Automation of old mechanic machines using Fab Lab developed modular analog to digital control system

Jari Pakarinen, Jani Ylioja, Georgi Georgiev, Ivan Sanchez Milara

Jari Pakarinen, Fab Lab Oulu,
University of Oulu, Finland
jari.pakarinen@oulu.fi

Jani Ylioja, Fab Lab Oulu,
University of Oulu, Finland
jani.ylioja@oulu.fi

Georgi Georgiev, Center for Ubiquitous Computing,
University of Oulu, Finland
georgi.georgiev@oulu.fi

Ivan Sanchez Milara, Center for Ubiquitous Computing,
University of Oulu, Finland
ivan.sanchez@oulu.fi

Abstract

We describe the design and manufacturing process of an automation prototype for a workshop machine. We decided to augment and automate a Through Hole Plate machine in use, instead of buying a new one. To that end, we have built off-the-shelf modules that can be easily attached to the machine. The modules either augment the machine with new functionality, or utilize the actual mechanical actuators of the machine to automate desired tasks.

The machine is in daily use and thus the automation development cannot interrupt its normal use. Hence, the whole automation structure is removable in a “add-on-top” manner. This makes it easier to replicate the automatisation in another machine without any further modification.

We have always utilized Fab Lab processes and built easily fabricable mechanics to facilitate the replication at Fab Lab environment. Reusing old machine instead of buying a new one, and utilizing local resources support degrowth and urban resilience, as well as the circular economy.

The prototype is built as a part of Academany Diploma Thesis, following the thesis pilot program structure and implementation. We believe that local and facilitated development of automated machines is a good way to modernize manufacturing with a low environmental impact.

Keywords

Fabricability, adaptability, automation prototype, reuse, modularity, PCB, through hole plating, retrofit, Fab Lab, Fab Thesis, digital fabrication

1 Introduction

Digital fabrication presents a new digital revolution which empowers individuals to design and fabricate physical objects wherever and whenever they need them (Gershenfeld, 2012). At its core, digital fabrication brings programmability to the physical world: an individual may define the behaviour of

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different types of manufacturing machines utilizing different types of CAD (Computer aided design) and CAM (Computer Aided Manufacturing) software tools.

Hand in hand with the universalization of digital fabrication processes we have observed the blooming of maker movement (Dougherty, 2012). Members of maker community share the interest in the creation of new devices or artefacts either from scratch or by tinkering with existing ones utilizing technological resources such as digital fabrication, physical computing, electronics and programming (Papavlasopoulou, Giannikos & Jaccheri, 2017). In recent years, maker movement has broadened its boundaries moving from its traditional niches (people with interest in hardware and software), to more general fields such as government, international cooperation, education, and business.

Fab Labs are quite connected to the maker culture and the digital fabrication. They are small digital manufacturing working areas that enable the design of own products from scratch utilizing specialized equipment such as 3D printers and laser cutters. Fab Lab network is formed by more than 1000 Fab Labs distributed all around the world. All Fab Labs share the same core of processes, enabling an active exchange of ideas and the replication of any project implemented by one member of the network (Walter-Hermann & Bunching, 2014).

Fab Lab processes are slowly being integrated into education environments (Blikstein, 2013; Bevan, 2017) and are getting more impulse in the field of open government and participatory city development (Diez, 2012), humanitarian help (Loy et al., 2016), and as key infrastructure for business incubator/accelerator or as a support for SMEs (Morel et al., 2015).

In this paper, we would like to put the emphasis in a field in which the role of Fab Labs might not have been explored deep enough: automation and digitalization of machinery. Most of the modern manufacturing machinery is automated (Smith & Light, 2016). We are quickly moving into Factory 4.1 (Strozzi et al., 2017) where machines are not only automated but they are working together with people and communicating with each other. However, there is still legacy machinery in many factories and workshops that are not ready for this transition. For instance, there are machines that, in spite of their sequential, mechanical and repetitive operations must be fully driven by a human operator. He/she might just need to be in front of the machine pressing different buttons in a sequential order so the machine can perform the different processes to complete a task. This represents a clear waste of resources. Also the environment can be hazardous or unpleasant for the worker, even when today's work environment is well controlled and risks minimized. These conditions could include chemical exposure, bad lighting conditions or bad working postures. This is an unnecessary exposure to the worker. (Carayon P, Smith M J, 2000) Possibly most importantly, in an automatized environment the human operators' time will be freed to perform more complex tasks. Replacing old machines with new ones to get them automated could be expensive and it does not support degrowth, urban resilience and circular economy (Prendeville et al., 2016). Finding a way of automating the machine would bring it into this century and extend its meaningful usable life. In addition, there might be situations in which the automated version of the machines do not exist.

In this paper, we propose to automate and digitalize legacy machinery by fabricating off-the-shelf modules that are able to activate machines' mechanical actuators (e.g. buttons). These modules are placed on the machine structure and enable its automatization. In addition, thanks to our modular design, we can augment existing machines by adding functionality that they currently do not have. We aim to make our approach simple, cheap and repeatable in other Fab Labs.

In order to validate our concept, we have automatized a THP (Through Hole Plating) machine that is located in our PCB (Printed circuit board) fabrication workshop. A PCB THP (Figure 1) is a simple machine that enables making connections between layers in multilayer PCBs using electrochemical process by adding copper to the drill hole walls. This process uses a lot of the operators' time since he/she needs to periodically move a PCB from one bath to another and activate certain buttons and switches in a sequential order. The process is sequential and iterative what makes it ideal for automation. There aren't any automated machines on the market for this level of PCB production. The only way to get automation is to either build one by ourselves or augment the existing one.

