compared to Gerber et al.'s Lego robot, our system supports multi-material and sterility by utilizing tip replacement, has a more flexible UI and is more robust and industry-ready. Regarding droplet size, comparing a similar 1ml syringe in both systems, Gerber et al.'s minimum droplet size is 2.5 µL while we reach 0.2 µL. The difference comes from our use of a more precise linear actuator operating a syringe pump controlling the vacuum between the syringe and the disposable tip. Gerber et al. were able to reach 0.15 µL droplet size using a smaller 25 µL syringe. We did not test with smaller volume syringes, but we estimate the result to be proportionally smaller.

Bioprinters or bioplotters are XYZ dispensing robots that print bio-materials and cells for the bioprinting industry. Commercials examples include bioplotter by EnvisionTEC [15], NovoGen by Organovo [42] and BioBots by ASLS [2]. CELLINK [9], a Swedish company is selling the 40,000 USD BIO-X a 3D Bioprinter that has three piston driven syringe heads and requires purchase of the syringes that cost hundreds of dollars per unit. Biobots from Advanced Solutions have developed the first six DOF Bioprinter, it also uses syringes that can be replaced (Up to eight replaceable tools), and a basic system that supports five cartridges and three-axis motion including rotational stage movement. In addition they have software that supports functional tissue structure design and design vascular systems.

The xPrint system is a novel smart material printing prototype used for bioprinting, developed at the MIT Media Lab. xPrint [51] is a significant milestone in the process of making LH tools more open and relevant for creative use. The system allows for a wide range of printing by active extrusion of thick gels and uses custom made cartridges. The system is not yet available commercially but is estimated at 7000 USD, and can be built by experienced makers with significant effort.

The following aspects are the key differentiators of OpenLH: Affordable: OpenLH is as accurate as professional lab-grade liquid handlers and XYZ gantry systems such as Opentrons with a standard 200 µL tip, while parts cost is much lower (under 1000 USD).

Multi-tip: our novel mechanism of linear-actuator operated syringe, using stepper motor on a linear rail, works with standard pipette shaft that transfers accurate quantities of liquid using a disposable tip from a tip rack. Leveraging tip replacement allows for multi-material usage and supports sterility. This novel mechanism supports: (1) multi-material deposition; (2) adequate accuracy; and (3) lab-grade sterility.

Customizable intuitive UI's: a Python API enables custom creation of interfaces. A Blockly-based interface was created to enable novices to code non-standard protocols and a bitmap-to-bioprint interface was created to convert images to biological prints. These two interfaces promote creative exploration empowering novices. Expert users with programming ability can also leverage the Python API to program protocols, or to extend the system.

Creative expansion: our system is designed to encourage exploration, with an open architecture both from the technical and operational aspects. From the technical aspect, the uARM robotic arm has an active community of developers that can broaden the system's capabilities, for example a UV LED for hydrogel crosslinking, and a camera for online assessment and colony recognition. From the operational aspect, the system is literally open, users can intervene with the LH process in many creative ways, for example by changing environmental factors such as using a flashlight to light specific areas in the agar plate while the LH is in progress, or inserting the system into a refrigerator.

TECHNICAL IMPLEMENTATION

The OpenLH system is comprised from the following modules: a uArm Swift Pro robotic arm for spatial positioning; a linear-actuator based syringe pump for LH; a custom attachment

Figure 3. Closeup of the custom-made liquid handling attachment extracting bacterial culture from a tube (left) and disassembled (Right). 1. pipette shaft. 2-3. 3D printed parts for tip displacement. 4-5. 3D printed adapters. 6. uArm end-effector.

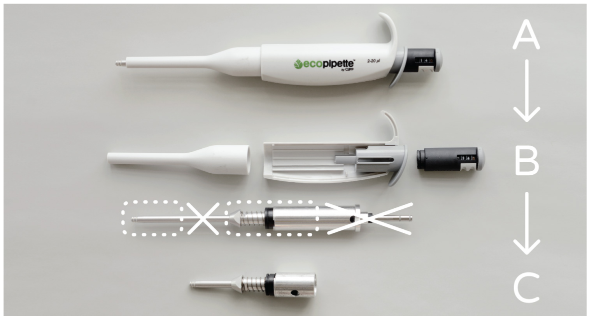


Figure 4. Pipette modification: (A) Original commercial pipette; (B) Disassembled pipette and modification guidelines; (C) Custom-made parts to be embedded in the LH attachment.

for programmable tip switching; custom software; and two custom UI's: a block-based programming interface and a bitmap-to-bioprint script.

