

ON ACTIVE LEARNING AND SHARING THROUGH DIGITAL FABRICATION

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Abstract

During the last years architecture and engineering practices have been incorporating digital fabrication technologies on their processes and university programs have been pushed to accommodate new demands provided by the opportunities of all these next generation technologies. The paper will show how digital fabrication is modifying and implementing the curricula of architecture and engineering students of CEU University's Institute of Technology, showing the projects carried out by students at the Digital Fabrication Laboratory (FabLab Madrid CEU) during the Fab Academy Program. Directed and taught by the director of the MIT's Center for Bits and Atoms, Neil Gershenfeld, Fab Academy has been designed to teach hands-on skills in FabLabs, training students on a wide variety of digital fabrication, electronics, molding and casting and composites practices. The paper will be focused on the explanation of the processes that are conducted during the program, that allow students to improve their curricula thanks to the use of new technologies as 3D scanning and printing, computer controlled cutting and computer controlled machining, as well as advanced technological languages.

Thanks to Fab Academy, students learn a set of digital fabrication tools and skills that allow them to produce an innovative work through the file-to-factory process of CAD/CAM fabrication. During the program global lectures on different topics are held every week by Gershenfeld. Besides, instructors in local laboratories provide hands-on activities on these topics and offer their practical knowledge to help students develop a week's assignment. Students work on the assignment using lab materials, equipment and machines, immediately applying all the concepts covered in the global and local classes and document their progress in a personal blog.

In parallel to the weekly assignments, students work on a personal final project which integrates mastery of all the skills learned during the course: the use of computer-controlled laser cutter for press-fit assembly three-dimension structures from two-dimensional parts; a large numerically-controlled milling machine for making larger sized parts; a vinyl cutter to produce printing masks, flexible circuits, and antennas; a desktop sized precision micron resolution-milling machine to make three-dimensional molds and surface-mount circuit boards and finally, 3D scanners and 3D printers. The paper will show how all these tools are related to the main objective of the program: the use of advance languages and technologies to help students on the digital fabrication of conceptual, analytical, constructive and structural models as well as prototypes that improve their curricula.

Keywords: FabLab; digital fabrication; active learning; design; architecture; engineering.

1 INTRODUCTION

Fab Labs¹ are a global network of local digital fabrication laboratories that enable invention by providing access to tools for digital fabrication. They share an evolving inventory of core capabilities to make things, allowing people and projects to be shared. So, it could be said that a Fab Lab is a technical prototyping platform for innovation and invention that provides stimulus for local entrepreneurship, allowing the users to produce an innovative work through the file to factory process.² It is comprised of digital fabrication and electronics tools, wrapped in open source software and programs including a laser cutter that makes 2D and 3D structures, a sign cutter that plots in copper to make antennas and flex circuits, a high-resolution milling machine that makes circuit boards, a large wood router for building furniture and housing, and a suite of electronic components and programming tools for low-cost, high-speed microcontrollers for on-site rapid circuit prototyping.

¹ Gershenfeld, Neil (2005). *FAB. The Coming Revolution on your Desktop*. Basic Books, New York, 2005

² Rifkin, Jeremy (2015) *The Zero Marginal Cost Society: The Internet of Things, the Collaborative Commons, and the Eclipse of Capitalism*, Palgrave Mcmillan, New York.

The idea of FabLab materialized in 2001 when Neil Gershenfeld, director of the MIT's Center for Bits and Atoms (CBA), began to teach the course "How to Make (almost) Anything"³ to teach MIT students the possibilities of new digital fabrication technologies. In 2003 he received funding from the National Science Foundation to set up the first digital fabrication outside the MIT: the South End Technology Center. Since then, the community has grown at incredible speed supported by the Fab Foundation, which was created in 2009 to support the relationships of the digital fabrication laboratories. Although Fab Labs were originally designed for communities as prototyping platforms for local entrepreneurship, they began to be adopted by universities, research centers and schools as platforms for project-based, hands-on education. In educational settings, rather than relying on a fixed curriculum, learning starting to happen in an engaging personal context, where students could find solutions to challenges and bring their ideas to life.

