Embodied Coding; Exploring human-machine collaboration in the linear 3D printing paradigm.

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ABSTRACT

FFF 3D printing is often applied as a fabrication tool for design and research, it starts with design and ends in a part. However, when exploring new printer behavior this linear process becomes restrictive, one needs to predetermine the desired part and "guesstimate" the machine movement. Embodied G-coding proposes a method that starts with exploring the final product, and results in machine code. This is achieved by collaboration with the 3D printer, by manually controlling one of its axes, this making process allows for exploration and in situ adaptation to plastic behavior. The manual manipulation is recorded and captures the complex human-machine movement, which in turn can be used to create new prints with the recorded behavior. Embodied Coding allows researchers to experiment with FFF behavior directly, which results in the research output, instead of pre-determining every step of the way.

Authors Keywords
Fabrication, Digital Craftmanship, Embodied, 3D printing, Gcode

CSS Concepts
Human-centered computing --> Human computer interaction (HCI); Interactive systems and tools; User interface toolkits

INTRODUCTION

Digital fabrication and design are often seen as the perfect companion of designers. However, the standardized workflow (Fig 1.1) necessitated by CAD and CAM restricts the material engagement of the designer. Specifically, in FFF 3D printing this is limiting as the expressed materiality is hard to capture in digital format. Developments in FFF 3D printing often come on the individual layer level, where precise machine movements create plastic properties. These plastic properties are often explored systematically, after which they are analyzed and captured in a G-code editor. This poses two main problems:

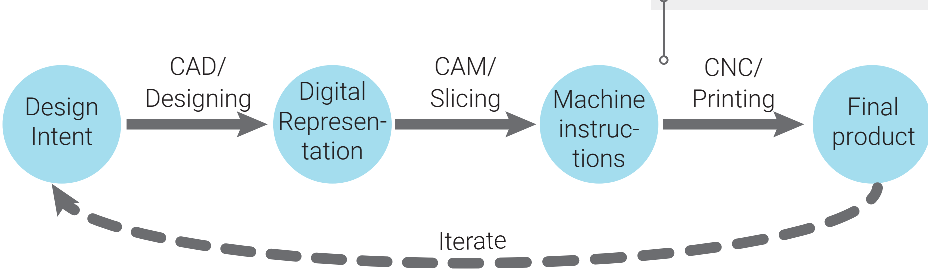
First is the chance of coming across new print behavior, this process is either a happy accident, or an experience-based exploration. The standardized process of CAD/CAM aims to eliminate all flaws and by this takes away the unpredictability of making. Secondly is the challenge of creating the code, the maker must think what the final part should look like, then guess how the machine should move, and write code that exhibits that movement beforehand, while printing there are little options for adapting the code. This increases the time necessary for preprogramming, and increases the samples made before a desired result is printed.

Embodied G-coding started by experimenting with human input in the 3D printer process, by manually moving the machines axes. The collaborative approach opens opportunity for in situ adaptation of machine movement, and the uncalculated human movement provides a larger error space for happy accident to occur. The experiments were adapted to a proof-of-concept design research workflow (fig 1.2), with tools and design editor to streamline the process. The workflow starts with a base design, after which the human-machine collaboration generates a physical part and digital representation. Which can later be used in a digital G-code editor, applying the researched movement to new design.

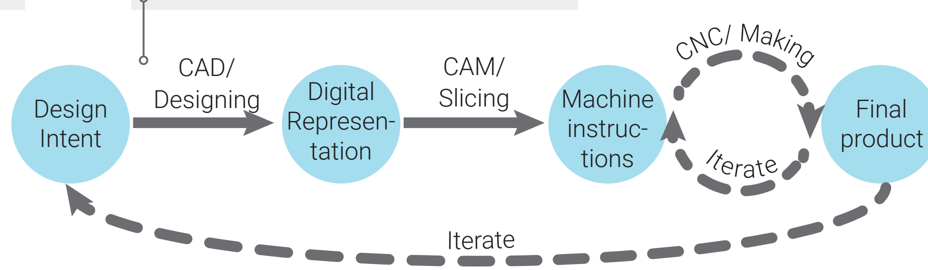
This workflow was tested in one-on-one workshops with five designers experienced with 3D printing, which opened the discussion about the possible advantages compared to traditional practices as well as highlighting the shortcomings.