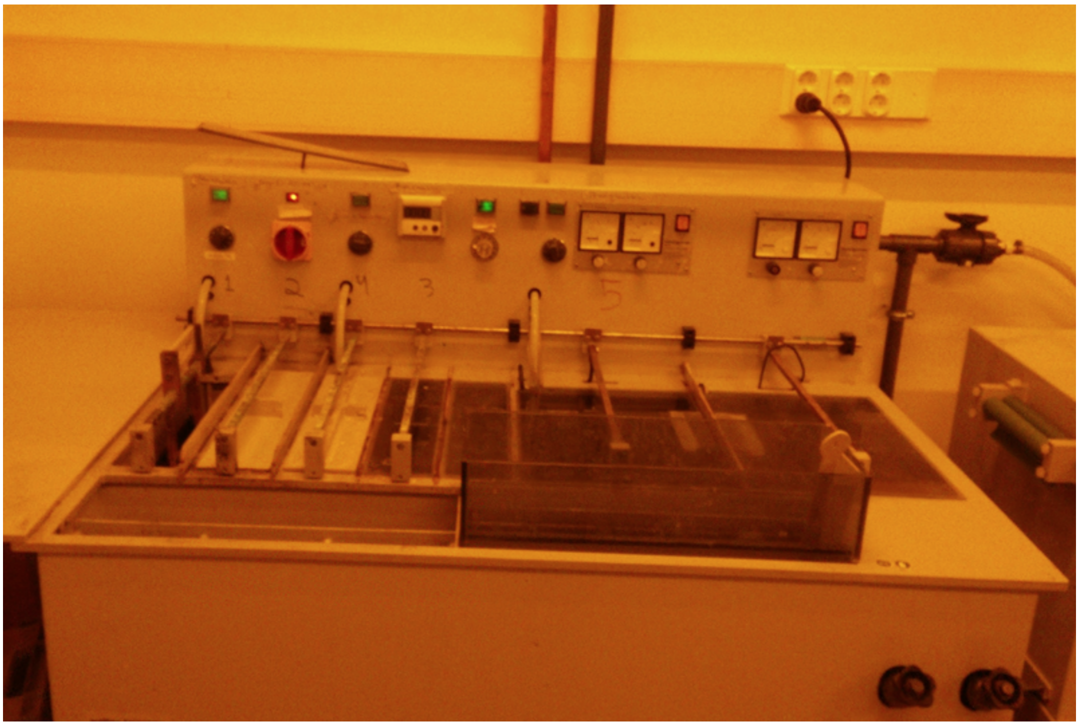

Figure 1: Through hole plating machine operated and modified in this work in its original stage.

We are now in a third iteration of our prototype. During the first iteration we focused on the automatization tasks. During the second iteration, we improved the mechanics of the automation and sought after solutions for interface automation. In the third iteration we have focused in the modularity and the fabrication off-the-shelf modules.

This project was implemented as a part of the Fab Thesis, a fab network incubator program to further develop Fab Academy final projects to impact and benefit Fab Lab network and society around them. The first author of this paper has designed and fabricated all the modules presented in the paper.

Our main contribution to the Fab Lab community is a novel idea to automate and digitize old machines utilizing simple, and cheap off-the-shelf hardware and software modules that are fabricated utilizing Fab Lab processes. Other Fab Labs can easily replicate our modules to customize their own machinery. All design files, and extra information regarding the product can be found in GitLab[16].

2 Academany Diploma Thesis

Academany (Academany, 2018) is piloting a Diploma Thesis program to nurture development of projects within the Fab Lab Network, and to increase the impact of Fab Labs in society. The contribution of this thesis program can be sought in providing knowledge of Fab Labs as alternative innovation platforms (Kohtala, 2016). The Academany Thesis aims to offer a distributed development platform for innovators and researchers within the Fab Lab network, in collaboration with worldwide experts in different fields of knowledge and practice. The Diploma Thesis could be considered as an incubation (business), research (education) or development (social) process to increase the impact of projects from the Fab Lab community (Osunyomi et al., 2016).

Thesis projects will be reviewed by the evaluation team, which will be formed by, student's advisor, Academany scientific committee members and an invited guest jury. Projects will be validated locally and should be documented online.

A two-week development cycle is used for timing the progress of the project. Tasks are two-fold, technical development and pilot implementation of thesis program structure requirements, i.e. documentation,

[16] https://gitlab.fabcloud.org/fabdx/2017-18/fablaboulou

landing page, presenting progress. The design and manufacturing of the prototype needs a multidisciplinary approach. These include mechanics, electronics and user interface design.

This project is a part of Academany Diploma Thesis program pilot. The first author started doing the PCB THP machine automation at the Fab Academy 2017 as his final project. During the Academany Diploma Thesis he came up with the modularity concept to control mechanical actuators.

3 Automatizing a THP utilizing Fab Lab processes

Through hole plating (THP) is a sub process of making printed circuit boards for electronics. When circuit board design needs two or more layers, the electrical connections between layers are done using holes (vias) drilled to the board. For these vias to form a connection between layers they have to be made conductive. THP is one method to achieve this in which copper is added to the walls of the holes to make them conductive. This process requires that the blank PCB goes through a set of chemical baths. PCB THP machine is a simple and manually operated machine to achieve this. A blank PCB needs to go through six different baths with correct timing (Figure 2). The whole process takes a lot of the operator time, during which he/she needs to move the blank PCB from one bath to the next every few minutes. Some of the functions of the THP machine have to be activated and deactivated during the process by pressing different buttons.

The process is sequential and iterative. However, there aren't any automated machines on the market for this level of PCB production. The only way to get automation is either build one or automate the existing one.