As support for advanced technical education, Gershenfeld started to teach Fab Academy, an internationally distributed campus for technical education that emerged from the use of the Fab Lab technologies. Fab Academy provides instruction and supervises investigation of mechanisms, applications and implications of digital fabrication. Fab Academy has been offering students from all over the world a new way to approach knowledge and technological tools. For many years, students, instructors and faculty have been engaging in an educational program to make things in a collaborative way. Fab Lab Madrid CEU,⁴ the Digital Fabrication Laboratory based at Madrid CEU University, has been running Fab Academy since 2014, providing university students access to our tools and machines. The present paper will present our experience teaching this educational program to show the potential of digital fabrication technologies to be used as tools, through which it is possible to create a working educational environment that runs in parallel to the university programs, allowing students to gain a better understanding of the concepts acquired on the theoretical classes and materialize their ideas through the fabrication of their own prototypes.

2 METHODOLOGY

The aim of Fab Academy is to initiate, mentor and train students through their participation and leadership in the global Fab Lab Network community and to teach them a wide variety of digital fabrication, electronics, molding and casting and composites practices and build skills. To that end, Fab Academy teach hands-on skills in Fab Labs all around the world with a methodology based on MIT's popular rapid-prototyping course "How To Make (almost) Anything", taught also by Gershenfeld.

The program takes place from mid-January to late June. Every week, Neil Gershenfeld holds a global lecture on a different topic thanks to a video conference system implemented in all the Fab Academy Nodes (Fab Labs with the required materials and resources to complete the program). In parallel, qualified instructors in local labs provide hands-on activities on the topic, and offer their practical knowledge to help students develop a week's assignment. Students work on the assignments using lab materials, equipment and machines, applying all the concepts covered in the global and local classes. Besides, students document their progress in a personal blog hosted in the Fab Academy archive and in parallel to the weekly assignments, work on a personal final project which integrate mastery of all the skills learned during the program.

Every week Fab Academy focuses on a different topic, giving a global view of everything related to digital fabrication. It includes principles and practices of digital fabrication, project management, computer aided design, computer controlled cutting, electronics production, 3D Scanning and printing, electronics design, computer controlled machining, embedded programming, mechanical design, machine design, input devices, molding and casting, output devices, composites, networking and communications, interface and application programming, applications and implications of digital fabrication, invention, intellectual property and the final project presentations. In order to learn all this topics, students should learn how to use a computer-controlled laser cutter, for press-fit assembly of 3D structures from 2D parts; a large numerically-controlled milling machine, for making furniture and larger sized parts; a vinyl cutter, to produce printing masks, flexible circuits, and antennas; a desktop micron resolution milling machine to make three-dimensional molds and surface-mount circuit boards; 3D scanners and 3D printers. The time commitment for students to follow the program is about sixteen

³ Gershenfeld, Neil (2012), *How to Make Almost Anything*. The Digital Fabrication Revolution. Foreign Affairs, 91/ 6, Council in Foreign Relations, New York, 2012.

⁴ Lorenzo, Covadonga (2017), *La fabricación digital y su aplicación en el ámbito de la educación superior universitaria*. El laboratorio de fabricación digital FabLab Madrid CEU, CEU Ediciones, Madrid.

hours a week at minimum, but could be far greater if the student is highly motivated, does not possess the background for a particular unit or just wants to really throw themselves into the program.

Each week a variety of activities are carried out within the program. First of all, weekly schedule include global lectures which are held once a week lasting for approximately three hours where Gershenfeld review the work of the students and teach the concepts to be developed during the assignments. Also once a week there are held recitations, where students have the opportunity to interact with leading representatives on the field of digital fabrication technologies. Besides, regional reviews, which are homework review sessions led by Gurus, are celebrated once a week to prepare the students for the global reviews. Local Instructors and Gurus are also required to attend to a weekly preparation meeting with Gershenfeld once a week before the start of class. And finally, hand-on workshops are carried out in each Fab Academy Node to help students to finish their week assignment. Fab Lab Madrid CEU has been a Fab Academy Node for the last four years, allowing our students access to a Fab Academy classroom where all the tools are ready during the program.

