2015

3D PRINTING, OPEN-SOURCE TECHNOLOGY AND THEIR APPLICATIONS IN RESEARCH

Chenlong Zhang
Michigan Technological University, czhang15@mtu.edu

3D PRINTING, OPEN-SOURCE TECHNOLOGY AND

THEIR APPLICATIONS IN RESEARCH

By

Chenlong Zhang

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Electrical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2015

This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Electrical Engineering

Department of Electrical and Computer Engineering

Report Advisor: *Joshua M. Pearce*

Committee Member: *Jinshan Tang*

Committee Member: *Lucia Gauchia*

Department Chair: *Daniel R. Fuhrmann*

Table of contents

Abstract:

Open-source software received tremendous success as it drives down the cost of software and expand the distribution. Open-source hardware, as part of the open-source movement, has just risen into public attention for its potential to further drive down the cost of all kinds of manufacturing goods and reshape the manufacture chain. In this report we explores the history, development and the future of open-source hardware project, summarizing the opportunities, challenges and possible solutions. 3D printing is demonstrated as a booster to assist open-source hardware's development. Low-cost 3D printer enables at-home and in-time fabrication, the download-print-use-improve-distribute cycle is established to encourage more to make and in turn to benefit more. Researchers, teachers and scientists are the first to receive the benefit since they are often lack of budget to purchase much expensive research tools with only limited function. To demonstrate the power of open-source 3D printing in driving down research cost. A library of 3D printable optics components are designed, printed and tested. The study shows significantly reduced research cost – more than 97% equipment investment is saved with some of the optical parts representing only 1% of the cost of its commercial version. Cost reduction stimulates a much broader participants that can further help in modifying, improving the project or even developing new project, this is how open-source hardware innovation chain is established. In the end it is summarized as the technology advances, printers suitable for all kinds of material such as metals, bio-materials, semiconductors are become feasible, the open-source paradigm has the potential to replace the tradition manufacture and activate the new future.

1. Introduction

1.1. Open-source hardware research in brief

Open-source hardware (OSH), by definition, is physical artifacts whose design is made open to the public so that everyone can use, build, modify, distribute and sell it free of charge[1]. Open-source hardware arises as part of the open design and open-source culture movement. It inherits many of the concepts developed for open-source software, however, unlike open-source software, OSH applies these terms and principles to physical artifacts. OSH designs are comprised of schematics, bill of materials, circuit layouts and the associated software[2]. OSH requires much higher transparency standards than most patents and scientific journals: end users who have little or no knowledge about OSH or the OSH design should be able to assemble an OSH product by following the product manual or instructions. OSH designers hold nothing of their own designs and must make sure their products are reproducible by others. This is because the core concept hidden behind all open-source products is sharing, which is the way open-source projects evolve. Most OSH designs are available online and free for download. [3,4]

The main hindrance is coming from the fact that OSH relies on physical entities. Open-source software distributes much faster simply because of its virtual nature, making or distributing an open-source software costs no efforts on purchasing parts, building and assembling, and most of the open-source software are ready to use, user don't even need to compile the source code themselves. On the other side, OSH requires much more complicated procedures to setup, and the end users often have to build their product from scratches, purchase components or services, assemble, test and calibrate their OSH product, hence, additional time, labor and money are added that may hinder the distribution, resulting in much lower development and distribution life cycle compared to open-source software. Therefore, the key to boost the open-source hardware development and distribution is to solve the issue of where and how each open-source participant obtain vastly available resources at much lower cost.

Before the dawn of 3D printing and open-source microcontrollers, implementation of open-source hardware project has long been an issue for individual participants. Flagship OSH projects are often lead by large open labs with core members. Unlike open-source software, since the higher and stricter demand on resources, the barrier for personal developer is too high to overcome.[1] However, the emerging technology of rapid prototyping tools and DIY electronics projects have changed the situation, enabling each OSH participant to build their material at their home[5]. Normally an OSH project comprises of three major aspects: the framework and mechanical parts, the controller and electronics and the software and firmware. Open-source 3D printer makes it easy to download, print and use, exempting user from buying framework or parts, instead, user fabricate them at home using existing design at low cost, the open-source controllers and sensors, though are not free of charge, frees the user from designing their own chips or buying much more expensive commercial ones, greatly lower the barrier for OSH project, and at last, the software and firmware are part of open-source software project, which means they are naturally free. As the resource tension is released, the scope of the development and distribution of OSH project extends to every designer, hobbyist, researcher and everyone who wants to contribute to OSH projects.

1.2. Open-source microcontrollers

A microcontroller is composed of a microprocessor and peripherals. In theory, a microcontroller is basically a fully functionalized computing system, or a computer. The difference between the two is that microcontroller does not dedicate to general-purpose computational tasks, they are designed for embedded applications, providing control logic for modern electronic devices. The microprocessor is the brain of a microcontroller. Depending on its memory bus bandwidth there are several microprocessor categories such as 8-bit, 16-bit and 32-bit. Under memory mapped input/output design principle, all peripherals including sensors, other controllers or devices communicate with the microprocessor in the same way as accessing a memory

location. Microcontroller provides a set of communication protocols/buses to read and write information. Typical communication protocols are serial peripheral interface (SPI), inter-integrated circuit (I2C) and universal asynchronous receiver/transmitter (UART). A microcontroller is programmable using a variety of modern computer languages, however, for performance consideration the most widely used languages are C/C++ and assembly (or assembly and C/C++ in a mixed style). Microcontroller usually do not have external storage and only have very limited on-chip memory space, making the installation of complicated software impossible. However, as technologies evolves, modern microcontrollers with much larger on-board memory or even external media for storage are getting popular and installing software or even operating system become possible. Nowadays, the boundary of personal computer and microcontroller becomes very blurred. However, instead of installing complex general purpose operating system, modern microcontroller often chooses a light-weighted preemptive operating system kernel to perform time-critical tasks, those operating systems are often referred as real-time operating system (RTOS).

1.2.1. Arduino microcontrollers

Arduino is a single board open-source microcontroller. Arduino microcontroller itself is a product of open-source hardware movement, which means any experienced engineer can modify, extend or even develop his or her own board based on the open-licensed design[6]. The board was originally designed and developed by Massimo Banzi and his colleagues to help his students with their projects[7], soon it became popular due to its open design, low price and extremely easy-to-use programming pattern. Now Arduino grows into a microcontroller family, providing solutions from simple control to multi-media, covering all aspects of applications from microcontroller to microcomputer.

Arduino board design is relatively simple, the board consists of an Atmel ATMega microprocessor with on-board memory, input and output components and other chips and controllers to facilitate programming and circuit integration. Depending on the

type and model an Arduino board may have 8-, 16- or 32-bit microprocessor and the flash memory size may also vary. Most of the board has pre-installed bootloaders to ease the user flash the board and upload new software/firmware. This eliminated the use of a USB programmer or debugger which is often found in other microcontrollers to help with program upload/debug. The PCB design uses universal solder-less connectors that allows different shield or extension board to be installed and stacked in parallel to extend the board capabilities. Most of the Auduino boards have a 5 volt on-board regulator, some also have a 3.3 volt regulator, and both can be used to power peripherals.

On the software side Arduino's designers make a great contribution to the open-source community by largely simplifying the traditional embedded system programming pattern. Arduino programming uses an open-source software language called Wiring, which is basically a C++ derivative with most of the sophisticated and complex embedded programming pattern being encapsulated into user-friendly application programming interfaces (API) while maintaining its syntax identical to C++. Arduino designers also developed an integrated development environment (IDE) with well-defined libraries that covers most commonly used APIs such as motor drivers, Ethernet connections, LCD drivers etc. Considering the fact that most students, researchers, hobbyist does not have the professional training or electrical engineering degree, learning programming and electronics interfacing are of high cost that may distract them from their project. The insightful design of Arduino board allows anyone with basic or zero level knowledge to learn the basics and start programming the board within a couple hours. The benefits are users do not take costly trainings or courses as a prerequisite, they can focus on their project and work more efficiently.