This pictorial aims to illustrate and highlight a case study into the possibilities of human-machine collaboration in FDM printing. A proof-of-concept methodology with toolset was designed that facilitates the workflow from exploration of samples to appropriation to new design. This workflow is evaluated with a workshop and implications for design are highlighted. With this we aim to increase the creative opportunities for designers with FFF 3D printers.

1.1; Digital Fabrication workflow.



1.2; Proposed collaborative digital farbication workflow.



RELATED WORKS

Digital craftmanship workflow and standardization

As illustrated in previous work, the digital fabrication workflow outlined by Twigg-Smith et al. consists of design intent, digital representation, machine instructions and final product [26], This workflow is adapted and illustrated in fig 1.1. For the sake of explanation, we will assume that it is this simple linear workflow, however within this process multiple different in-between steps exist [10, 26].

This digital fabrication workflow is based on standardization, the different steps are executed with different tools which are designed to be easy and robust and are often optimized on costs and quality [13], a lot of research is focussed in optimizing the process from digital representation to final product especially with machine learning [4, 12, 32]. It is however this standardization which takes away the unpredictability and emergence of processes that harness materiality [5]. And thus, researchers and makers engage with the different steps to open opportunities for creative exploration [26].

Designing

The digital manufacturing workflow starts with the design intent, which in research is often based on previous experience [24]. In design practise often to gain insights physicalizing and making creates design input; Research through design (RTD)[20], Learning through making [9] and Material driven design (MDD)[17], pivot around making and designing as a base for itineration, and happy accidents play a large role in researching new things. 3D printing is a form of making, however when designers do not understand or control the processes at large, they are just tools to manufacture a preconceived idea [5].

CAM/ Slicing

Slicing is the process of translating a digital design into code, in 3D printing this is called G-code. This process is often where research or design goes away from standardization [15], "low-level machine behaviors … are the cruces of expressiveness for products made or customized with digital design and digital fabrication" [8]. In multitude of projects, specific properties are explored, mapped, and captured in a design editor that either slices or post-processes g-code [15, 31, 6, 25]. Other projects propose slicing software that provides expanded controls for direct toolpath control facilitating more creative use of machine code [3, 21]. However, these are still digital interfaces and aim to improve the coding experience or increase the possibilities and facilitate the general approach of designers to write their own G-code post-processing [26], which is time-consuming and cumbersome. Thinking of machine level code e.g. XYZE is based on expertise and guesswork.

CNC/ Printing

The generated machine code is executed by an FFF 3D printer and creates the final product. However, this translation is not arbitrary especially with FDM printing. There is an aspect of materiality, Wakkary et all argue that: "the dynamic and unpredictable nature" of the material is "in stark contrast to the inert nature of materiality in digital form"[27]. This materiality is often the source of inspiration and exploration [7, 18, 24]. Research is often done with clay as its materiality constantly changes while fabricating and afterwards. However, all of digital craftmanship exhibits this non-trivial translation, especially when designing expressivity [11]. And designing expressivity requires iteration: "We experimented extensively in order to find good input values for extrusion amount and frequency of pulsing" [3].

Within this process of printing, human machine collaboration can create an interesting opportunity for exploration. Çapunaman explores the turn taking between human and machine in creating physical shape in concrete printing [1], other research augments the 3D printer by performing tasks like casting within the print [14].

Interactive fabrication

Other research aims to explore outside of this printing paradigm. Like fabrication machines that create based on human-machine collaboration [1, 14, 30] and aiming to synchronize exploration and fabrication [29]. Other research experimented with the agency between fabrication machine and human [2, 19, 23]. Other research decreases the steps in the process from design intention to final part, On-the-fly print creates a wireframe print and starts printing while designing [16], Dynablocks are automatically configured blocks speeding up fabrication [22] and ReForm proposes a fully iterative additive and subtractive human machine collaboration, automating translation steps in between the processes [28]. These alternative 3D printing paradigms are promising, however difficult to integrate back into the regular FFF printing paradigm.