3 PROJECTS

During the last four years students from different backgrounds have joined the Fab Academy program to learn how to apply digital fabrication to their specific field and students and instructors have been engaging in the fabrication of a wide variety of prototypes. The paper shows some of them trying to explain the processes that are conducted during the design and fabrication of the projects, which are oriented to improve student's capabilities thanks to the use new technologies and advanced technological languages. In order to organize the presentation of the projects, we have grouped all them in two categories: technologies and projects.

3.1 Learning Digital Fabrication Technologies

Week assignments provide students all the necessary skills to use digital fabrication technologies. Along the semester, they learn how to use a computer-controlled laser cutter; a vinyl cutter; a large numerically-controlled milling machine; a desktop sized precision micron resolution-milling machine and finally, 3D scanners and 3D printers. Related to the cutting technologies it should be mentioned the wide variety of projects developed by students with a laser cutter machine. Lasers are very flexible manufacturing machines; they can cut, etch, engrave, etc. This flexibility allows students to explore multiple possibilities, from small scale design products to large scale architectural models. Among all of them it is worth to mention the design and fabrication of wooden glasses using a laser cutter machine, which demonstrate the possibilities of this technology to transform consumers into producers. In this case, after finishing the design using 2D software, the wood was laser cut before starting to stick some layers of material together to fix the glass and give full consistency to the final product.



Figure 1. Design and fabrication of laser cut wooden glasses by Adolfo Gutiérrez (left and center) and Eduardo Chamorro (right). Photo credits: Adolfo Gutiérrez © 2014

Lasers have also been used for making press-fit assembly three-dimension structures that were designed with Antimony being completely parametric. It is possible to change material thickness, dimensions and size and cut out using the laser cutter after testing and adjusting tolerance, overlap and connector gap parameters to get a precise snap-fit joint. The final result once all pieces are assembled was dodecahedrons made with pentagonal sides and sixty degree angle joints and cubes made using square sides and forty five degree angle joints. Students and instructors have also applied

press-fit laser cutter design on packaging, making design products as a four beer packer using cardboard or a wine rack, which was designed on Inkscape and fabricated in 3 millimetre thick acrylic.



Figure 2. Press-fit assembly 3D structures by Javier Buron (left), Adolfo Gutiérrez (center) and Epifanio Lorenzo (right). Photo credits: Javi Buron García licensed the pictures under a CC BY-NC-ND license; Adolfo Gutiérrez © 2014; Epifanio L. Cueva © 2013.

Some other laser cut designs explore the fabrication of products that allow instructors to encourage students to shift from a consumer to a producer society. In a time of crisis, we need a new economic strategy that stimulates production rather than consumption and we think we have to contribute to the transformation of the society through the transformation of our community. Some examples of easy to do everyday objects could be the parametric lamps made with paper, the laser cut fan that was designed and made using wood and paper, or the laser cut glasses case; an open source design that was fabricated using a cut technique that makes wood flexible to be easily bended.



Figure 3. Design and fabrication of everyday objects by Andrés Velasco (left), Álvaro García Segura (center) and Epifanio Lorenzo (right).

Although there is no doubt about the versatility of the laser cutter machine, the vinyl cutter has many advantages. One of the benefits of the vinyl cutter versus the laser cutter machine is that it does not require a water pump to cool the laser tube, a compresses to clear way the cutting surface or a form of ventilation to get rid of the smoke. All of these things may have an impact on the work space. Besides, it is not possible to cut vinyl on a laser cutter as it is poly-vinyl chloride (PVC), which produces chlorine gas and it is injurious to health. So with the aim of exploring the possibilities of the vinyl cutter machine the Fab Academy program encourage students to use it for different purposes. Among the projects developed by our students it is worth to mention the design and fabrication of T-shirt stickers. Inspired by the windows of the Italian architect Carlo Scarpa, a design for a sticker was drawn in Illustrator. After the file was ready to be cut, it was necessary to remove the transfer and to apply heat evenly to attach the final design to the T-shirt.