Arduino boards are a light-weighted, low-cost and ready-to-use, these features are critical for development of an open-source hardware project, and Arduino quickly becomes an evolutionary phenomenon among all open labs, individual developers and interested researchers. Arduino now has more than 30 so-called Arduino-based companion boards[8], they all share the same design and compatible with Arduino IDE.

Arduino boards has the largest user group and community, they are well-established and well-developed and will continue to evolve and enrich the family in the future. Therefore Arduino boards are the first choice of most OSH participants.

Although the success and domination of Arduino board among OSH project, the lower performance yield of the ATMega microprocessor, lack of versatility in programming languages and the emerging demand on multimedia, multifunctional microcontroller shakes its position in OSH microcontroller arena. High performance, OS-based microcontrollers, or say, microcomputers with open-source operating system like Linux are getting popular these days. The two enter open-source realm are Raspberry Pi and Beaglebone. They all have an ARM 32-bit Cortex processor with high frequency and a much larger on-board memory. Many other features such as USB ports, HDMI support and external memory card slot make them more like a computer rather than a controller, however, they do have general purpose input/output pins (GPIOs), SPI, I2C and UART protocols so that they are compatible with most microcontroller jobs with much higher performance throughput.

1.2.2. Raspberry PI

Raspberry Pi is a Linux-based small personal computer that can be held in hand. It was originally designed by a group of British teachers, computer enthusiasts and computer academics to teach students how computer works and to build interesting projects. The first version of Raspberry Pi was released in early 2012 known as Raspberry Pi 1. Four models(A, A+, B, B+) were announced and released from early 2012 to late 2014, and recently the 2nd generation Raspberry, called Raspberry Pi 2 is formally released which inherits the design with upgraded hardware.

On the hardware side, the Raspberry Pi is designed more like a computer. It has a 700MHz Broadcom BCM2835 SoC, a video card with GPU acceleration and HDMI output, 256 MB RAM, later updated to 512 MB, USB and Ethernet port. It has all the necessary parts of a modern personal computer and hence provides the foundation for computational tasks like HD movie playing and gaming. On the other hand, Raspberry

Pi does have GPIO pins including functionality like SPI, I2C, UART and PWM, enables it to be used as a microcontroller with much better performance, however, the number of pins is 8 in the first model and 17 for the rest models, and the lack of on-board features such as ADC make it less competitive with Arduino and other microcontrollers that dedicate themselves as a microcontroller rather than a microcomputer. Nevertheless, the good side of being a microcomputer is, besides all the hardware merits, installing operating system and expanding the board versatilities become much easier. Raspberry Pi allows user to flash an SD card with a system image, by far it includes nearly all the Linux distributions, Android, and Windows 10 loT Core[9]. Installing software is just like the same thing you do on a desktop computer, user can also choose the most comfortable programming languages for his or her projects, as adding these new languages support are as equally simple as installing new software. There are well-established libraries, sketches and examples for C, C++, Python, Perl, Java and many other languages[10,11].

The Raspberry Pi is sold at no more than 35 US dollars for all models, the price is even cheaper than the most of the Arduino series, making it very attractive for developers, makers and hobbyists. Although Raspberry extensions boards (shield) is not as abundant as those for Arduino, it constantly grows. The versatility of this small computer gathers a batch of loyal developers keep contributing excellent projects to the open-source community.

1.2.3. Beaglebone

Like the Raspberry Pi, BeagleBoard is a performance microcontroller designed and launched by Texas Instrument. Unlike the Raspberry Pi, BeagleBoard is designed with open-source idea in mind. Its hardware design and software development are open-sourced. The BeagleBoard itself is an OSH product.

BeagleBoard was originally launched in 2008 for educational purposes, and has kept updating in the following years. BeagleBoard now has 6 models, and the latest model, BeagleBoard-X15, is planned to be released in November 2015. It has an ARM

Cortex-A15 dual core processor at 1.5 GHz, with 2 GB of on-board RAM, on-board dual core DSP and GPU, 8 USB ports, an HDMI output, microSD card and SPI, I2C, CAN and up to 7 UART peripheral lines[12]. BeagleBoards put performance as its highest priority, and the hardware is about the same as a medium class smartphone's on the market. However, its performance achievement doesn't degrade its role as a microcontroller, because the BeagleBone Black (5th generation BeagleBoard) has 92 GPIO pins that are capable of all kinds of tasks (Arduino Mega has 74 GPIO pins). The price for the 5th generation BeagleBone Black is about 45 US dollars, not much higher than the Raspberry Pi, but its performance is greater than the later. However, BeagleBoard community is not as large as Arduino's and Raspberry Pi's, Partly because of the higher barrier for beginners to enter: its relatively low resources, like well-written libraries, tutorials, and extension boards (capes for BeagleBoard), limits its popularity. Nevertheless, BeagleBone Black is currently the fastest board with the most reasonable price among the three, and its higher entrance level makes it more attractive for professional developers to produce move advanced, more complex projects.

1.3. Introduction to open-source 3D printing

3D printing, also known as additive manufacturing, is a general term to describe the process of fabricating three-dimensional objects in the layer by layer fashion. The typical 3D printer is a robot repeatedly depositing materials along a programmed path, and 3D printed objects form as liquid materials solidify. Traditional 3D printing materials are polymers with lower melting points that can be easily heated to liquid and quickly cooled down to its solid form. Most popular materials being used currently are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). For metals, the same principle also applies; however, the furnace temperature needs to be much higher, and usually the process takes metal powder as raw material as they are easier to be sintered with laser or electron beam. 3D metal printers are usually expensive and inaccessible for individuals. To help 3D printers to reach full scale industry level manufacturing, new materials have been developed such as conductive

thermoplastics, polymers and inks[13–15], metals[16–19], nanoparticles[20–22] and biomasses[23]. Now researchers can directly fabricate light-emitting diodes (LEDs) using customized 3D printers in nano-scale[24]. As to bio-printing, researchers are not limited to biomass printing. More attractive technologies such as organ printing and tissue printing are getting more attention. A U.S. company has already started services in printing organ replacements for patients[25]. The 3D printer itself is evolutionary and capable of replacing traditional manufacturing in many aspects. Its flexibility and versatility in thermoplastics, metals, biomass and organs and nanotechnologies all enable 3D printing with endless possibility.

1.3.1. Initiation and development

3D originated from 1980s, the idea is derived from photolithography where UV light are used for polymer hardening. In the very first 3D printing machine, the same idea is applied to generate pattern[26]. The UV curing idea was later used to develop additive manufacturing machine which process is now known as stereolithography, the difference is the later, instead of using a mask, uses UV laser whose position is controlled by a computer interface. The earlier models were very difference from today's extrusion based 3D printer, but the layer by layer deposition ideology is inherited through all 3D printer prototypes. The explosive development of 3D printing started from 2010s[Find ref], with the open-source movement and open-hardware project entering the 3D printing realm. Low-cost 3D printers become affordable for beginners and hobbyists. Price of commercialized 3D printers has been impacted and reduced to hundreds to a thousand US dollars. On the industry side, the explosion continues as 3D printer enables the rapid prototyping and on-demand prototyping. It's about the same time industry giant like General Electronics (GE) started to build their jet engines through 3D printing. NASA has already launched a project to build their next generation spaceship engine using 3D printing. The layer by layer bottom up assembly process has its advantages to fabricate sophisticated intersected mechanics over tradition manufacturing process, which involves of using several different tools

12

for prototyping. The whole process is much simplified and much faster when adopting 3D printing techniques[27].