In this work, a specific machine used at the University of Oulu printed circuit board manufacturing line will be automated. It is an old manual THP machine from German manufacturer Walter Lemmen GmbH[17] (Figure 1).

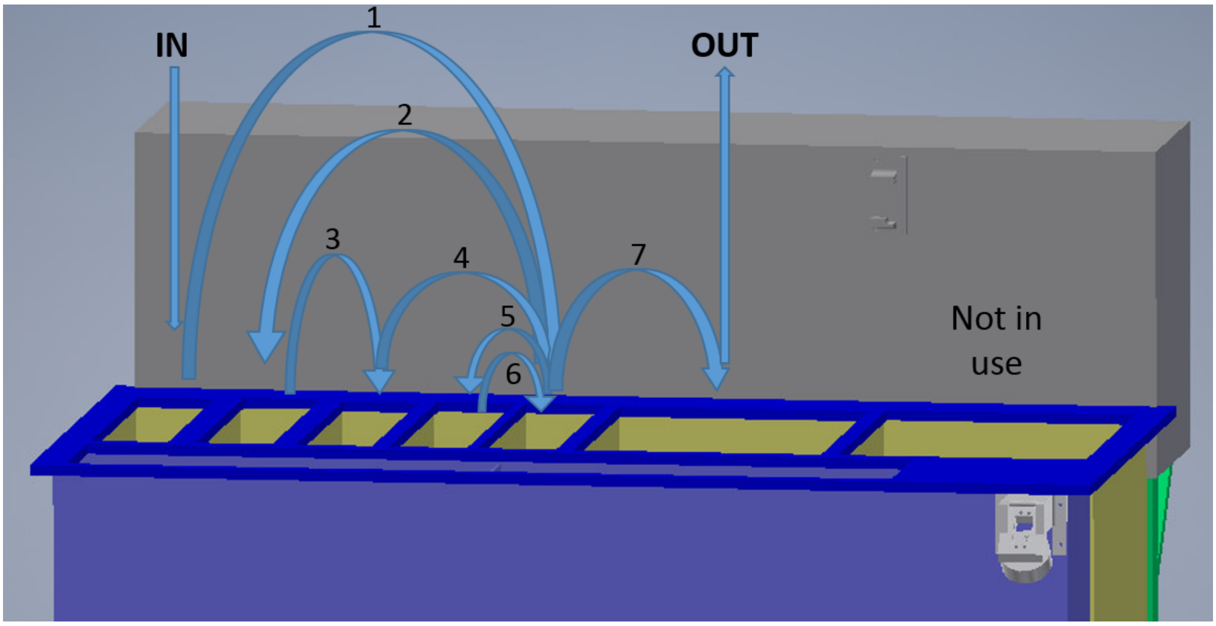

Figure 2: Through hole plating process flow in our machine. The numbers represent the order in which the blank PCB is inserted in the different tanks.

One important aspect that we had to consider during the whole development cycle is the fact that the THP machine is in daily use, so prototypes had to be done in such a way that automation system could be added on the existing machine to automate it. But the machine must always be up for use.

We are now in our third development iteration. During the three iteration cycles we added the necessary mechanics, electronics and software to automate the process. Next, we will explain the main line of

[17] https://www.walterlemmen.de/

thought for the design in the different iterations. We will describe the modules in much more detail in section 4.

3.1 First iteration. Basic automation.

During the first iteration (Fab Academy final project) we focused only on the automation of the PCB movement (shift from one tank to another) for that particular THP machine. In this case, we built a two axis machine using a lead screw, what ended in a sturdy and heavy solution (see figure 3). On the first prototype, a servo arm was used to put the board in the tanks. The weight of the board was too much for the servo to handle, and that posed an issue with larger PCB blanks.

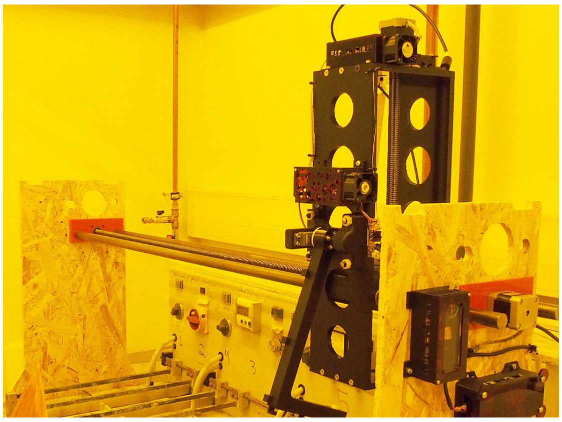

Figure 3: Automation done for the machine during Fab Academy (iteration round one).

3.2 Second iteration. Improving mechanics.

During the Fab Thesis (second and third iteration) the project developed into an idea of general automatization of legacy machinery automation. PCB THP became a specific case in the process.

During the second iteration lead screw was removed from the lateral movement mechanism and replaced with a toothed belt. Vertical mover unit was also rebuild to be much lighter. The servo needed to move the PCB out of the line of tanks was removed. The support structure was re-designed so that it would be attachable without structural modification of the original machine (Figures 4 and 5).

In electronics development point of view the modularity started to seem as the best option to proceed with.