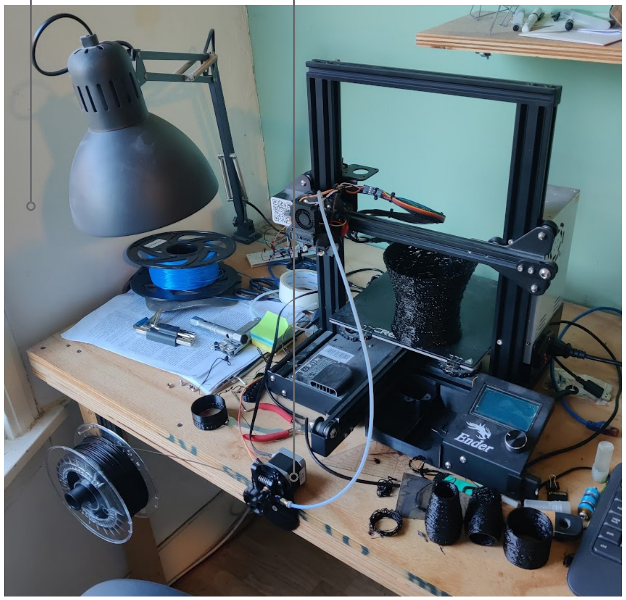
METHODOLOGY AND CONTEXT

This project was initialized with research through design enquiry into human machine collaboration. The author and a 3D printer collaborated on 3D prints. These results were analyzed and compared and resulted in the design workflow. Continuously a process of optimization, exploration and reflection informed the process. Within this process choices were made to speed up the process in favor of exploring the complete workflow from collaboration to new research output. Instead of diving into every nitty gritty opportunity, the complete workflow was kept in mind.

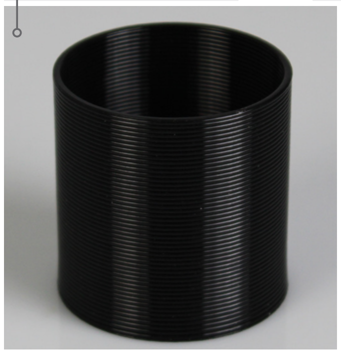
The printer used was an ender 3 V1 (fig 2), with a 1mm nozzle, a BLTouch bed level sensor and PLA filament. One of the initial goals was to stay close to the original state of the machine, to ensure its standard printing capabilities. The system was generated as an add-on with limited additional components.

2; Setup of 3D printer in authors home

Extruder motor mounted on table for easy acces.



4.1; Base print, no axis modified



4.2; Y-axis, manually pushing the bed back and forth

4.3; Z-axis, rotating the lead screw.

4.4; E-axis, manually extruding material by rotating the stepper shaft.

4.5; Y-axis, bad layer alligment created a slinky.

Process

Human-machine collaboration

The first explorations were based on a standardized print, a 50mm-by-50mm cylinder which was sliced with a spiralized contour with 1mm layer height and 1 mm layer width (fig 4.1). These normally draft 3D printer settings were chosen for speed purposes.

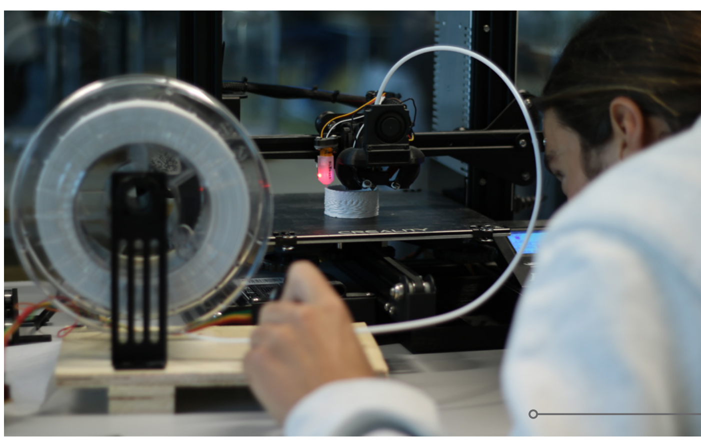
Samples were made by unplugging the stepper motor of 1 axis, and manually moving that axis (fig 3). This resulted in samples that were distinctly different from regularly sliced files. What was immediately obvious was the interesting aspects of manually controlling an axis of the printer, without any programming very complex machine movement can be simulated. When moving the z-axis, you are suddenly printing nonplanar, or when using extrusion, you are creating extremely diverse textures. But also unintended results emerged like bad layer adhesion, causing a spring like geometry to be created (fig 4.5).

Summary of samples (fig 5)

In Y-axis manipulation (fig 4.2) the dimensional accuracy is very low. Making a cylinder by hand in this setup is really challenging and requires full focus of the designer, just creating a 3D print which would self-support itself was quite challenging. The manual manipulation is very inaccurate, and it is quite easy to over- or undershoot. Especially when the target is the previous 1mm line (+/- 0.5mm). The expression potential is high, however the expressiveness off the result was more often than not a result of unintended inaccuracies, making the process feel somewhat random.