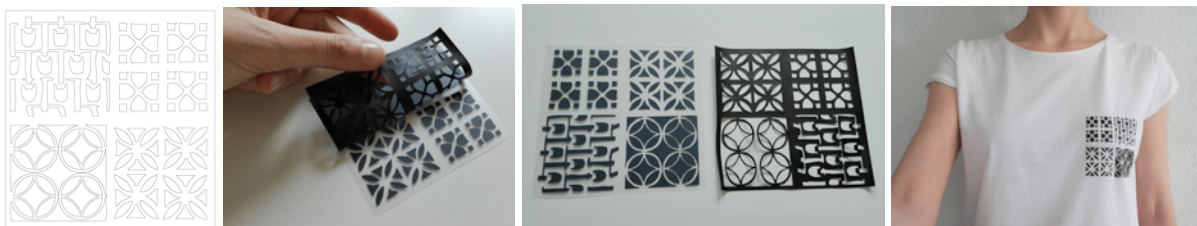


Figure 4. Design and fabrication of a T-shirt stickers by Victoria Retana. Photo credits licensed by Victoria Retana under a Creative Commons Attribution 4.0 International License.

Using a vinyl machine students have also worked on the design and fabrication of wall decals and graphics for our Fab Lab as well as for the exhibition entitled *Transformad: Taller de Arquitectura* that was shown in the space called Centro Centro Cibeles at Madrid Town Hall. Wall decals are images or graphic printed directly onto an adhesive opaque vinyl material. A low-tac adhesive is used, allowing the vinyl to be removed, reused, and repositioned many times without damaging paint or drywall. They are able to be cut to shape, have unlimited color options, and come in a wide range of sizes being designed mainly for indoor use, as in the presented exhibitions and installations.



Figure 5: Design and fabrication of wall decals and graphics for the exhibition *Transformad*, coordinated by Aurora Herrera. Design and fabrication by Eduardo Chamorro.

In relation to the use of subtractive technologies, our Fab Lab has a large numerically-controlled milling machine for making larger sized parts and a desktop sized precision micron resolution-milling machine to make three-dimensional molds and surface-mount circuit boards. Learning the use of a CNC machine has allowed students to fabricate large prototypes as pieces of furniture. For example, inspired by the furniture collection *Made in Ch-I-Italy* by Stefano Pugliese a student designed a table and four stools using a press-fit plywood system. Also, a bench based on the *Infinity Bench*, an original design from Carl Fredrik Svenstedt, was made starting with the design in Grasshopper, a parametric software. Later on, MDF was used to get the pieces in a CNC machine that were assembled and varnished to be used in an outdoor terrace. The *Vitra Chair* was the inspiration for another piece of furniture that was designed in AutoCad and then exported to 123Dmake where it was possible to get interlocked slices to give stoutness to the chair. Once the desired number and slice distribution was exported, it was possible to prepare the files to be milled using a unique 1.20 x 2.40 meters plywood board 7 millimeters thick.



Figure 6: Wooden furniture made by Victoria Retana (left), Adolfo Gutiérrez (center) and María Santisteban (right). Photo credits licensed by Victoria Retana and María Santisteban under a Creative Commons Attribution 4.0 International License, Adolfo Gutiérrez © 2014.

Using wood as construction material, students also explore creative solutions for solving their needs within the framework of innovation. It is worth to mention the surfboard designed using AkuShaper open software, cutting the pieces from a plywood that was finished afterwards using a fiberglass composite. Also, a 'headquarters' organizer to gather the laptop, some books, a lamp, a printer and a router was designed to be fabricated in plywood and assembled without any screws. Also, a do it yourself Arcade Bartop machine was designed to be milled in plywood and press-fit assembled.