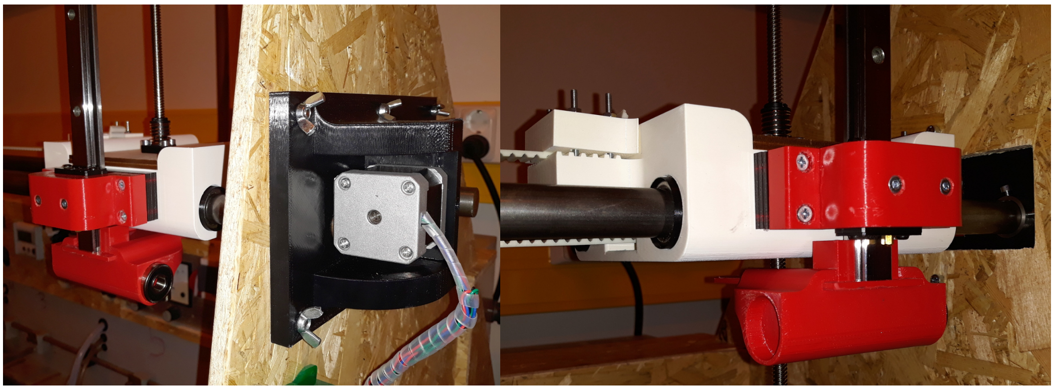

Figure 4: Second iteration mechanics for PCB blank movement. A lead screw was selected again for vertical movement i.e. dipping.

3.3 Third iteration. Modular control automation.

During the third iteration we focused on the modularity, what enhanced the potential impact for the Fab Lab community. We developed the control interface modules (e.g. to manipulate buttons). The concept of general automation block was devised and developed further. The utilization of mechanic actuators means that there is no need to modify the original machine or work with high voltage systems. Modules and their implementation is explained in the next chapter in detail.

4 Modular architecture: design and implementation

4.1 Modularity principles. General architecture.

Since, we aim our approach to work not only in our THP machine, but also in any other legacy machine, our architecture is based on off-the-shelf customizable modules. Although this is not totally achieved yet, our goal is that each module has its own mechanics, electronics and software.

The automation hardware presented in this paper is considered as modular mechanic objects that can be used as a “toolbox” for automation of many different machines that need automatization. Each module would be a self-contained artefact, performing a reduced set of functionalities, that can be attached to the machine main structure and that is able to communicate with other modules (via Bluetooth) with the final goal of fully automate the whole set of machine tasks. Communication between modules and other devices will open possibilities to extend to IOT environment machines. Software and communication among modules are still work in progress.

Two types of modules would be needed, (1) modules to implement or automatize a functionality that the machine does not perform by itself, and that usually is performed by the operator (e.g. THP machine does not have the capability of moving the blank PCB from one tank to another) (2) control automation modules to activate some of the machine’s actuators for example rinsing water jets (activated by rotary valve) or activating electrolysis current (by rocker switch).

Right now we have managed to encapsulate the mechanics and electronics of the modules so they can be easily attached to the machine structure.

4.2 Automation unit main structure

The automation unit main structure will hold all the modules. Modules are currently fixed to correct places with screws. In addition, the main structure contains holes to access mechanical actuators in the machine. The structure is designed in a way that makes it easy to attach it to the machine and to remove it. The whole automation system is an on-off type single block and will not require extra structure modification or connections to the original machine. This design makes it possible to manufacture and test the automation without disturbing the machine’s normal use. The main unit only needs to be placed on top of the machine and when needed, it can be easily removed (see Figure 5). The whole structure is built out of OBS and machined with a CNC router. Final version will be machined of suitable material like Polyoxymethylene (POM) that can handle acidic environment.

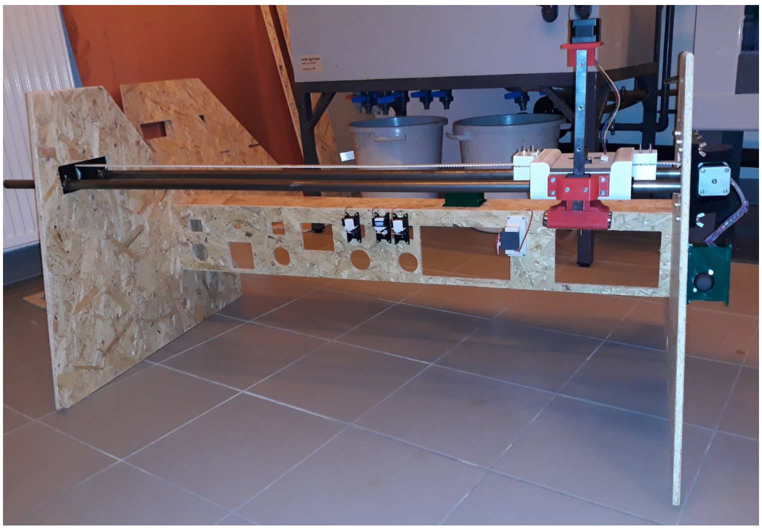

Figure 5a: Automation unit main structure

Figure 5b, c: machine without automation unit (bottom-left), automation unit on the machine (bottom-right).

4.3 Lateral and vertical movement enabling modules

To be automated PCB THP machine needs to have lateral movement over the baths and vertical movement to dip the PCB blank into the bath. Baths are placed in a row next to each (Figure 2) other so only two directions are needed. When moving the blank PCB over the baths, there is a problem of chemicals getting mixed by dripping into wrong baths. This was solved by moving the board out of the line of movement by tilting/lifting the blank PCB to the side.

4.3.1 Mechanics

The general automation of x- and z-movement is implemented in this module. Most of the mechanics parts were 3D-printed on our Stratasys printer out of ABS.

NEMA 17 Stepper motors were used for vertical and lateral movement. These are commonly available, cheap and with good resolution.

Lateral mover unit was made using toothed belt. The lateral mover unit is shown in Figure 6 (left).

Vertical mover tilt unit was a hard part to develop and it is not fully developed yet. The part needed to be simple and durable. It is realized with lead screw which converts turning motion of a stepper motor into linear motion of the unit (see Figure 6, right). The tilting will be fully mechanic on the third iteration.