Nowadays 3D printing falls into two major parts: the industry-grade printer and consumer-grade printer. The former includes Stereolithography (SLA) and Selective laser sintering (SLS) technology based UV-curing material printer, 3D metal printer and special function printers such as bioprinter and nanoprinter. Consumer-grade printer are like extrusion and sterolithography based thermoplastics printer and low-cost metal printer etc. As the open-source movement evolves, low-cost open-source 3D printer begins to dominate low-end 3D printer market, with the development of better firmware/software and improved hardware engineering, the open-source 3D printers can compete with some of commercialized 3D printers in accuracy and resolution.

1.3.2. 3D printer: How it works

To best explain the theories and concept behind a 3D printer, taking a close look at a normal 2D desktop printer and compare it to a 3D printer, the 2D desktop printer used in daily life prints ink onto paper, the process repeats only once. 3D printer works in the same way; however, it repeatedly print 2D layer one on top of another, the accumulated 2D layer forms a 3D object. Instead of using inks, 3D printer have to choose materials that have the properties to be fit in the layer-by-layer principle, and develop techniques for different materials. The following summarize the techniques used in 3D printing.

1.3.2.1.Stereolithography (SLA)

This is the techniques used in first commercialized 3D printer. The materials used for this type of printer is UV-curing polymers. The process involves of using a UV laser head moving in X-Y plane, curing the polymer resin underneath. The liquid polymer resin is held in a vessel that only moves in Z direction. When printing starts, the laser head continuously adjust its position as the according to the 3D data supplied by the

object model. As the laser beam traveling along X-Y coordinates, the polymer resin hardens when receiving enough energy from the layer, and hence generate pattern. When the first layer finishes the vessel moves down to allow the hardened body immersed into the polymer liquid and the process repeats until the object model is finished. Because the process is done in liquid it generally required some level of supporting, modern software/firmware have the options to automatically build the supporting frames so customers does not have to build their own.

The biggest advantage of SLA techniques is the high accuracy, and high resolution it delivers. SLA is one of the most accurate 3D printing techniques. The layer thickness reached 25 micron[28]. SLA printer works at room temperature or slight higher than room temperature, making it more energy efficient than other 3D printing techniques. The unused liquid polymer can be easily collected for printing the next. The disadvantage is the high price which elevates the threshold for individual customers.

1.3.2.2. Digital light processing (DLP)

DLP works pretty much the same way as SLA, the only difference is the light source: DLP allows users to choose much more ordinary light sources such as Xenon arc lamps and light emitting diodes. The light shines through a deformable mirror device (DMD) to create a 2D pattern on the whole surface of the resin, pretty much the same way a projector works. Upon curing the resin hardens and the motor lifts the model to allow more resin fills in the vessel. The reason is that DLP instead of moving a laser head to travel each single point on the 2D pattern, shines UV to cover the surface and creates pattern at a single pass. It's faster than the SLA technique. DLP and SLA both have the same layer resolution as they work the same way in Z direction, the resolution is dictated by the motor that pulling or sinking the vessel. Clearly, when laser is used for curing, the smaller the spot (full width half maximum), the better the solution.

1.3.2.3. Fused deposition modeling (FDM)

This the most widely deployed 3D printing techniques, hundreds manufactures and commercialized 3D printers adopt the FDM printing paradigm. In a nutshell, the FDM techniques do not use any light source, and the patterning and shaping is done by extruding melt thermoplastics through a heated extrusion head working at a temperature slightly higher than the thermoplastics melting point; the melting plastics quickly cools down and solidifies onto a platform; the successive layer are printed onto the first layer and the process repeats itself over and over until the object is completed. Typical material for FDM working mode are PLA and ABS for their stability, vast availability and low price (UV-curing material are very expensive). However, the resolution is dictated by the movement of the extrusion head, which usually moves in contact to the hardened polymer, causing unnecessary fiction between the head and the hardened parts; on the other hand, the thermos expansion effect result from the large temperature difference between melting and room temperature is often not negligible, causing shrinking and peeling effect on printed parts. Using light makes printing in smaller feature possible and SLA printers work at nearly constant temperature. The light introduces less process cycle and zero force on the object, and ensures the smoother surface. Nevertheless, FDM dominates the entry-level 3D printing market and its accuracy is constantly improving.

1.3.2.4. Selective laser sintering (SLS)

SLS stands for selective laser sintering, it works with powder materials. This is normally the technology used in most of the world metal printer. The principle is the same: one layer after another, however, the process is slightly complicated for metals: A powder tanks filled up with compacted metal powders; a fiber laser with significant power throughput travels in X-Y plane across the powder surface, the laser heats the underneath powder to allow them to sinter and form a patterned solid, this finishes the first layer. Before the next layer to be patterned, the tank moves downward a bit and a roller spreads new powders onto the tank surface, and the sintering process repeats. Usually to increase the binding force between newly formed layers, adhesive or binder

is introduced prior to sintering. The printed metal parts are often subjected to a post-print annealing process to allow internal crystallization to happen, which increase the part's mechanical properties. The advantage of the process is that the powder tank supports the structure during the entire process, and the fabrication is just a couple of 2D cross-section, it does not consider the 3D structure, which enables fabricating much complicated design in the simplest way. SLS has been implemented to build spacecraft engines, cars and ships, and other machineries. This technique will never enter the consumer market, but it's getting more and more industry preferences.

1.3.2.5. Other techniques

Other than the described techniques, there are a vast number of applied 3D printing technology and methods. They have their unique capabilities that favor in very specified application such as selective deposition lamination (SDL) and electron beam melting (EBM). It worth mentioning that the 3D printing as a technology is constantly evolving. On March 2015, a chemistry professor introduced a new type of 3D printer, it combines the use of oxygen and UV light to control the process, and boosts the printing speed 100 times faster than currently thermoplastic printer. It may have the potential to change the game completely[29]. All 3D-printing techniques required the object is digitalized in a file, normally a .STL or .SLC file. The next pre-print process is to analyze the file to extract the geometric data of the object and convert them into coordination instructions; the instructions are then grouped into instruction set with the granularity of an object layer, This process is generally known as slicing - a vivid description as the output is a pile of 2D patterns of a 3D object cross sections, just like slicing an apple into apple slices.

1.3.3. Open-source equipment for scientific research

3D printing, though its noble born, lays a relatively low technique threshold to designers. The high end 3D metal printer and SLA printer are too much complicated for hobbyist and DIYers to implement. However, the low cost FDM 3D printer

quickly become the open-source movement's playground. The open-source self-replicating rapid prototyper (RepRap) is the most productive project that enables low-cost fabrication and distribution of other open-source hardware projects. RepRap projects arises from Bath University where two professors accidentally developed a robot that can automatically print out a large fractions of its own components[30]. RepRap is basically a FDM 3D printer using a variety of thermoplastic materials to fabricate components of other products. At the time the RepRap was developed, the cheapest rapid prototyping machines on the market was about 37,000 US dollars. In contrast, the RepRap costs only 400 US dollar in material and the designed is open-sourced and free to be distributed. The open-source paradigms worked and showed enormous potential on RepRap project: RepRap has now grown into the largest open-source 3D-printing community in the world and contributes to 25% of the global 3D printer market[5].

When open-source movement and fast developing 3D printing techniques twist together, the new era of open-source hardware emerge from the horizon. As discussed in the previous section, open-source hardware projects are often hindered by the cost of manufacturing. One way to overcome the challenge is to allow the end users to download the blueprint and fabricate the component they need right at their home with low cost and vastly accessible materials. The RepRaps are the solution to this challenge. In addition, the merit of open-source is that, as people keep sharing their own project, more can be inspired and developed and the community grows exponentially, eventually every benefiter enjoys the benefit or feedback from the community.