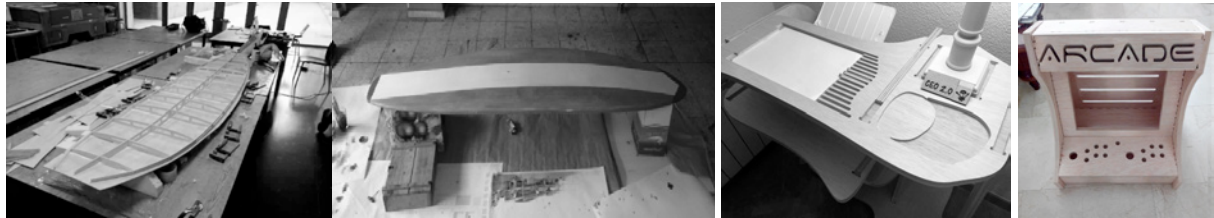


Figure 7: CNC milled wooden surfboard by Eduardo Chamorro (left), desk by Juan García-Maestro (center) and Arcade machine by Álvaro Fernández La Roja (right). Eduardo Chamorro © 2014, Juan García Maestro © 2017, Álvaro La Roja © 2017.

Parametric design was also used for the desing of a baby walker, a toy for a one year old baby that was also painted and varnished with a water based paint and varnish. After having the design in Onshape, the toy was fabricated with plywood. Also, it is worth to mention a window that has been designed as a three axis milling machine compatible design for high performance timber windows up to Eurocode standards. The design is fully parametric allowing extensive customization and adaptability to different glazing systems, seals and stock timber. Thanks to this design, it is possible to transform a highly skilled woodworking task into a flat pack design that can be assembled with almost no experience with satisfactory results.

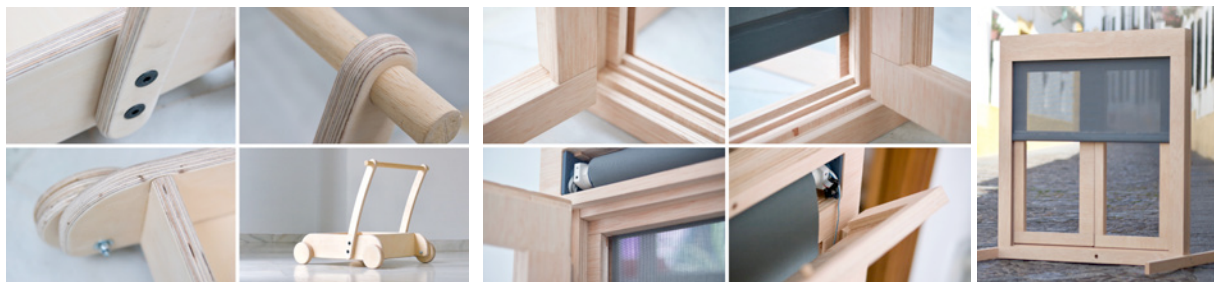


Figure 8: CNC milled baby walker (left) and window (right), both by Javier Burón. Photo credits licensed by Javi Buron García under a CC BY-NC-ND license.

In addition to the large milling machine, we also have at the Fab Lab a precision micron resolution-milling machine to make three-dimensional molds. With this technology, students have developed small scale jewellery pieces using molding and casting techniques. After the first sketches of the necklaces, a mold made up of two different parts was designed and milled using wax. Later on, following the idea of replicating the 3D model in resin, the mold was made in silicone so that it could be bend and do the casting easily. Finally, the casting was made with polyurethane resin.