Robotic Arm Base

The system is built as an extension on top of the uArm Swift Pro robotic arm (see Figure 2), commercially available since 2017 for the cost of 749 USD. It has a small footprint, weighs 2.2kg and has 4 DOF. It allows for 0.2mm repeatability and a max speed of 100mm/s. It can lift 500g and has a range of 50-320mm [50]. It can communicate through USB cable and Bluetooth connection. The uArm structure enables assembling various attachments to the end effector unit, including a 3D printing head and a laser engraver. This setting enabled customization and allowed us to integrate our LH parts. The dependency on a specific, commercial, robotic arm may become a limitation in the future, however with little adjustments the system can support many other robotic arms with similar architecture, including DIY ones. The choice to use a commercially available arm was made to lower costs, lower the barriers of building a system, and to improve consistency.

Custom Hardware

Syringe Pump

The pump was constructed by using an off the shelf linear actuator mounted with a syringe (See Figure 2). The Linear actuator used was an openbuilds-C-Beam Linear Actuator Bundle (129 USD) [40], operating a standard 1ml syringe with needle. A flexible tube from MasterFlex model 96410-13 (5 USD) connects the syringe to a custom-modified pipette. The result is an airtight environment from syringe to tip enabling professional-grade LH. The syringe is connected to the Linear actuator with custom designed 3D printed parts.

LH Attachment

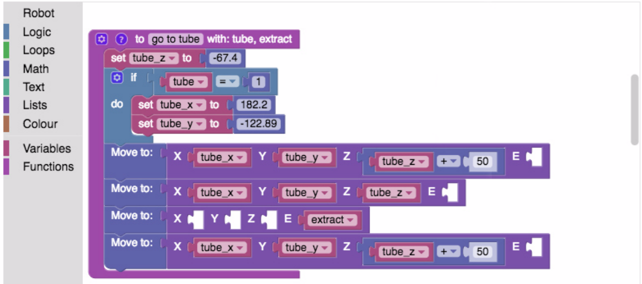
We used parts of a standard pipette (65 USD) in a custom made assembly to allow attachment to the robot and tip switching (see Figure 3). We used a shortened shaft of an ecopipette (sold by Capp, see Figure 4) including the spring, and connected it to the arm with a custom 3D printed part. The tip removing accessory is made from two 3D printed parts (see Figure 3). The disc connects to the end-effector motor of the uARM (see Figure 3) that rotates 90°, designed to push the pipette and lead to tip removal. After a tip is disposed, the disc rotates back to 180° and the spring pushes the part back up so another tip can be picked up. All 3D printed parts are made with standard PLA and printed with the Ultimaker 3, an accessible 3D printer.

In summary, we utilized an existing, low-cost robotic arm and designed custom 3D printed parts to enable a unique mechanism: (1) attaching the pipette shaft from an industry grade dismantled pipette to the robotic arm to increase reliability; (2) attaching the syringe to the linear actuator enabling precise control of the vacuum between the syringe and the disposable tip; and (3) used the robotic arm servo attachment as a compact pipette release mechanism, leveraging the disassembled pipette original spring. Detailed assembly instructions, BOM, and design files are available in the supplementary materials, and updated versions will be shared online on the project's Instructables page [23].

Control Software

The uArm runs on top of an Arduino Mega 2560 with a custom version of Marlin firmware (available under GPL licence). The robot operates using G-code definitions sent through UART protocol, which complies with both industry standards and with most tools used in the maker community such as open source 3D printers. uFactory provides several libraries for interacting with the robotic arm including pyuf [49] - a Python interface (others are a ROS interface, a Marlin firmware implementation, the uArm for CURA 3D plugin, and uArm studio which is not open source). We chose to use the Python library, available under BSD licence, for the ease of use of Python in prototyping. This library wraps around the serial connection and the G-code encodings. We modified the provided code of the Python interface, allowing us to send the position of the arm and the desired rotation in the extruder motor.

As we used the stepper motor for operating the syringe pump in a similar way to how it is used for 3D printing, we were able to take advantage of the control commands already available for it. To achieve this, before every execution we send an M code that will disable cold extrusion protection, then we can send G-code in the following format: G0 [E<pos>] [F<rate>] [X<pos>] [Y<pos>] [Z<pos>], where E represents the length of filament extruded by the feeder when used for



```
to go to tube with: tube, extract
  set tube_z to -67.4
  if tube = 1
  do set tube_x to 182.2
     set tube_y to -122.89
  Move to: X tube_x Y tube_y Z tube_z + 50 E
  Move to: X tube_x Y tube_y Z tube_z E
  Move to: X Y Z E extract
  Move to: X tube_x Y tube_y Z tube_z + 50 E
```

Figure 5. Example for writing a function "go to tube", that extracts liquid from a tube.