As OSH penetrates to every corner in manufacturing, scientists and researchers are the first ones to have that benefit. Scientific equipment and tools are used to be very expensive and hence often unaffordable or inaccessible to researchers with limited budget. Some experiments or tests do not require a full instrumental setup, nor do they need high precision, accuracy or resolution for some basic level prove-of-concept. However, scientists and researchers are forced to buy the high-end equipment that is

supposed to be fully utilized, the close-box design leaves little room for customization. The advantages of OSHs starts to excel. Scientists and designers have been working together to bring plenty of OSH products including optics and optical system components[31], liquid automation machines[32], fluidic autohandler[33], colorimeters[34], turbidimeters[35], phasor measurement units[36], and MRI components[37]. The state-of-art equipment designs are brought to researchers for free, and building them with open-source 3D printer are at incredibly low costs[38], which is generally between 90-99% less than the commercial equipment.

1.4. Conclusion

In the first chapter we briefly review the history of open-source hardware development. Open-source hardware originates from the open-source movement, the goal is to apply the open-source paradigms to hardware, allows massive distribution of free hardware design. However, open-source hardware project has its built-in restrictions, unlike open-source software, open-source hardware requires not only the design, but also the physical entities and the whole setup altogether make the product. The cost and labor associated in building the product are not negligible. The challenge is resolved by the emergence and fast developing open-source 3D printers (RepRaps). Using extremely low-cost material a blueprint can be implemented in a couple hours with comparable qualities to the commercialized products. The open-source idiom also encourages collaboration and sharing, if one is made to be successful, more can be inspired or improved in the future. The future potential can be enormous or to some extent replace the traditional manufacture line.

2. Open-source 3D printable optics library

2.1. Introduction

The open-source movement presents a transparent, collaborative and decentralized perspective for both software development and hardware design. Compared to the close-boxed, standardized commercial approach, by driving down the cost and inspiring coloration, open-source design are about to expand the accessibility to everyone. To assist the goal to acquire state-of-art scientific instrument with low cost using open-source hardware design and rapid prototyping equipment, and also showcase and enrich the open-source hardware projects, a 3D-printable optics equipment libraries are built from scratch. The development process follows the general open-source hardware design and build routine. First, optics hardware blueprints are designed, fine-adjusted and finalized using open-source computer aided design software pack. Second, open-source rapid prototyping tools (3D-printers) are used in optics components fabrication, detailed construction involves of using the product of other open-source projects, such as open-beams. Third, the hardware automation and control are implemented using open-source microcontrollers. Fourth, all the design details and system specs along with the experiments/tests examples are published to open-source hardware community to allow more to download, reuse, discuss, improve and modify in the future. Finally, it has been concluded that the system cuts down 97% cost of the commercial system with similar function and performance. The instrument can be both used for scientific optical property measurement or as a tool for high school or university level science education.

2.2. Materials and Methodology

The open-source optics hardware are sketched in open-source computer aided design (CAD) software called OpenSCAD[39]. OpenSCAD is a command based CAD tool box that allows user to create three-dimensional objects by coding or scripting in the command window. It requires little programming knowledge, but the user should be familiar with the syntax and commands to create and modify 3D objects. Design in OpenSCAD starts with simple common 3D objects called primitive shapes, such as spheres, boxes, cylinders and polygons, the complex 3D objects are derivatives of those primitive shapes created using combination, extrusion, Boolean operation and many other commands. The parametric design is the core advantage of OpenSCAD, which parameterizes the geometrical specification of an object and passes the relational parameters to its derivatives. This allows simple modification to the objects created by just altering the user-defined variables.

To demonstrate the parametric design a set of optical equipment are designed and built using OpenSCAD and RepRap. These equipment consist of an optical chopper wheel, optical foot, screen holder and optical rod base, a lab jack, a full photoluminescence (PL) system setup, including sample holder, lens holder, mirror holder and fiber switcher. The first to demonstrate is the optical chopper wheel, which is a device used in many opt-electrical system for light amplitude modulation: the wheel has multiple slots orbiting its fringe, when operates at optimal frequencies it blocks the incoming light periodically, resulting modulated light intensity. As shown in Figure 2.2.1, using parametric design in OpenSCAD, only one wheel is designed and the number of slots can be easily changed just by altering the parameters. Figure 2.2.1a, b and c show a single design with variable in code of 10, 15 and 60 slots, giving a chopper wheel frequency of 20Hz-1kHz, 30Hz-1.5kHz, and 120Hz-6kHz, respectively.
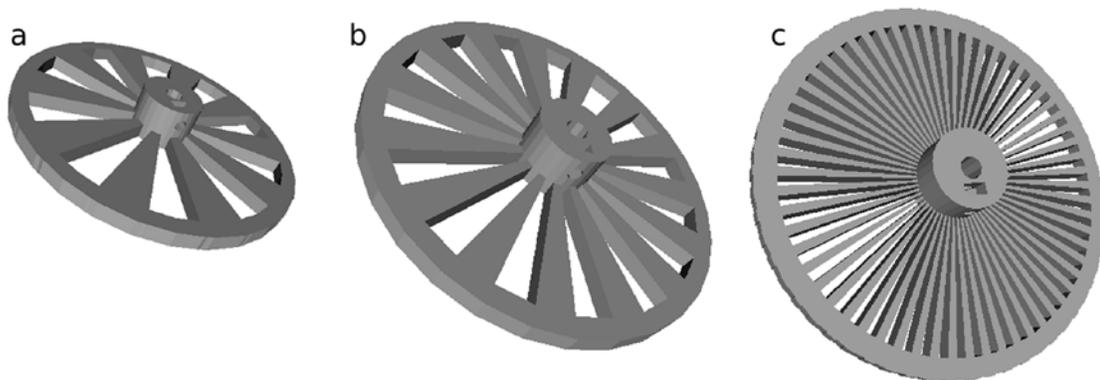
Figure 2.1. A parametric design of an open-source optical chopper wheel with a) 10 slots, b) 15 slots and c) 60 slots.

Exported .SLT files are then sliced into 3D printer recognizable gcode, which provides the three dimensional coordination information of the objects and vector instructions for RepRap. Printing finishes in 3 hours 8 minutes for each wheel. The design has left space for installation of a DC motor and electronic speed controller to automate the wheel at specified frequencies.

RepRap and the whole setup are automated by open-source electronics. Currently, there're multiple options on microcontrollers and motor controllers, the most popular one is to use an Arduino based microcontroller plus an open-source motor shield called RAMPS. The reason of not choosing previously introduced Linux based microcontrollers like Raspberry Pi and BeagleBone Black is that the application itself doesn't rely on density computational tasks, The only tasks are to drive the step motor, to heat the bed and extruder and to monitor the temperature; an 8-bit microcontroller with megahertz-level clock speed is sufficient to supply these kind of functions. There's also debates on whether or not should real-time operating system (RTOS) be installed for 3D printers, I personally prefer the installation of RTOS as most of tasks for 3D printing are time critical; however, at current stage increasing the on-board memory and installation of RTOS only increase the cost with little performance boost. The RTOS would certainly be an optimal choice in the future as the cost of performance microcontroller because cheaper, and open-source RTOS kernels become free and open-source.