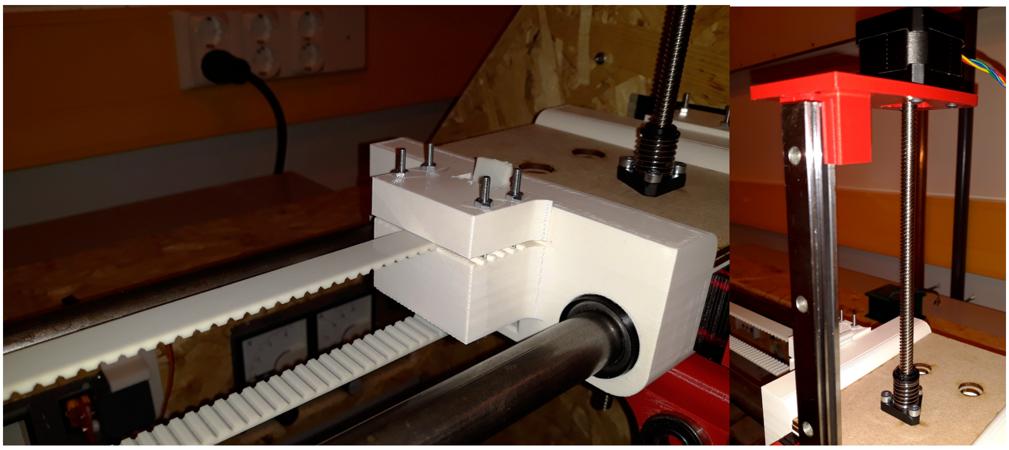

Figure 6: Using toothed belt and lead screw on the second prototype.

4.3.2 Electronics

The electronic components of this module is formed by:

1. Stepper motor drivers. This includes two stepper motors that need to be controlled separately.
2. Closed loop monitoring and end switches of the positions of moving parts (under development).
3. Inter control module communication (i.e. networking) using cable or Bluetooth.

Figures 7 shows modular electronics for controlling stepper motors that drive the lateral and vertical (dipping) axes. Electronics module includes a joystick interface so the operator can move the x- and z-axis. All the electronics are encapsulated in an laser-cut acrylic box, that can be easily screw to the unit main structure.

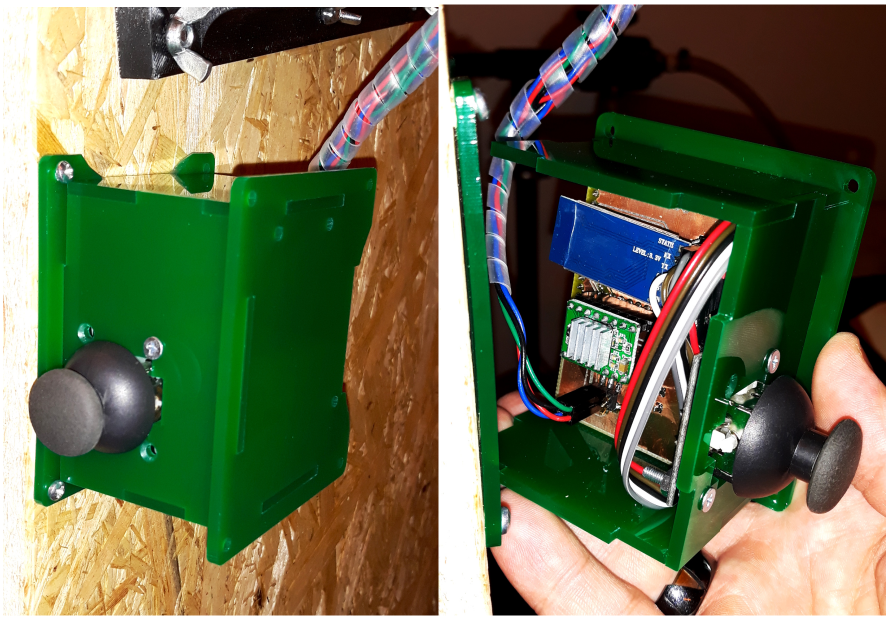

Figure 7: Modular control electronics for mechanics modules (left) and stepper driving (right).

4.4 Control automation modules

4.4.1 Overview

One main idea of the Fab Thesis work was to generate a type of modular mechanics/electronics units that are used for automation (Weyrich & Klein, 2012). The control interface of the original machine controls high voltage (230V) electronics through different kinds of mechanical actuators (buttons, knobs…). Making electric connections to this system would require licensed electronics specialist. To avoid this issue, we produced different types of mechanical modules to automate the operation of those actuators, without modifying the electronics of the machine at all. In Figure 8 we present the different actuators that we are controlling using our off-the-shelf modules.