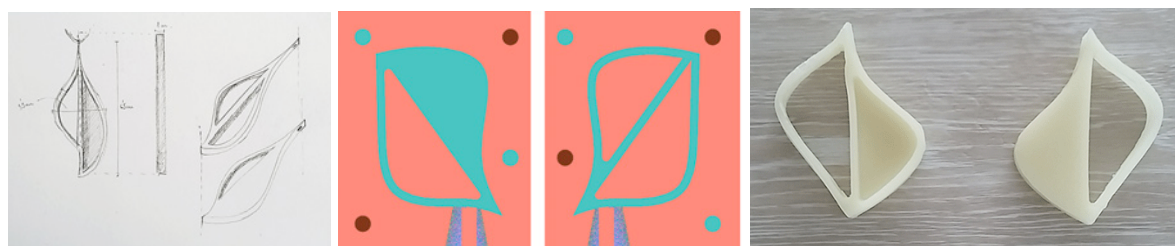


Figure 9. Design and fabrication of jewellery pieces by María Santisteban. Photo credits licensed by María Santisteban under a Creative Commons Attribution 4.0 International License.

Another interesting project using a mold was the fabrication of a canoe shape plate. In this case, insulating green foam was used to do the mold, producing a fibre composite part in it. A large milling machine was used for that purpose and after that, the fabric pattern was cut in a laser. Once the resin and the different cloth and plastic layers were put it over the mold, it was introduced in a vacuum bag with the idea of extracting all the air from inside. After five hours the result was a perfect product design produced with a fibre composite that allow students to explore with new materials and learn the combination of laser cutter and milling machines to fabricate molds.



Figure 10. Design and fabrication of a canoe shape plate by María Santisteban. Photo credits licensed by María Santisteban under a Creative Commons Attribution 4.0 International License

Another application of the desktop milling machine has been the fabrication of the molds for some pieces to be assembled as an structural model. Inspired by the beams designed by the Spanish architect Miguel Fisac, a beam was designed in Rhinoceros and then prepared to be milled in wax to get the mold. Once the wax was ready, a negative mold was fabricated to cast the multiple pieces that make up the whole beam. The last example that shows the application of milling machines is the fabrication of molds for a piece of furniture that was made with composites. Based on the Ray and Charles Eames fiberglass chair, which was one of the first design in using fiberglass reinforced resins, a 3D design of the chair adapted for toddlers was finished in Rhinoceros. Later on, a positive shape of the mold was made, scaling it to fit the scale of a fifteen month old baby and slicing it in three sections to be carved using 38 millimeter thickness MDF. Once the three sections were carved, stacked, glued together and sanded the composite was produced to get the final chair.



Figure 11. Design and fabrication of molds for making a structural beam (left) by Covadonga Lorenzo and fabrication of a chair (right) by Javier Buron. Photo credits licensed by Javi Buron García under a CC BY-NC-ND license.

3.2 Making Projects and Machines that Make

Teaching through a project based learning approach allows students gain knowledge and skills by working for an extended period of time on a personal project to investigate and respond to an authentic, engaging and complex question, problem, or challenge. The core idea of project-based learning is that real-world problems capture students' interest and provoke serious thinking as the students acquire and apply new knowledge in a problem-solving context. The teacher plays the role of facilitator, working with students to frame worthwhile questions, structuring meaningful tasks, coaching both knowledge development and social skills, and carefully assessing what students have learned from the experience. The project should solve a real problem so that students could learn concepts related to problem solving and creative making of products.

Among the projects developed by our students at Fab Academy program, it is worth to mention a reactive façade for buildings made with a mechanism that moves depending on the amount of light that receives, thanks to computer controlled software. It was designed using two supports, one on each side of a façade panel, that allows the façade to move in a vertical axis as well as to rotate up to 360 degree angle. Thanks to this mechanism installed in all the glass panes, the façade becomes a kinetic architectural element that moves depending on the intensity and direction of the sunlight.

The aim of the Fab Academy program is to allow a student to use the knowledge acquired during the week assignments to build the physical parts of a final project prototype, as well as the electronics components. In this case, it was used a laser cutter machine for the fabrication of a box to fit all the circuits, cables and batteries and for cutting and engraving the methacrylate used to act as the glass pane of the façade. To make the glass supports it was designed a truss system that was 3D printed and assembled before adding the sensors and servos that allowed the movement of the panels. All the electronics boards were designed and fabricated by the student as well as the programming.