3D printing. We used these values to specify the amount of liquid dispensed or drawn. With this architecture we were able to create a variety of non-technical interfaces, that increases accessibility to novices. With this modified API, users with programing ability can use Python to control the system directly, or to create new interfaces for different user groups. We created two initial interfaces to demonstrate how non-technical interfaces can empower non-biologists and non-programmers: (1) A block-based visual programming interface using Google Blockly for intuitive creation of highly customizable protocols; (2) A printing script that enables conversion of bitmap images to LH instruction (bioprinting). The two custom interfaces are described below.

Block Based Interface

We chose to create a block-based interface (see Figure 5) to provide an accessible method for non-programmers to control all of the system's abilities. Block-based interfaces such as Blockly, Scratch and many others are commonly used to introduce novices to programming, and Scratch has been shown to be successful in letting novices learn programming and use it to explore a new domain [12]. While uArm already offers a block based interface, it is not available in an open license and free to edit, so we were not able to expand it with our added capabilities. We chose to use Blockly which is a visual programming platform, similar to Scratch. It enabled us to create custom blocks as functions, allowing users to accurately control the arm and LH process with a minimum number of blocks, and can easily develop the operations needed for their specific experiment. In order to use the publicly available Blockly interface we created two components: a web server and a UDP server. The web server is responsible for serving the Blockly files, saving programs in blocks, converting the blocks to the Python code, and sending this code to the UDP server. The UDP server is connected via USB to the arm and constantly waiting to send incoming commands to the robotic arm, which enables remote operation of the system. With system flexibility in mind, we only added a -move X Y Z E-block that allowed control of each of the location and extraction variables, so users can create their own control functions for other operations. X, Y and Z are represented in millimeters, and E is represented in extrusion mm (extruder steps) as used by uArm for 3D printing. Based on the measurements taken for system accuracy evaluation (see Figure 8 and 6), we calculated a ratio of 3.55 µL to extruder step. This ratio will change if a different tip is used, or if the system is assembled using substitute syringe or linear actuator. To allow for such changes, a calibration manual was added to the supplementary material.

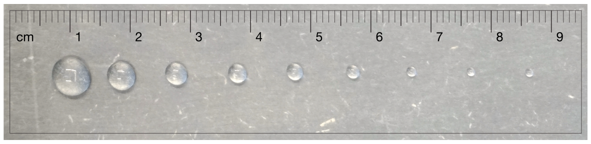


Figure 7. Demonstration of the system's dispensing accuracy by measuring water droplets in different diameters.

Bitmap to Bioprint

In order to test the ability to create custom interfaces for new audiences and applications, we developed an interface that would load a bitmap, select all the pixels of a single color, and print these pixels in an agar plate. The conversion process was done with several existing tools. It starts by using the ImageMagick [22] conversion app to convert a jpeg/png picture into a list of (X,Y) coordinates and RGB color value; next, to filter out the unwanted colors we used grep, a text filtering program, and piped the results to a text file (coordinates file). We used a Python script based on our extended version of pyuf to read the coordinates file and generate the Z value for the printing surface and the starting coordinates. The system then iterates all the coordinates and deposits in a 3mm resolution 0.3 microliters of a solution containing live bacteria (the reso-

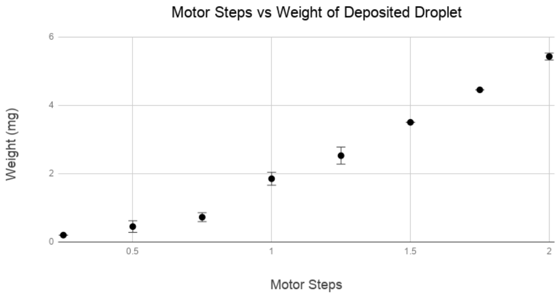


Figure 6. 0.25-2 extruder steps and weight of water deposited in mg.