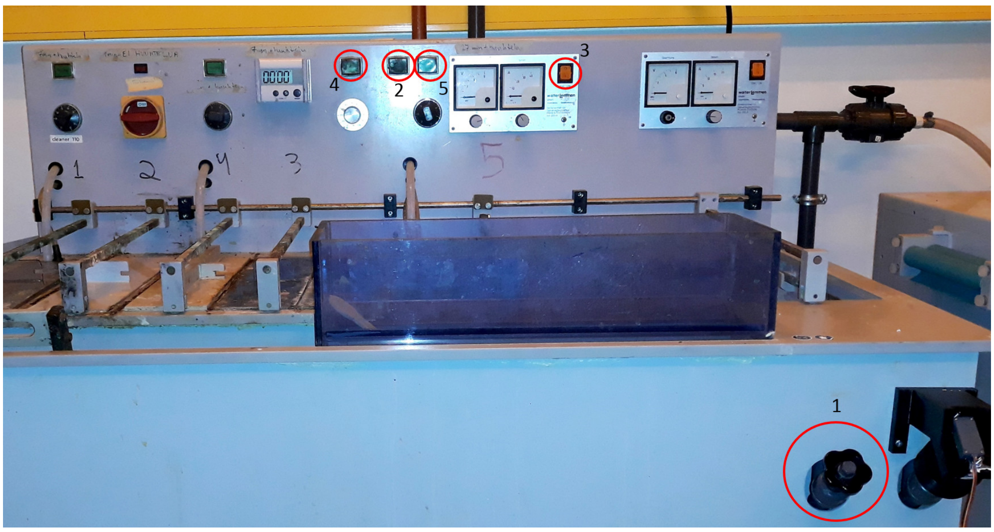

Figure 8: Controls that have to be automated: Rinse water rotary valve (1), Agitation air activation push button (2) and electrolysis current activation rocker switch (3).Buttons 4 and 5 are not necessary at this stage.

The mechanics of each module depends on the actuator to be manipulated (button, switch…). In the particular case developed in this work, we are interacting with three different types of mechanic controls, namely: push buttons, rocker switches and rotary valves.

Since, generally it is problematic to attach the modules directly to the machine, we have personalized the skeleton of the main structure (section 4.2). The structure will contain slots that fit the position and shape of the different actuators, dials and screens (Figure 9). This enables the manual use of the machine and easily screw the modules in place.

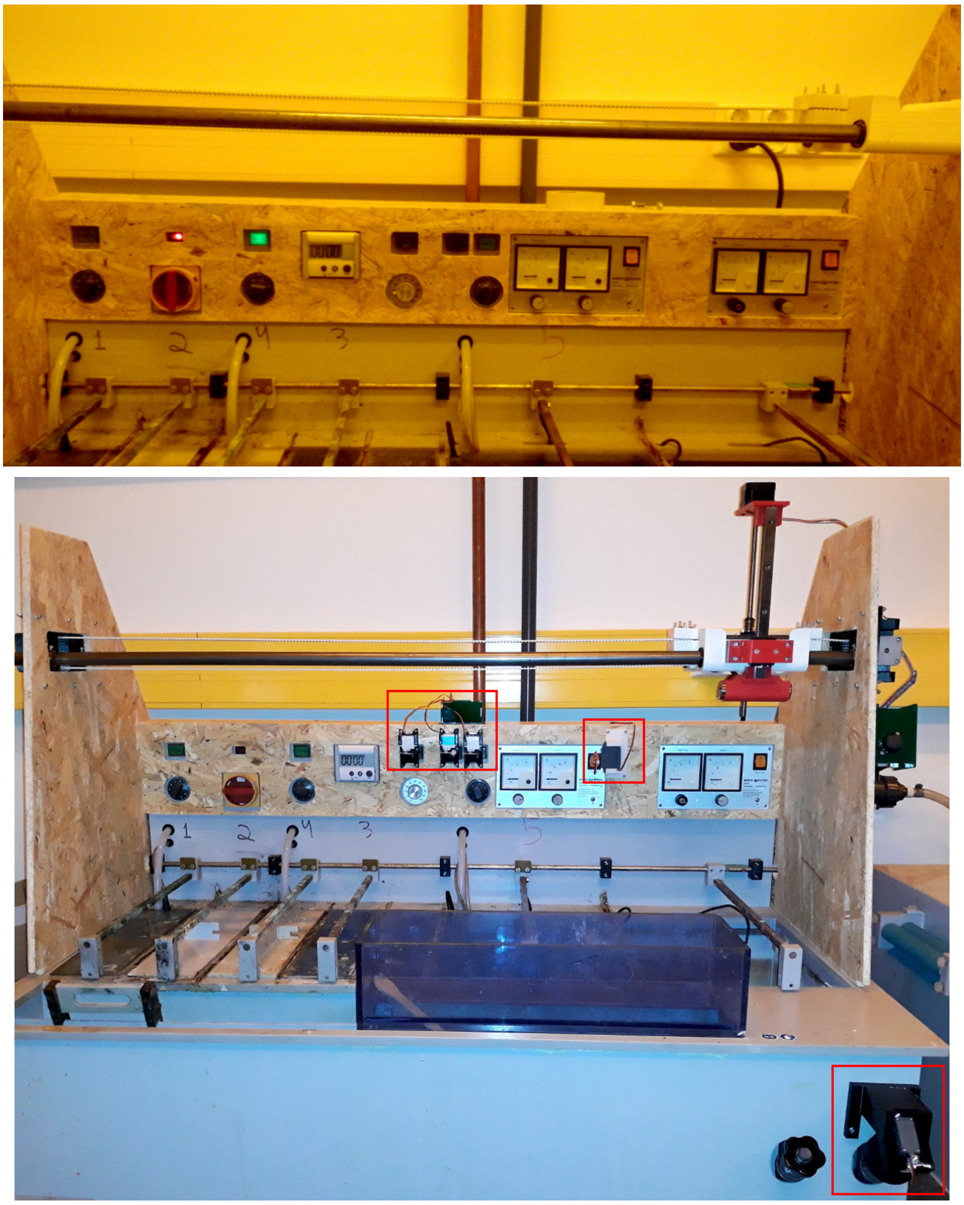

Figure 9: Automation unit main structure on the machine (top). All original controls are visible and ready to be interfaced. Automation modules attached to the structure (bottom).

4.4.2 Mechanics

Mechanics parts are specific to a certain actuator (e.g. a rocker switch), but currently all of them are implemented using servos. The main modules built till now and basic operations are summarized in Table 1.