Following the same line, it should be mentioned the Fabulous Window, an interactive façade with distance sensors to interact with the people that use light translucent transmissive materials. To make a prototype of the window, it was built one module of the facade with distance sensors as inputs and LEDs as output, integrated in a structure that support a single engraved acrylic pane that illuminates showing the interaction of the building with the users. The press-fit structure was made using MDF boards, cut with the laser, which was used also to cut and engrave the methacrylate. 3D printed pieces were designed to hold the acrylic before placing the sensors that allow the interaction.



Figure 12. Kinetic façade (left) by Eduardo Chamorro and Fabulous Window (right) by Victoria Retana.
Photo credits: Eduardo Chamorro © 2014, Victoria Retana licensed under a Creative Commons Attribution 4.0 International License

Another project was focused on making mobile spaces to open new forms of creativity in exhibition spaces. A scale model of an interactive exhibition space was made to be conceived as a multipurpose space for the exhibition of pieces. To that end, a light support structure made with acrylic with punctual motors in specific points, allowed the exhibited objects hanged on the structure to move according to the position of the viewers. Three capacitive sensors captured the presence of people and allow the interaction and make the observer being participant of that set. The structure was made with the laser cutter machine, the hook and hoist system was 3D printed in PLA, the boards were milled with the micron-precision milling machine, the vinyl cutter was used for cutting the copper vinyl for the sensors and all the electronics were based on networking and communications between boards though I2C.

A safety urban space for cities was explored by an architecture student that designed and fabricated an anti-run over security enclosure for protecting crowded areas from accidents and terrorist attacks. Surrounding a public space, it was designed a security system to be activated when a car or a heavy vehicle cross the detectors with high speed. The prototype of the barrier was designed as a hinge with a spring on its axis, connected to the sensors which activate the safety mechanism allowing the spring causes the ramp to rise. It was fabricated a 1/3 scaled prototype using a milling machine for the larger pieces; a 3D printer to make the drawer for the latch, the servomotor and the precision pieces and finally, composites for the barrier that were covered with vinyl.



Figure 13. Showroom (left) by María Santisteban and Safe Square (right) by Álvaro Fernández La Roja.
Photo credits: María Santisteban licensed under a Creative Commons Attribution 4.0 International License. Álvaro Fernández La Roja © 2017

The last project to mention is a low-cost newborn incubator by a engineering student enrolled in the Fab Academy Program, which is already being used in maternities of three different African countries. It has been awarded as Best Medical Project in the *Global Fab Awards* and presented in the International Congress *Medicine X* that is celebrated every year at Stanford University. The baby incubator was made with a wooden structure milled in the CNC machine and 3D printed precision pieces, as well as electronic circuits that allow the use of a thermostat, a ventilator and a heater, giving the suitable temperature conditions for the baby. In addition, the 'scissors legs' allows the inclination of the bed for the treatment of certain pathologies. After several prototypes, the last one has improved the isolation and has reduced considerably the quantity of air to heat, so the electronics is less stressed. Also, it assures good ventilation with higher comfort parameters thanks to the use of computational models of dynamics of fluids and finally, it has been added two new modules: one for the treatment of jaundice and another one for the battery supply.

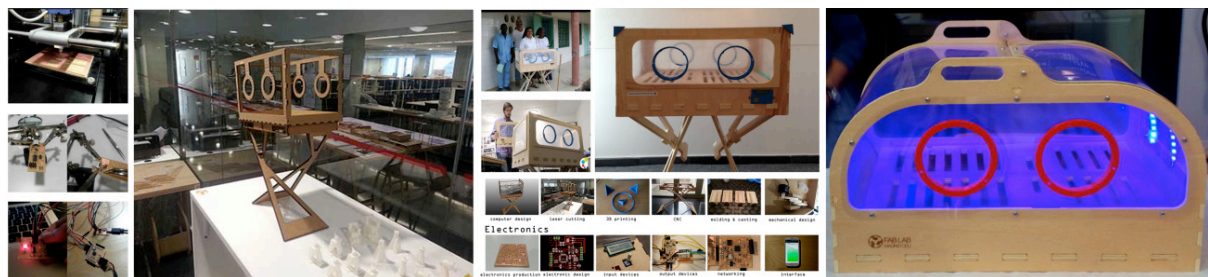


Figure 14. Low-cost Incubator by Alejandro Escario. Photo credits: Alejandro Escario © 2015.