This time the microcontroller being used is an ATMEL ATmega328, which is a low-power AVR 8-bit controller with maximum speed of 16MHz, 32 kB program memory and SPI/I^{2}C/UART communication ports[40]. The detailed RepRap build procedure can be found elsewhere[41]. Figure 2.2.2 shows RepRap printing a filter bracket.
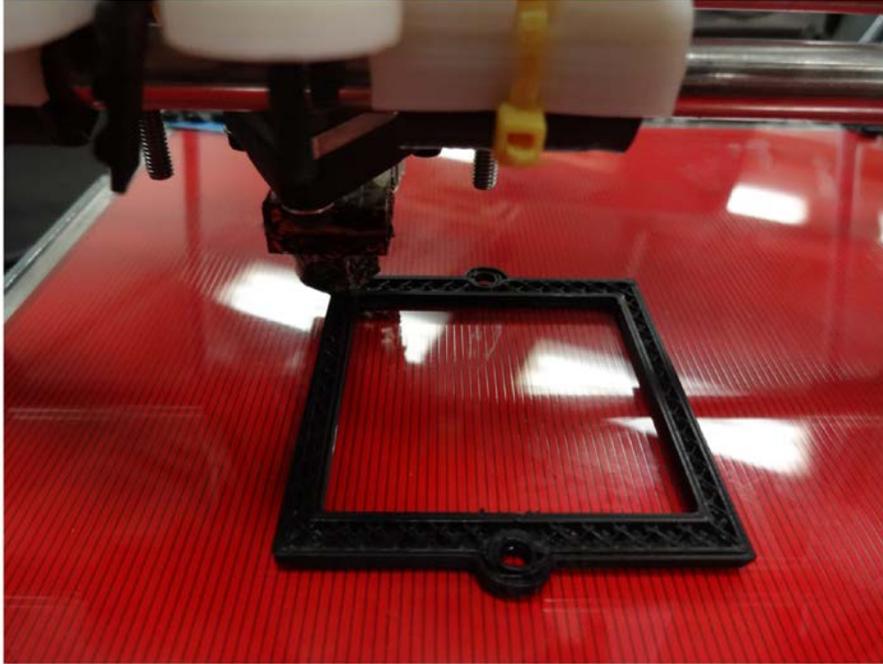
Figure 2.2.2. Open-source 3D printer (RepRap) printing a filter bracket.

2.3. Result

Optical system often requires an optical rail that allows optical component to move freely along the rail and be fixed at center position on the rail. A commercial optical rail is around $380/m, which is rather expensive for education level optical experiments. An alternative way is to switch to open-source construction frame called OpenBeam. OpenBeam is a desktop sized extruded aluminum framing system for machinery building. The biggest advantage is the optimized cost make it available for $12/m, almost 3% of the commercial system. Each OpenBeam is a T-slot system that captures M3 nuts, the nuts can move inside the slot and be repositioned anywhere along the beam, making it easy to attach components to the beam. Figure 2.3.1 shows different attaching scenarios used in optical library: a) a 3D printed magnetic holder

holding a magnet with its bottom nailed into the rail slot, b) a T bracket footer, c) a 3D printed rod holder and d) an off-set rod holder.
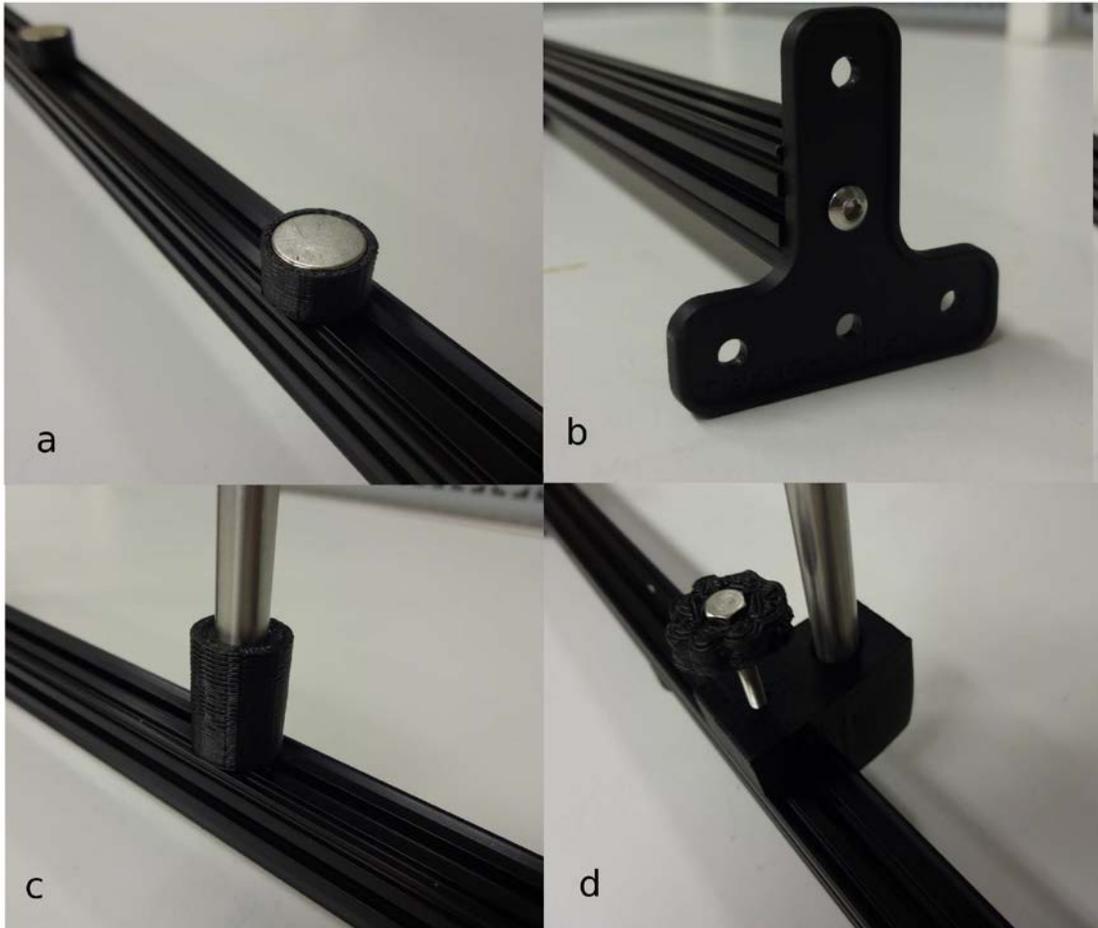

Figure 2.3.1. Open-source optical rail fabricated from OpenBeam using a printed a) magnetic base or b) T-brackets, c) simple rod holder, and d) off-set rod holder.

For non-linear optical experiment, the setups can be based on a magnetic optics base as seen in Figure 2.3.2. The base is 3D printed with a smaller cylinder opening in the bottom to receive a magnet. The base can be easily attached to a magnetic surface table and hold its position on it, though with less stability. It's more flexible to be moved away and repositioned anywhere on the surface. More to mention, the parametric design also allows building larger or smaller rods and magnets in a simple variable change.