Mechanic action to be performed	Example	Description
Push button		A servo pushes the button, and will go back to its original position
Rocker switch		An additional flat structure attached to a servo is used for switching
Rotary valve		A servo will rotate the valve
Knob's		Under develpoment

Table 1. Examples, models and implementations of different modules.

Following picture (Figure 10) shows more detailed view of the designs.

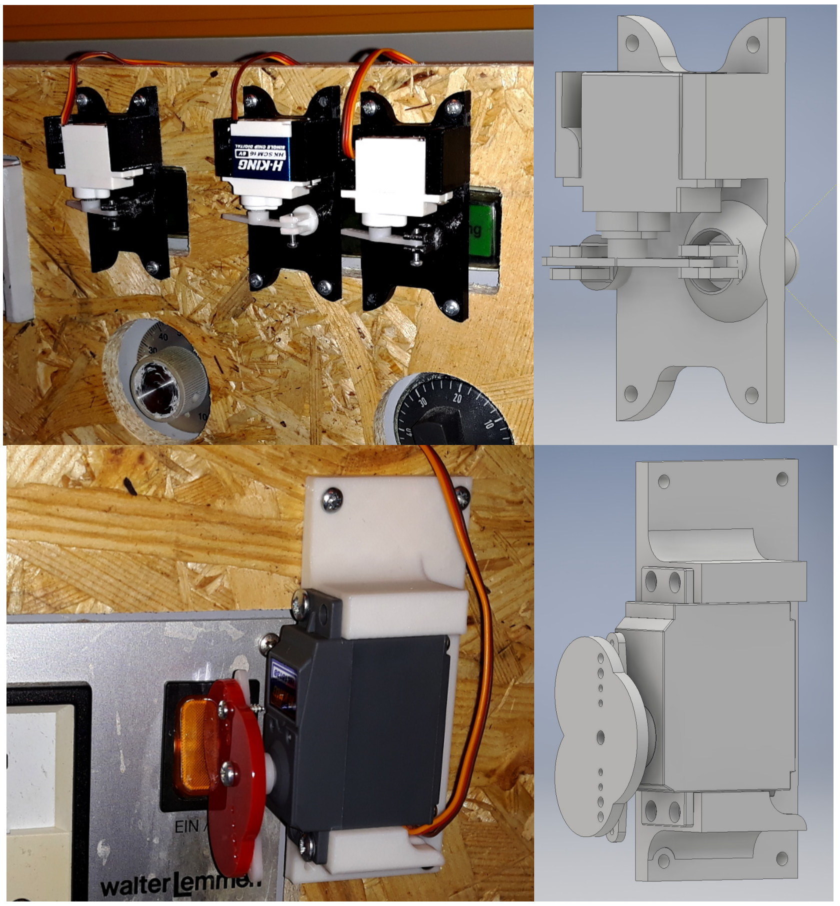

Figure 10a, b: Design and implementation of the modules to control the button (top), r ocker switch (bottom).

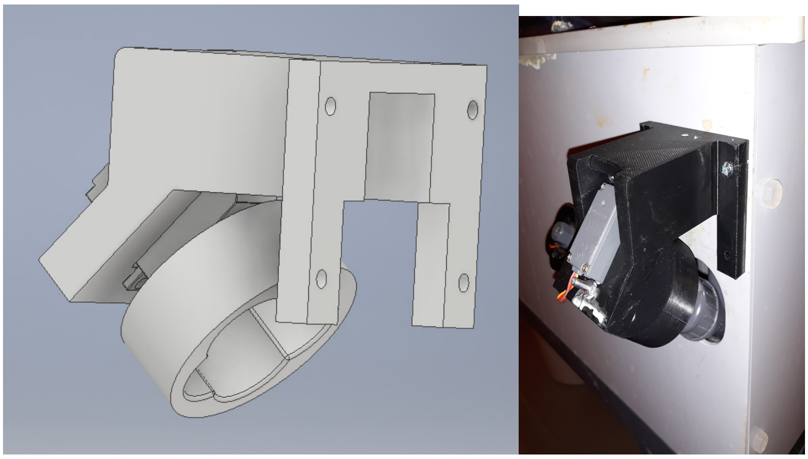

Figure 10c: Design and implementation of the rotary valve (bottom).

4.4.3 Electronics

Electronics heavily depend on the type of actuator to be manipulated. In the case of the push buttons and the rocker switch we used servos, while to manipulate the rotary valve, a stepper motor or servo could be used. We used servo. An Arduino board drives all the servos. In addition, Bluetooth HC-05 module or cable are utilized to interact with other parts of the system. Figure 11 presents the encapsulated electronics. They are inserted into a laser-cut acrylic box that can be placed next to the actuator.

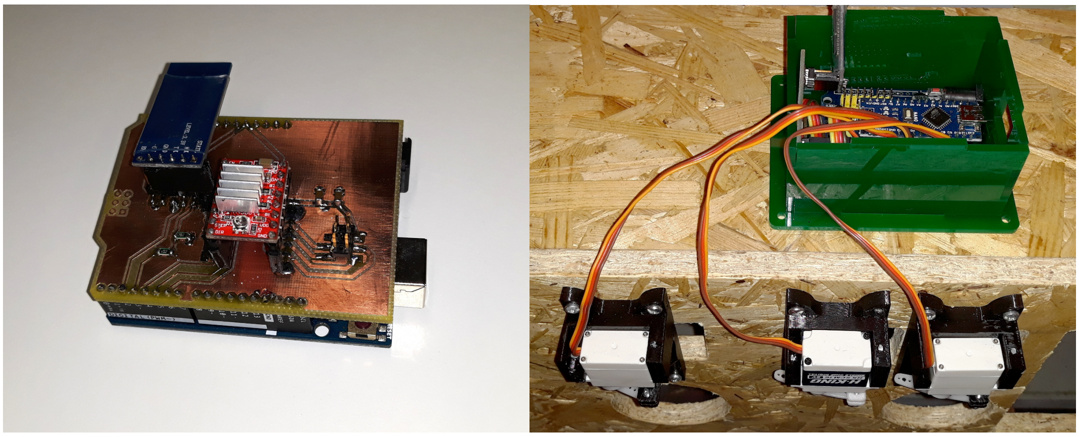

Figure 11: Modular electronics for stepper modules (left) and stepper driving and button controlling servos (right).