With z-axis (fig 4.3) manipulation the potential expression was limited, it was difficult to move the machine z-axis for a large distance rather quickly because of the lead screw used. It was quite easy to create relatively smooth looking prints because of this fine control.

With e-axis (extrusion, fig 4.4) manipulation the expression was quite high, and a lot of different visual aesthetics were possible, which remained comparable to each other because of the dimensional accuracy. Moreover, the experience was quite pleasurable, as it was not a challenge to make a viable 3D print, but it was a challenge

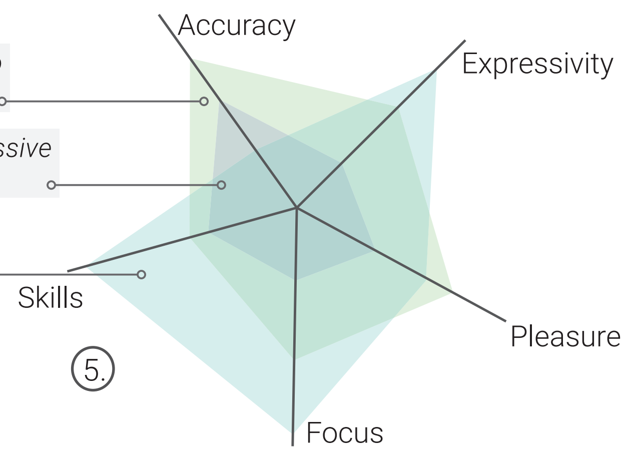


3; Manually moving the E-axis, direct visual feedback and influence on the printing requires attention

The z-axis manipulation, easy to use, not very expressive

The e-axis manipulation, expressive and quite easy to use

The y-axis manipulation, expressive yet difficult to use



5.

to create visually complex textures.

Role of initial settings
From the initial explorations it was evident that some parameters could influence the potential explorations. Different designs and speeds were used to explore this role in the collaboration.

When, for instance slowing the print speed down, manipulating the E-axis very large blobs of material could be extruded, and placement of these blobs could be accurately repeated. When speeding up however it became easier to make rhythmic textured patterns. Similarly with the manual Z-axis manipulation, the lower the speed the more detailed, however time of interaction becomes a very limiting factor. To be focused on the 3D print process for more than 30 minutes becomes quite challenging.

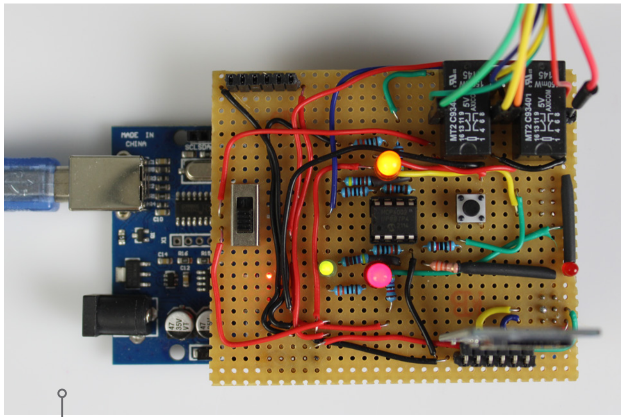
Different designs also allowed for different explorations to be made, with the y-axis changing the specific design made the interaction way more pleasurable (fig 9.3), as just making a physically supported print was easier compared to a cylinder.

Embodied G-coding
The explored samples were interesting as research objects, however, to use these to create meaningful designs still would require expertise as well as trial and error. To reduce this abstraction the movement made by the designer in the collaboration was recorded. This was achieved by using the stepper motor as a rotary encoder, a small operational amplifier circuit was implemented, and an Arduino Mega with SD card breakout was used to capture the movement (fig 6). This approach allowed limited modification to the 3D printer.

For speed purposes the choice was made to use two standalone systems. For one the 3D printer, and the separate recording circuitry. The movement was recorded over time, while the 3D printer was just executing the G-code over the other axis. While recording the axis would be unplugged from the 3D printer motherboard and the recording circuitry would be plugged in.