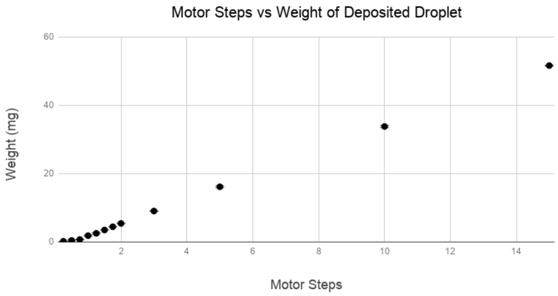


Figure 8. 0.25-15 extruder steps and weight of water deposited in mg.

lution can be as high as 0.2mm). The result is a non-technical interface that allows designers to "print" visual designs using microorganisms. We demonstrated this ability in one of our use cases.

TECHNICAL EVALUATION: SYSTEM ACCURACY

We evaluated the system's dispensing accuracy by weighing (see Figure 6 and 8) and measuring the diameter water droplets deposited by contact dispensing (see Figures 7). Contact dispensing means that a touch-off is necessary to complete the liquid dispensing. When the liquid attaches to a substrate, a drag-back action is done to overcome the surface tension between liquid and the dispensing tip, without which the liquid will not drop [27]. In Figure 6 we show results of accuracy test (table included in supplementary materials) including standard deviation of water weight deposited. In Figure 6, the chart describes the amount of water dispensed for 0.25-2 extruder steps, resulting in 0.2-5.4 mg on average, with a low error (0.15 mg). As we extracted and dispensed larger amounts of water we noticed the error is becoming less significant and a clear linear function appears.

We used four measurements per extruder steps similar to previous work [3]. We calculated Standard Deviation (represented as error bars in Figure 6 and 8). We acknowledge that a standard error of 0.15 µL can be considered high if the mean is 0.1 µL, however 0.15 µL standard deviation is calculated across all data points on average. A 0.15 µL error is considered insignificant for most protocols in manual micropipette and comparable commercial liquid handlers.

The OpenLH throughput per tip is dependent on the tip volume. In our current configuration 200 µL can print 1000 drops of 0.2 µL for each droplet at a 0.2mm resolution (per tip). It is possible to use a 1ml tip and increase throughput by a factor of five. This is the main limitation but also differentiation of the OpenLH system in a bioprinting context, most high-end professional systems have large disposable syringes. For LH the OpenLH has one pipette head, other systems have a multi pipette head reducing operation time when working on standard protocols mostly in 96 wells plates, the OpenLH is thus less useful for such experiments but can support other experiments that are less standard.

Our system design goals were accuracy performance and accessibility rather than speed. In addition, we wanted to make it possible for users to safely intervene in the pipetting process in creative ways. Therefore, our system's speed was designed to be comparable to a human-hand pipetting speed in a single transaction.

USE CASES: EXPERIMENTING WITH LIVE BIOLOGY

We performed two different experiments with the system, to test its potential for creative exploration in non-biology fields: visual design and beer brewing.

Use case I: Bioprinting for Visual Designers

We created the Bitmap to Bioprint script to enable users who are familiar with graphic design tools to bio-print their design using OpenLH as a bioprinter. The goal is to create visual art using live bacteria as bio-ink. The process starts with a standard graphic design tool that supports layers (most graphic software do). Each layer contains one color and represents a different print bacterial cultures. The print materials in this experiments were live pigment-expressive E.coli microbial cells, each expressing a different color. Genetically altered bacteria are available for online order through services like Odin. As "bio-canvas" for the bioprint we used a a standard agar plate (LB-agar-Kanamycin) which we stained with active charcoal (5g per liter) to color it black, for aesthetic reasons. In the graphics software, each image layer is saved as a separate file and loaded to the OpenLH bioprinter using the Bitmap to Bioprint script interface. The printer runs the script, and the robotic arm loads live bacteria cultures from a tube and dispenses 0.3 µL accurately on the designated print coordinates. When the printing process is done, the canvas still appears empty, as the bacteria needs to grow. The original design appears over 12-24 hours (see Figure 9 and 10), depending on the specific environmental conditions (the optimal temperature is 37 °C). In order for the bacteria to be colorful we used the E. coli strain NEB Turbo, the color was induced by 3 different plasmids pSB1.107, pSB1.108, pSB1.109 (sequences available in supplementary material) promoting pigment expression in each cell.