A variety of optical components can be attached and mounted to either the rail or the magnetic base. Then plenty of them can be easily printed rather than purchasing from the market. The library is enriched by adding more components like a static mirror holder (Figure 2.3.3a), a lens holder (Figure 2.3.3b), a kinematic filter (Figure 2.3.3c) and fiber-optic holder (Figure 2.3.4a), a photoluminescence sample holder (Figure 2.3.4b), and a screen holder (Figure 2.3.5).
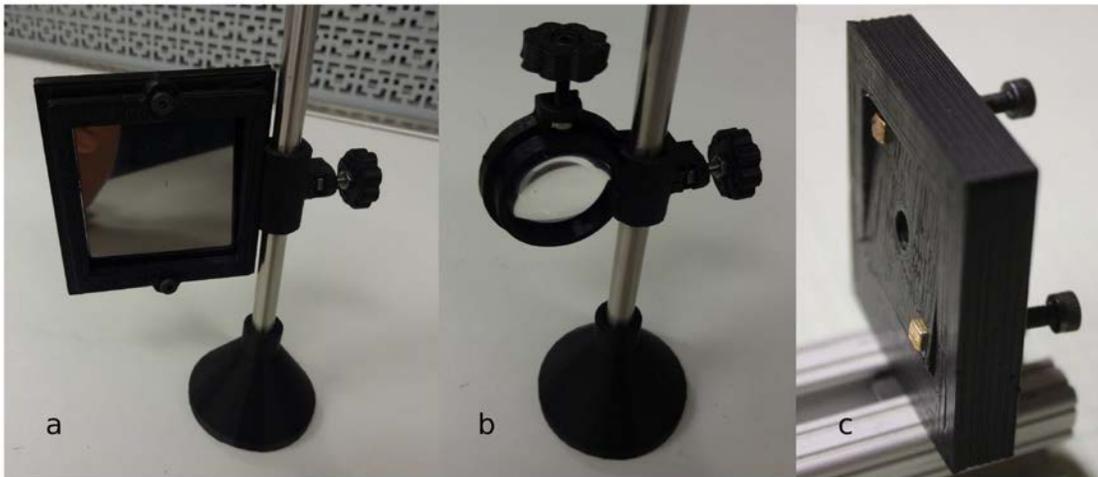
Figure 2.3.3. a) Static square filter holder, b) static circular lens holder and c) kinematic filter

The optical library consists of a rail-based linear setup and a non-linear setup. The linear setup has all its components attached to the rail by using either magnets or straight/off-set rod holders. This is the setup commonly used in middle school optical experiments to show light reflections, and ping hole imaging, general components like screen holder, which holds a screen to show the image, mirror or lens holder, and kinematic filter holder, which is a device has living hinge and two magnets to lock an mirror or glass filter at center. The non-linear setup are all based on magnetic rod holder. These are used in educational middle school experiments as well as university labs for photoluminescence measurements, general setup consists a set of wafer/sample holder, which is a small slotted container holds a piece of wafer, mirror holder, lens holder, to hold the optical components and a lab jack, which is a height adjustable platform for supporting other optical components or devices that need to adjust its height frequently.

To facilitate the filter change in filter-related experiments, a filter wheel is printed and automated through an Arduino controller(Figure 2.3.6): An Arduino Uno microcontroller is wired to a step motor through an Arduino compatible stepper shield, a small photocell still detect the light intensity and set high or low on a Arduino pin, which tells the microcontroller the position of the wheel. Through a computer interface the user can control the microcontroller by sending commands through a serial port. The device is initialized and calibrated to inform the microcontroller of the wheel's origin. When it reboots, the current position is read from the sensor in combination with the origin to locate the proper filter. The logic then works to drive the step motor to the target filter.
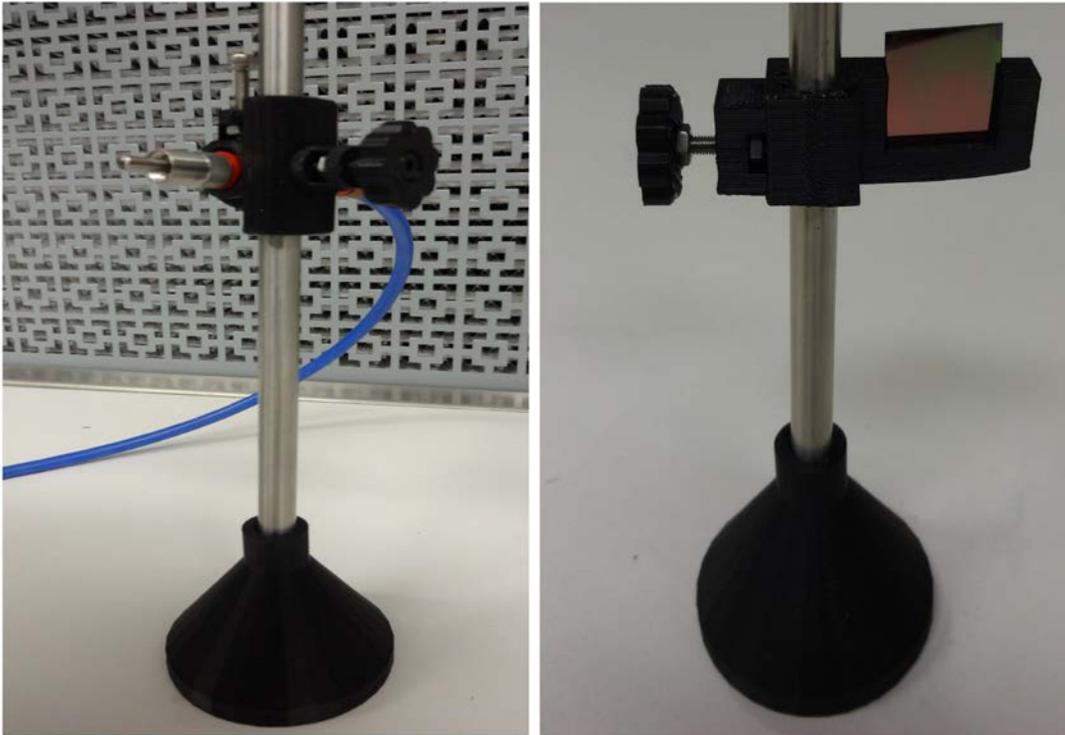
Figure 2.3.4. a) optic-fiber holder and b) photoluminescence sample (wafer) holder

Figure 2.3.5. Screen holder

2.4. Discussion

The entire design STL files are posted on an Internet open-source hardware community for reviewing, sharing and discussing. Anyone who is interested in replicating the whole work, or wants to contribute or improve the library can download the files and build their own. Low-cost 3D printer bill of material is posted as well along with step-by-step building and troubleshooting documents. The cost and properties of open-source optical equipment are summarized in Table 2.4.1 in comparison to the commercialized equivalents. As it can be seen from the table that the cost reductions is over 95% and some of the components have less than 1% of commercialized model. Open-source 3D printer are around US$1000 while DIY printers cost even less, about US$600. The open-source library provides an easy way for budget-limit teachers or researchers to access their equipment and helps in saving. The more the teachers or the researchers plan to do with the open-source setup the

more they save. For example, a middle school teacher plans to do demonstration by using optical lens, lab jack, lends holder, viewing screen and screen filter, the total cost could be US$16,500 for the commercial version; in contrast, with the open-source setup, he or she only needs US$500 or less, which could save $US16,000. The economic savings make the whole setup friendly to less-developed countries, schools in remote or rural areas, budget-tight teachers or researchers, hobbyists and DIYers.

Components	Filament Consumption (g)	ABS Costs (USD)	Electricity Cost (USD)	Total Cost (USD)	Estimated Commercial Price (USD)	Percent Savings (com.-open)/com.
Optical rail	--	--	--	10-12/m	320/m	97
Base on Optical Rail - optical foot (2x) - optical mag (3x) - rod base (4x)	39.52	1.50	0.27	3.08	150-730	>99
Filter holder	8.98	0.34	0.06	0.40	58-80	>99
Lens holder	5.35	0.20	0.04	0.24	20-180	>98
Mirror holder	7.40	0.28	0.05	0.33	18-200	>98
Fiber switcher	10.41	0.40	0.07	0.47	22-138	>97
Screen holder	1.55	0.06	0.01	0.07	18	99
Thumb screw (6x)	7.98	0.30	0.06	1.32	12	97
Sample holder	6.00	0.23	0.04	0.27	18-109	>98
Lab jack	133.20	5.06	0.92	5.98	35-1000	83-99
Automated filter wheel changer	295.1	11.21	2.02	20.43	1000-4250	>98
Optical base (4x) + steel sheet vs. optical table 1m^2	46.28	1.76	0.32	2.08	3619-5288	>98

Table 2.4.1. Optical library components cost comparison table

Besides the economical merits, the open and customizable nature brings great flexibility to anyone who wants to personalize the setup. Compared to commercial types, which is close-box designed and often not customizable by users, if the users want to add functions to one or more parts of the setup, they have to re-purchase the one with that desired function, and that doubles the cost, not even to say there's probably no such setup with the functions needed. With the open-source design at hand, users can customize the design or reprogram their microcontroller to add more features, and functions to the current version. The OpneSCAD's parametric design as well as Arduino's simplified programming syntax make it much easier for people to access, modify and improve the blueprint.