When we started to run the Fab Academy Program we also adopt participative and interactive pedagogies where teachers guide students on their learning processes promoting a collaborative working space to exchange knowledge and ideas.⁵ Following this line, every year it is asked Fab Academy students to work together in a group assignment on an ambitious aim: the manufacture of a machine. To reach that aim, students have used the kits of components designed by the MIT's researcher Nadya Peek's,⁶ which include a set of modules endowed with engines and drivers, that allows to easy assembling any type of machine. Using them students have designed a variety of machines as for example, an augmented reality machine, that draws based on a series of coordinates. A video camera registers the real space where the user is working and the software turns it into a two-dimensional virtual space where it is possible to draw. As users are drawing in the virtual space, the machine calculates the coordinates obtained from the camera's perspective and placed itself precisely on the coordinates, shaping point to point a precision drawing.

⁵ Papert, Seymour (1993). *The Children's Machine. Rethinking School in the Age of the Computer*. Basic Books, Nueva York.

⁶ Peek, Nadya (2015), *Making Machines that Make: Object-Oriented. Hardware Meets Object-Oriented Software*, op.cit.

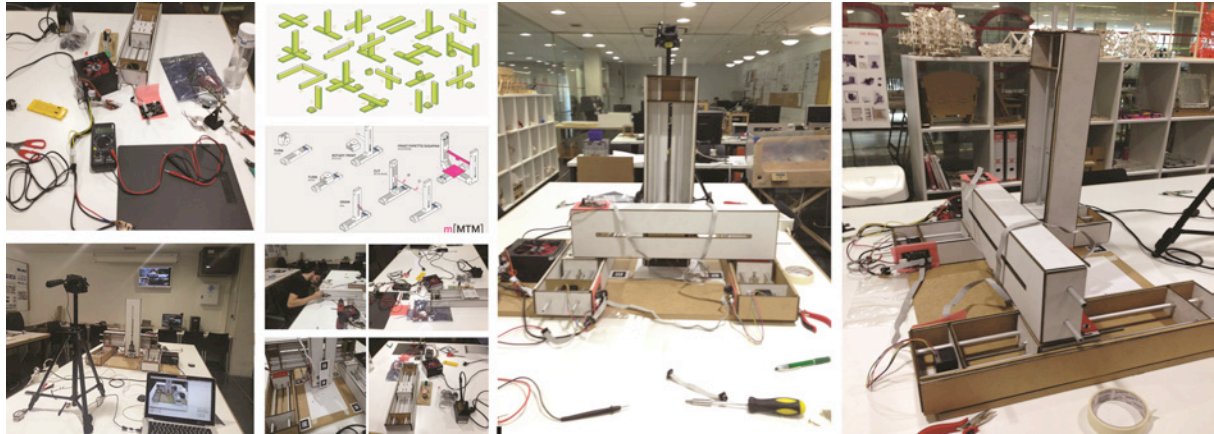


Figure 15. Virtual Reality Machine by Alejandro Escario. Photo credits: Alejandro Escario © 2015.

4 CONCLUSIONS

The paper have tried to illustrate the possibilities of a project-based learning and sharing experience that run in our Fab Lab: the Fab Academy Program, showing some of the applications of the digital fabrication for architecture and engineering university students. The aim is to show how digital fabrication technologies are used in the Fab Lab to the main objective of the program: initiate students into effective ways to engage in hands-on activities based on projects to materialize theoretical concepts into prototypes designed and fabricated entirely for the students. They work in groups and share their learning experiences with students allocated in other Fab Labs around the world. It is our intention to continue working on this line, convinced that the digital fabrication laboratory can contribute to improve the professional profile of our students through the Fab Academy Program, a pedagogic environment based on innovation, active learning and sharing.

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