Use case II: Demonstration of Serial Dilution

In this use case we envision a beer brewer hobbyist that wishes to conduct a systematic experiment and maintain consistency

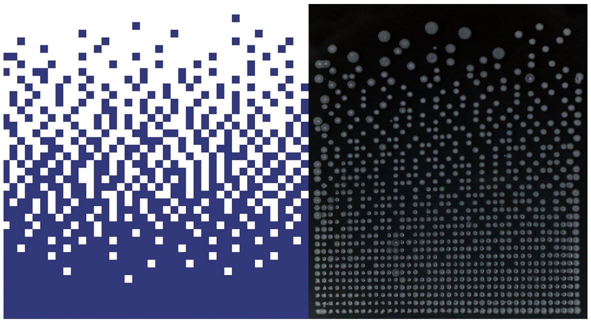


Figure 9. A print created with OpenLH bitmap (left) to bioprint (right) using non-modified E.coli printed on charred LB-agar plate, after 12 hours of incubation at 37°C.

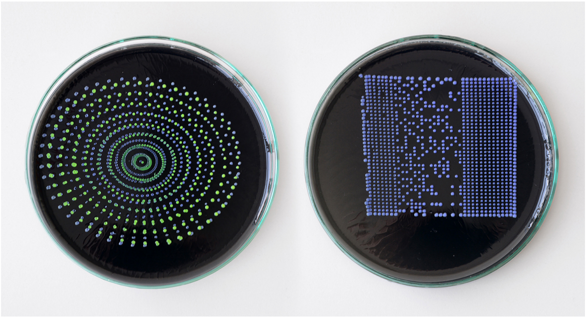
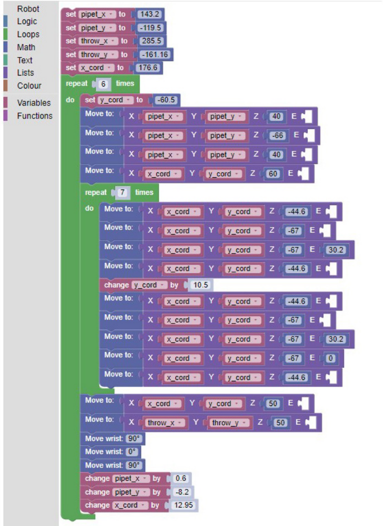


Figure 10. Two prints created with OpenLH using genetically modified E.coli expressing yellow and purple fluorescent protein, after 12 hours of incubation at 37°C.

Figure 11. Demonstration of serial dilution in a 48 wells plate, a standard biology lab procedure of repetitive precision operations.

in her use of yeast. The process leverage a standard biology lab procedure, called serial dilution, and is programed using the visual block-based interface. When conducting serial dilution a highly concentrated solution is diluted in accurate steps until a highly diluted solution is made. In this case small amount of that solution is dropped on a LB-agar plate, and after incubation overnight in 37°C it is possible to count the number of colonies that grew on the plate. Knowing the original volume and that each colony started from a single cell allows to calculate the number of microorganisms in the original solution, and the brewer can decide on the time to extract and the amount of yeast solution they wish to use, being consistent with the amount of yeast used every time. In our experiment we diluted a sample of stained water into a 48 wells plate (see Figure 11). In the first column we had solutions of 100, 80, 60, 40, 20 and 10 percent, and wrote a Blockly code (see Figure 12) that mixes 100 µL of the previous well with 900 µL water in the next one. This use case demonstrates how the system enables the streamline of repetitive precision operations, adopting a professional biology lab procedures to a non-lab environment. As the block-based code is easily shared and modified, professional users can empower non-professionals and vice versa. The code in Figure 12 shows how we set the pipette pick-up location, the first cell location and the throw location. Then, we iterate through the cells with two loops: the inner loop traverse through the cells in each line. Each iteration starts with dispensing the material into the pipette from the current cell. Then the arm moves to the next cell and dispenses the material. At the end of each line, the arm throws the pipette tip in a specified location, picks up a new one and starts again. This procedure allows to maintain sterile conditions. The outer loop repeats this process for each line demonstrating high-throughput abilities of OpenLH.



```
set pipet_x to 143.2
set pipet_y to -119.5
set throw_x to 285.5
set throw_y to -161.16
set x_cord to 176.6
repeat 6 times
do  set y_cord to -60.5
    Move to: X pipet_x Y pipet_y Z 40 E
    Move to: X pipet_x Y pipet_y Z -66 E
    Move to: X pipet_x Y pipet_y Z 40 E
    Move to: X x_cord Y y_cord Z 60 E
    repeat 7 times
    do  Move to: X x_cord Y y_cord Z -44.6 E
        Move to: X x_cord Y y_cord Z -67 E
        Move to: X x_cord Y y_cord Z -67 E 30.2
        Move to: X x_cord Y y_cord Z -44.6 E
        change y_cord by 10.5
        Move to: X x_cord Y y_cord Z -44.6 E
        Move to: X x_cord Y y_cord Z -67 E
        Move to: X x_cord Y y_cord Z -67 E 30.2
        Move to: X x_cord Y y_cord Z -67 E 0
        Move to: X x_cord Y y_cord Z -44.6 E
    Move to: X x_cord Y y_cord Z 50 E
    Move to: X throw_x Y throw_y Z 50 E
    Move wrist: 90°
    Move wrist: 0°
    Move wrist: 90°
    change pipet_x by 0.6
    change pipet_y by -8.2
    change x_cord by 12.95
```