Increasing accuracy
Initially the data file was updated every time stepper movement was detected, however SD-card writing time quickly became problematic, writing one line takes 15ms which is way too long to ensure reliable recording. The final implementation works by storing measured steps in an array, if the array reaches a certain length and there is no movement measured, the array is written to the file. This writing happens every 5 seconds and takes around 100ms where no steps can be measured, which is an acceptable loss of accuracy.

Merging the two codes
To facilitate use of the generated code the recorded movement (designers' input) and printer movement (G-code) had to be merged. This was done with a python script. It follows a general flow of generating a time estimation per code line, interpolating the results (for higher fidelity), and merging the two based on the time estimation (fig 7). The calculated time was matched to the Cura slicer time estimation and calibrated to match this estimation as closely as possible. This resulted in printable G-code which would in theory replicate the explored sample.



6; Final measuring system, with OpAmp circuit to measure steps, and integrated relais for seamless switching between recording and printing.

7.

The recording consists of two collumns, time and steps. Every 26ms an updated stepcount is logged.

Time,	Extrusion
537962,	4484.3
537988,	4484.5
538014,	4484.5
538040,	4484.8
538066,	4484.8
538092,	4484.8
538118,	4485.1
538144,	4485.1
538170,	4485.1

+

The Gcode used for the print, consists of all normal machine movement except for the extrusion.

The calculated time is determined from the F speed and distance, every layer it is synchronized to the slicers estimate.

Gcode,	X,	Y,	Z,	Calculated time
G1	X111.3	Y85.7	Z37.1	537988
G1	X111.5	Y85.8	Z37.1	538000
G1	X111.7	Y85.8	Z37.1	538020
G1	X111.9	Y85.8	Z37.1	538038
G1	X112.1	Y85.8	Z37.1	538040
G1	X112.3	Y85.8	Z37.1	538061
G1	X112.5	Y85.8	Z37.2	538087
G1	X112.7	Y85.9	Z37.2	538110
G1	X112.8	Y85.9	Z37.2	538126

=

The combined result is Gcode, the movement is however the same as the recorded movement. Looking at a machine execute this code is rather strange as it contains unlike machine movement.

Gcode,	X,	Y,	Z,	E
G1	X111.3	Y85.7	Z37.1	E4484.5
G1	X111.5	Y85.8	Z37.1	E4484.5
G1	X111.7	Y85.8	Z37.1	E4484.5
G1	X111.9	Y85.8	Z37.1	E4484.5
G1	X112.1	Y85.8	Z37.1	E4484.8
G1	X112.3	Y85.8	Z37.1	E4484.8
G1	X112.5	Y85.8	Z37.2	E4484.8
G1	X112.7	Y85.9	Z37.2	E4484.8
G1	X112.8	Y85.9	Z37.2	E4485.1

8.1; Recording using the Z-axis.

8.2; Copy of sample on the left.

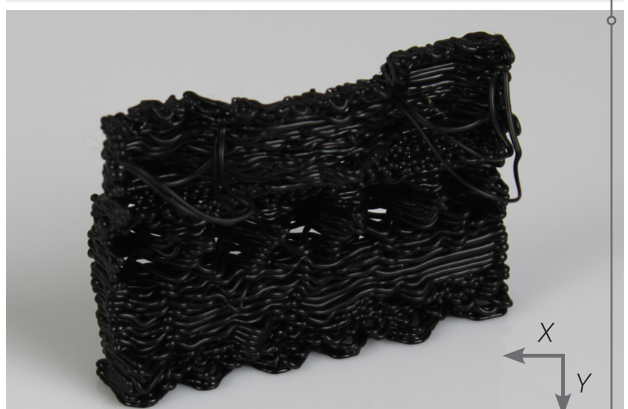
8.3; Second iteration copies.

9.1; Above, recording of a y-axis exploration.

9.2; Below, A copy of the recorded movement, you can clearly see there is a big synchronisation issue.

9.3; Above, Y-axis manipulation, the shape of a beam is much easyer to accuratetely stack layer lines.

9.4, Below, A copy of the recorded movement.



Challenges in time synchronization

The G-code time was calculated based on the speed and acceleration and jerk, this does not however mean that this is 100% accurate, and with 1000s of coordinates the calculated time differs quite substantially during the print. Moreover, the printing process has an influence on the actual time, if there is a lot of resistance the speed is reduced slightly as the motors must work harder. This accumulates over time and is thus not fully predetermined.