4.5 Other modules

User interface will be made with necessary buttons to control the machine. It will consist of a push button and joystick type control interface. This will function as central module to control other modules when the process is running on automation mode.

A connection to an app either on PC or mobile device will be developed. Machine will monitor its operations and collect data to be sent to the database. An app can also inform the user when the process is ready or if there are any issues with it.

4.6 Operations description

The automated machine is easy to operate. Operator can move the x- and z-axis using joystick interface (see figure 7). To go through the THP process all the user has to do is attach the PCB blank and activate the process by pressing the start plating process button. This will command the automation system to run through the THP cycle including moving and dipping the blank PCB in the right baths in the right order and timing as well as activating needed functions from control panel. These functions include rinsing (rotary valve), air agitation (push button) and plating current activation (rocker switch).

5 Discussion and analysis

5.1 Related work

The search for retrofitting and automate old devices has existed for many years. For instance, there has been some efforts for the robotization of agricultural machines (Serebrenny et al., 2018). However, we are not aware of similar general purpose framework to automate legacy machines using Fab Lab processes. Epple and colleagues, shown how to refit an old etching machine by modifying completely the electronics (Epple et al, 2017). We found also a commercial product, named Switch Bot (SwitchBot) that resembles our mechanical modules. It can be used to switch on/off a button and it can be controlled from the mobile phone. It is not targeted to professional use.

5.2 Summary of results.

This work has shown that it is possible and feasible to automate an old machine to modernize it and give it a new life as a modern production machine. The third iteration has not been finalized yet, however the automation modules work as planned. Once the automation is finished it will be utilized in our workshop. This experience, will set the guidelines for the next iteration.

We are convinced that this system will free operator's time to more productive work.

5.3 Automatization process

During the first iteration the main focus was to develop a THP automation. No modularity or automation system were considered. During the second iteration, a need for automatization was observed. Through different iteration cycles and after testing different ideas we found good solutions to be taken into the final system. In spite of the fact that the project started as a single machine automation, it was developed into a more universal, and modular approach that can be utilized in many other machines.

We could have solved the automation problem by building a new machine from a scratch. However, it would have involved higher complexity, would have been more expensive, and would have been against reusability, resilience and circular economy. The idea of machine reutilization gave as a good environment to develop the modular automation concept presented in this paper.

5.4 Fab Thesis and idea development

As this study is a part of an Academany Diploma Thesis pilot, it has been a challenge to meet all the requirements of the project, as well as developing the machine prototype. The main focus has been on development of the machine, even though the driving idea of this thesis is to develop a working prototype and tune it towards commercialization of the work. The initial focus of automatizing one specific machine (THP) has evolved into a universal and modular framework for the automatization of legacy machines. We are convinced that this approach supports better Fab Lab community. We aimed to build a sort of a tool box for modular automation. Another important evolution from the initial concept was that the automation framework could be easily attached and detached from the machine, so the machine can also be operated manually.

5.5 Replicability and contribution to Fab Lab network

The contribution of this paper, as a part of the Academany Diploma Thesis program pilot, is towards definition of the form and purpose of Fab Labs (Troxler, 2013). Fab Lab community can benefit not only from the machine automation itself, but also from the detailed description of the fabrication process and from our learning process.

THP machine might not be common in other Fab Labs. But the idea of automating old mechanic machines is something that can be useful. The developed method can be used to bring old mechanic machines to today's digital world. For instance, Figure 12 provides pictures of other machines with similar actuators that can be augmented with our proposal.

Figure 12: Different controls of the machines at PCB prototyping line at University of Oulu.

We are providing detailed documentation[18] of our whole design process, including all design files and software. Software files are distributed under open software licenses. We are also eager to provide support and collaboration if other Fab Labs would be interested in building a similar automation for their own old machines.

5.6 Ongoing and Future work

There still is a lot of work to do. Control module for knob type of control needs to be developed. Vertical movement unit i.e. the dipping unit in not completely finalized. We should increase the modularity of the system by integrating the mechanic units in the control electronics. We should also improve the communication among modules. We would like to develop an UI, for the operator to develop new process flows. However, in most cases, a pre-programmed process will be used.

6 Conclusions

In this paper, we present a modular framework to automate old machines by utilizing off-the-shelf modules. Each module encapsulates adequate electronics and mechanics parts taking inspiration from Peek's work (Peek 2010).

This work was developed as a part of Academany Fab Diploma Thesis. From the start of the project the focus of the work shifted quite a lot. The original idea of creating just a single PCB THP machine automation changed at the end towards general concept of developing a method to automate any old manual machine.

Not having commercially available machines, opens up an option to create a product of this type to fill the void in the market. Also there are a lot of old machines that are not automated but still widely in use. Currently, to modernize these machines one should discard of them and purchase new ones. Reusing and modernizing these machines instead of buying new ones supports urban resilience and circular economy.

We aim to publish all documentation, design files and code in Gitlab[19]. We have always followed Fab Lab processes for replicability. Our goal is that any Fab Lab in the world could implement modules for our framework.

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