Figure 12. Blockly code for serial dilution in a 48 wells plate.

DISCUSSION AND FUTURE WORK

To support the biological prototyping revolution, new tools are needed to empower users to experiment with biomaterials, microorganisms and cell cultures in an affordable, intuitive, creative, and safe way. We presented OpenLH, a system that empowers makers, bio-enthusiasts, HCI researchers, designers, and bio-hackers to conduct accurate and repetitive LH experiments with live biology in an open and affordable way. OpenLH is fully automatic, with a simple block-based programming interface, reducing usage cost to that of a professional manual pipette set. All the parts used to construct OpenLH are available for users to purchase or print: the uArm robotic arm and the hardware parts can be purchased; our code files and 3D printed accessories fabrication files, as well as the two interfaces (Block-based programming and bitmap-to-bioprint) are all available online [23].

Automatic LH marks a significant milestone in the development of professional biology labs. In the past 30 years LH gained massive adoption in research and industry labs [27]. Automatic high-end LH solutions are sold by firms such as Tecan [48] and Biotek [6] and allow scientists to conduct experiments that were not possible before at such a scale and speed, enabling accurate LH with high throughput and in a repeatable manner. An accurate yet affordable LH technology can empower biologists and non-biologists with no access to such high-end professional tools to conduct high throughput experiments [20], including bioprinting [39] and dispensing-based prototyping. These type of experiments are relevant for a wide range of fields, from simple experiments such as mixing and dispensing reagents from diagnostics by PCR or ELISA plate preparation, to more advanced experiments in bioprinting of tissue and biomaterials such as tissue scaffold [38], skin scaffold [37], and even vascularized heterogeneous tissues [26].

We hope our OpenLH system can empower bio-enthusiasts to experiment with live biology in a variety of creative and untraditional domains. For example: a textile designer experimenting with color-expressive bacteria for creating non-chemical prints; through a child engaging in bioprinting Agar art while learning scientific concepts; or a baker experimenting with yeast fermentation placing bacteria in exact accuracy to form a unique design for a loaf of bread.

Future work should evaluate how makers and end-users work with the system. Furthermore, OpenLH can be extended in several ways to further fulfill the mission of "low-cost tools for performing biology work in non-professional settings". In a similar way to existing remotely-operated solutions an OpenLH cloud lab can be setup to serve a larger community of people interested in experimenting with live biology. A cloud-based web interface can turn a small biohacker space into a service, listing all possible reagents and interfaces available. Regulatory, economic, and other barriers prevent biology enthusiasts around the world from performing their own experiments. Using a cloud-based service, the remote user may design their protocols using the block-based programming interface and the actual experiment will be performed by a member of the community that listed their OpenLH as available for remote use. Not only biology enthusiasts, but also many scientists around the world do not have access to automatic LH equipment, and today cloud labs such as Emerald and Transcriptic are providing commercial scalable robotic labs service. Cloud labs can also provide authentic inquiry-based learning at scale [21]. Another future direction can be for medical use. The Bitmap to Bioprint interface is relevant to more fields than design, as it can turn medical images directly into bioprints, for example when experimenting with functional tissue engineering by adding UV crosslinking for printing bio-compatible hydrogels. We hope OpenLH can empower interaction designers, HCI researchers, biohackers, artists and students to experiment and create with live biology.

LIMITATIONS

The current implementation of OpenLH has one pipette head, unlike high-end professional LH systems that can support up to 12 pipettes, supporting high throughput experiments. The current implementation was designed to support 200 µL tips, a limitation in printing volume, which is adequate for our system goal. In future versions we consider adding a 1ml tip. Some bioprinters have large syringes capable of printing solutions over 10 ml (as in the xPrint), OpenLH limited volume makes it harder to support printing of large volumes, but allows for multi material and high accuracy in small scales.

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