Moreover, the rapid prototyping tools accelerate the building and let all that modification made to current design be implemented faster, greatly saving the time and speed the product evolution life cycle. Timely access is valuable to all researchers who have suffered from international mailing and out-of-stock problems. The research nowadays are like competition and time is the most valuable resource to win the game. In conventional way, researchers send the design to machinery shop or factory to build, and wait until it's finished and shipped back. The time spent on designing, building, processing and shipping could be weeks or even months long. With the help of rapid prototyping, all such processes can be finished at lab, shrinking the weeks to hours, so that saving enormous time for researchers. Whenever the current design has flaws or the user simply wishes to improve it, or add more features, it can be modified, printed and updated just at the time. Since the components are designed with the parametric design principles, customizing parts on a finished design is simply variable changing, fastening the rebuild cycle by an order of magnitude.

Figure 2.3.6. Automated filter wheel switcher

However, it should be pointed out that the limitations goes along with all the advantages. First, the library itself is not complete. Many optical components cannot be designed and fabricated using currently technologies. For instance, the glasswares, like lens, mirrors cannot be fabricated using current open-source 3D printer. Second, the accuracy-cost tradeoff, the tradeoff arises from the printer's resolution limit, for the open-source 3D printer used in this report, the minimum feature size is 0.3mm, which is the thickness of a single layer, and anything designed smaller will loose its detail during printing. The resolution of open-source printer is however constantly improving. By the time this report is forged, the resolution has already reached 25micron for open-source FDM printer[42]. It is expected as the technology advances, so nanoscale printing becomes possible in a few years. Thirdly, since there's no standard for open-source designs, the product quality is largely depends on the user's

preference. For example, some users may build the product with faster printing speed and low in-fill rate, which helps in saving time and materials, but results in low quality product, some tend to build solid, robust product with high in-fill rate and slower speed, with support material underneath; this leads to better quality but more time- and material-consuming process. Future open-source designers may want to test their products with a set of different printing preferences and attach the suggested/optimized settings. However, this is not required as it may be considered going against open-source paradigm.

2.5. Conclusion

The chapter introduces an open-source hardware practice by designing, implementing and distributing an open-source 3D printable library using low-cost materials. The library is demonstrated to have comparable performance as its commercialized equivalents but at much lower cost – total cost reduction up to 97% or even more for some printed parts. It's clearly seen the open-source hardware project is a scientific research accelerator. It enables timely design, implementation of equipment, reduces the cost, inspires collaboration, benefits everyone and gains improvement from everyone. Great designers work with great users to bring great tools to people who need them. Although the current technology cannot fabricate a full stack optical library including lenses, mirrors, and metal parts. The technology continues evolves and new era of open-source fabrication can be expected within this decade.

3. Conclusion

The report has shown briefly the history, development and challenges of open-source hardware. As a branch of open-source movement, open-source hardware project along with the open-source software project are conceptually of equal importance, however, the later receives tremendous success and constantly develops at alarming speed, open-source hardware. On the other hand, the open-source hardware is not as competitive in achievement as open-source software is. Plenty facts account for this, the most eminent one is that open-source hardware are in the dry tree ever since it's born, open-source hardware project roots in the physical entity that to be built or distributed. Unlike the software that consists of virtual entities that are parasitic on everyone's computer or simply on Internet, hardware does parasitize on nothing, it must be built from designs, the material, time and labor to build these hardware are not free. The free software has incomparable superiority to the non-free hardware. The challenge to solve or to release the challenge is to develop effective fabrication techniques, low-cost and widely available materials to drive down the cost to an affordable level. The report points out, the rapid replication and prototyping machine and additive manufacturing is a solution to overcome the challenge.

3D printing has long been treat as a high-end technology alien until recently the low-cost desktop 3D printer entered people's daily life. Open-source hardware sees a chance for low-cost fabrication. Industry level metal printing, laser and electron beam printing and bio printing tools are not considered to help with open-source project because they are too expensive to buy as well as too complicated to operate. On the other hand, low-cost thermoplastic printer satisfies the two basic requirements: 1) affordable technology and 2) widely available and low-cost material. Additionally, the printer soon becomes a desktop fabrication center with great capability of replicating everything even itself. RepRap is the first open-source 3D printer; it's born as an open-source hardware project, and it not just servers the sustainability of open-source

project – a good example to demonstrate the autotrophy characteristic of all open-source project.

To demonstrate how open-source hardware project helps scientists, teachers and researchers with their academic, educational projects. A 3D-printable library was designed, built and compared with its commercial equivalents. The result shows the advantage of adopting the open-source paradigms: 1) The cost of the whole optical setup is only 5% as its commercial version. Low cost guarantees the wide accessibility and further ensures the distribution and product evolution; 2) Timely fabrication: using a 3D-printer researchers do not have to wait for their orders to be built and shipped at the front door, they can immediately try their new ideas out and start using the new equipment. 3) Sharing: open-source project is not and will never be a mature project because as people use it and continuously sending feedback, so the project evolves as a part of the whole ecosystem. As more people start to use the product, the more they can contribution made to the project, and the further the distribution, larger the community and the more inspired to build new projects. This evolution chain will eventually result in more evolution chains can bring more product to the community.

The open-source hardware project is at its youth, it has immeasurable potential to shake the conventional manufacture on Earth. As the technology advances, the next generation printer can print metals, medicines, organs, nanostructures, solar cells, batteries, and spacecraft engines. Who can ever imagine what will happen if those printers enters everyone's home, sitting right on the desktop, waiting for a command and start to make. What will it make?

It makes the future.

Reference

1. Hansen, A. & Howard, T. J. in *ICoRD'13* (eds. Chakrabarti, A. & Prakash, R. V.) 977–988 (Springer India, 2013). at <http://link.springer.com/chapter/10.1007/978-81-322-1050-4_77>

2. Harnett, C. Open source hardware for instrumentation and measurement. *IEEE Instrum. Meas. Mag.* **14,** 34–38 (2011).

3. Opinion, W. Why We Need Free Digital Hardware Designs. *WIRED* (2015). at <http://www.wired.com/2015/03/need-free-digital-hardware-designs/>

4. Opinion, W. Hardware Designs Should Be Free. Here's How to Do It. *WIRED* (2015). at <http://www.wired.com/2015/03/richard-stallman-how-to-make-hardware-designs-free/>

5. Pearce, J. M. *et al.* 3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development. *J. Sustain. Dev.* **3,** p17 (2010).

6. Arduino - Home. at <https://www.arduino.cc/>

7. Arduino. *Wikipedia, the free encyclopedia* (2015). at <https://en.wikipedia.org/w/index.php?title=Arduino&oldid=685679851>

8. List of Arduino boards and compatible systems. *Wikipedia, the free encyclopedia* (2015). at <https://en.wikipedia.org/w/index.php?title=List_of_Arduino_boards_and_compatible_systems&oldid=686849603>

9. Raspberry Pi Downloads - Software for the Raspberry Pi. *Raspberry Pi* at <https://www.raspberrypi.org/downloads/>

10. Oracle Java on Raspberry Pi. *Raspberry Pi* at
    <https://www.raspberrypi.org/blog/oracle-java-on-raspberry-pi/>

11. jwhitehorn/pi_piper. *GitHub* at <https://github.com/jwhitehorn/pi_piper>

12. BeagleBoard. *Wikipedia, the free encyclopedia* (2015). at
    <https://en.wikipedia.org/w/index.php?title=BeagleBoard&oldid=685746726>

13. Leigh, S. J., Bradley, R. J., Purssell, C. P., Billson, D. R. & Hutchins, D. A. A
    Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic
    Sensors. *PLoS ONE* **7,** e49365 (2012).

14. Czyżewski, J., Burzyński, P., Gaweł, K. & Meisner, J. Rapid prototyping of
    electrically conductive components using 3D printing technology. *J. Mater.
    Process. Technol.* **209,** 5281–5285 (2009).

15. Junfeng Mei, Lovell, M. R. & Mickle, M. H. Formulation and processing of novel
    conductive solution inks in continuous inkjet printing of 3-D electric circuits.
    IEEE Trans. Electron. Packag. Manuf. **28,** 265–273 (2005).

16. Berman, B. 3-D printing: The new industrial revolution. *Bus. Horiz.* **55,** 155–162
    (2012).

17. Lass, N., Tropmann, A., Ernst, A., Zengerle, R. & Koltay, P. RApid prototyping
    of 3D microstructures by direct printing of liquid metal at temperatures up to 500
    #x00B0;C using the starjet technology. in *Solid-State Sensors, Actuators and
    Microsystems Conference (TRANSDUCERS), 2011 16th International* 1452–1455
    (2011). doi:10.1109/TRANSDUCERS.2011.5969623

18. Sanchez-Romaguera, V., Madec, M.-B. & Yeates, S. G. Inkjet printing of 3D metal–insulator–metal crossovers. *React. Funct. Polym.* **68,** 1052–1058 (2008).

19. Anzalone, G. C., Chenlong Zhang, Wijnen, B., Sanders, P. G. & Pearce, J. M. A Low-Cost Open-Source Metal 3-D Printer. *IEEE Access* **1,** 803–810 (2013).

20. Ladd, C., So, J.-H., Muth, J. & Dickey, M. D. 3D Printing of Free Standing Liquid Metal Microstructures. *Adv. Mater.* **25,** 5081–5085 (2013).

21. Campbell, T. A. & Ivanova, O. S. 3D printing of multifunctional nanocomposites. *Nano Today* **8,** 119–120 (2013).

22. Sun, K. *et al.* 3D Printing of Interdigitated Li-Ion Microbattery Architectures. *Adv. Mater.* **25,** 4539–4543 (2013).

23. Doyle, K. Bioprinting: From Patches to Parts. *Genet. Eng. Biotechnol. News* **34,** 1, 34–35 (2014).

24. Lewis, J. A. & Ahn, B. Y. Device fabrication: Three-dimensional printed electronics. *Nature* **518,** 42–43 (2015).

25. Organovo. *Wikipedia, the free encyclopedia* (2015). at <https://en.wikipedia.org/w/index.php?title=Organovo&oldid=672753299>

26. Kodama, H. Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer. *Rev. Sci. Instrum.* **52,** 1770–1773 (1981).

27. GE fires up fully 3D-printed jet engine. at <http://www.gizmag.com/ge-fires-up-all-3d-printed-jet-einge/37448/>

28. Form 2 SLA 3D Printer – Formlabs. at <http://formlabs.com/products/3d-printers/form-2/>

29. *What if 3D printing was 100x faster?*. at

<https://www.ted.com/talks/joe_desimone_what_if_3d_printing_was_25x_faster?l

anguage=en>

30. Jones, R. *et al.* RepRap – the replicating rapid prototyper. *Robotica* **29,** 177–191

(2011).

31. Zhang, C., Anzalone, N. C., Faria, R. P. & Pearce, J. M. Open-Source 3D-

Printable Optics Equipment. *PLoS ONE* **8,** e59840 (2013).

32. Carvalho, M. C. & Eyre, B. D. A low cost, easy to build, portable, and universal

autosampler for liquids. *Methods Oceanogr.* **8,** 23–32 (2013).

33. Da Costa, E. T. *et al.* Getting started with open-hardware: Development and

control of microfluidic devices: Microfluidics and Miniaturization.

ELECTROPHORESIS **35,** 2370–2377 (2014).

34. Anzalone, G., Glover, A. & Pearce, J. Open-Source Colorimeter. *Sensors* **13,**

5338–5346 (2013).

35. Kelley, C. D. *et al.* An Affordable Open-Source Turbidimeter. *Sensors* **14,** 7142–

7155 (2014).

36. Laverty, D. M. *et al.* The OpenPMU Platform for Open-Source Phasor

Measurements. *IEEE Trans. Instrum. Meas.* **62,** 701–709 (2013).

37. Herrmann, K.-H., Gärtner, C., Güllmar, D., Krämer, M. & Reichenbach, J. R. 3D

printing of MRI compatible components: Why every MRI research group should

have a low-budget 3D printer. *Med. Eng. Phys.* **0,**

38. Pearce, J. M. Laboratory equipment: Cut costs with open-source hardware. *Nature* **505,** 618–618 (2014).

39. OpenSCAD. at <http://openscad.org>

40. Atmel ATMEGA328-MU, 32QFN EP, AVR, ATmega, Flash - Avnet Express. at <http://avnetexpress.avnet.com/store/em/EMController?action=products&catalogId=500201&storeId=500201&N=0&langId=-1&slnk=e&term=ATMEGA328-MU&mfr=ATL&hrf=http%3A%2F%2Fr.search.yahoo.com%2Fcbclk2%2FdWU9MDEzODNDOEZCRTY4NDlBRSZ1dD0xNDQ1NjMzMzk0NjQ4JnVvPTc3NzkwNjY3NzQQmbHQ9Mg--%2FRV%3D2%2FRE%3D1445662195%2FRO%3D10%2FRU%3Dhttp%253a%252f%252f2512275.r.msn.com%252f%253fld%253dd3RucTTaKMivb5zMt3YUx1UTVUCUxDck7dGcnfGksJVps3bfj7kr5Fm2-Bpwy-8fORE2LXTnXKjK3VA-b-YgKBAE31YHb1b2iL1qytXUnk6IuiUUqMcLbFO0-Gd0mfB6TKC2cYBWB2owc2T7VMcMljgeRhk-m_uPi8YYASvSc7O756dr8J%2526u%253dhttp%25253a%25252f%25252favnetexpress.avnet.com%25252fpart%25252fe%25252fATMEGA328%252525252DMU%25252fATL%25253fcmp%25253dNA-Global-PPC-bing-27485425-sw-2015-09%2FRK%3D0%2FRS%3DjksY1omSv7wko0G07oqOAAJRRtM-%3B_ylt%3DA0LEVjlynSpWicQArkonnIlQ%3B_ylu%3DX3oDMTB2c2lzOGFwBGNvbG8DYmYxBHBvcwMxBHZ0aWQDBHNlYwNvdi10b3A-%3B_ylc%3DX3IDMgRydAMx%3Fp%3DATMEL%2BATmega328&cmp=NA-Global-PPC-bing-27485425-sw-2015-09>

41. Category:MOST RepRap build - Appropedia: The sustainability wiki. at

<http://www.appropedia.org/Category:MOST_RepRap_build>

42. LulzBot TAZ 5 3D Printer | lulzbot.com. at

<https://www.lulzbot.com/products/lulzbot-taz-5-3d-printer>