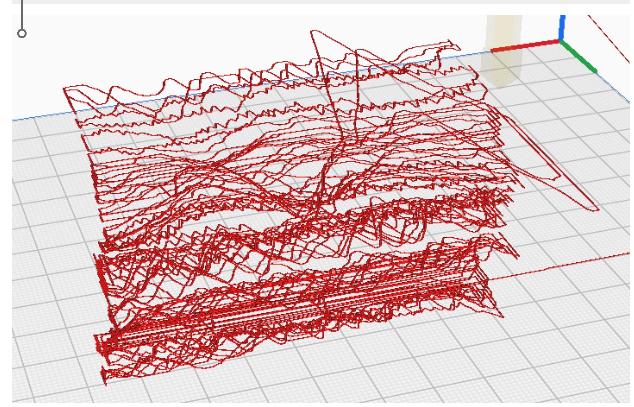
This problem was mostly visible in X/Y locational data, where alignment with previous layers becomes important. The manually manipulated Y-axis would not match the calculated x-axis position for that time. Figure 9.1 and 9.3 show recordings of a Y-axis exploration. Figure 9.2 and 9.4 show the copied samples, visible is the misalignment of layers. As the print time increases the inaccuracy of the locational data increases. When 3D printing non-location dependent parts this problem was of less importance.

To prevent spending a lot of time solving this synchronization issue the choice was made to explore further with extrusion data, because texturization is not as location dependent this formed a much smaller problem.

Grasshopper editor

The data was now captured, however very difficult to assess and use for further research, existing tools like

9.5; Digital copy from the sample on the left (in cura), it becomes very difficult to assess printability. The erratic movements made by the designer are difficult to visualize

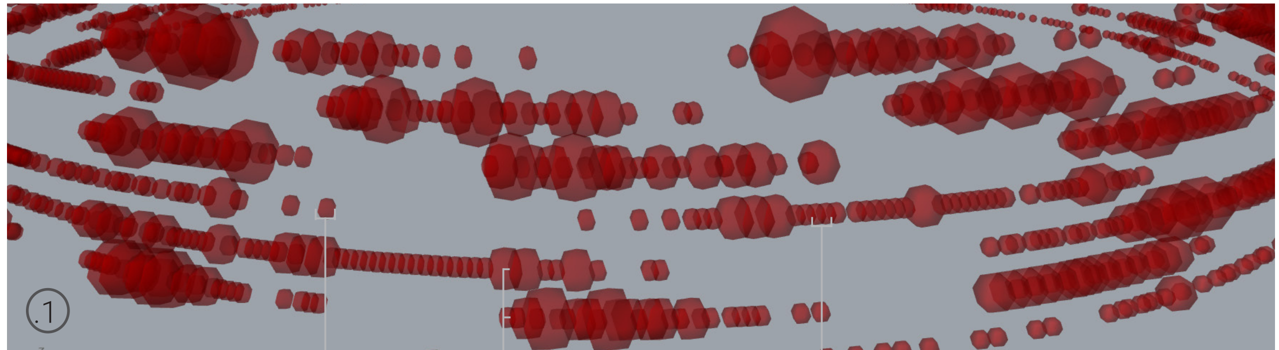


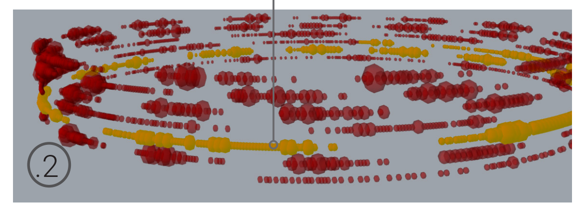
Cura for instance do not visualize extrusion volume or allow application of custom extrusion data to larger toolpaths (fig 9.5). To create these functionalities and streamline the research workflow a grasshopper G-code editor was made. Which visualizes the recorded data and allows for in-depth exploration of the digital representation of the sample. A secondary function was the possibility to select a part of the explored data and apply it to new geometry. The editor and results were tested and optimized for reliability in preparation for the workshop. The full overview of the grasshopper script is shown in fig 10 and consists of two main branches. Preparing the recorded data for application to new geometry and slicing a shape into points ready for implementation of extrusion data.

Cumulative errors
When applying data to new geometry one of the main challenges was the selection of the data. Assessing the embodiment of the code in physical form was non-trivial. In the exploration sample the previous layers were already printed. However, when replicating we are changing the previous layers, thus influencing the height of the nozzle, which in turn changes the plastic flow, which means that the expression of the data changes.

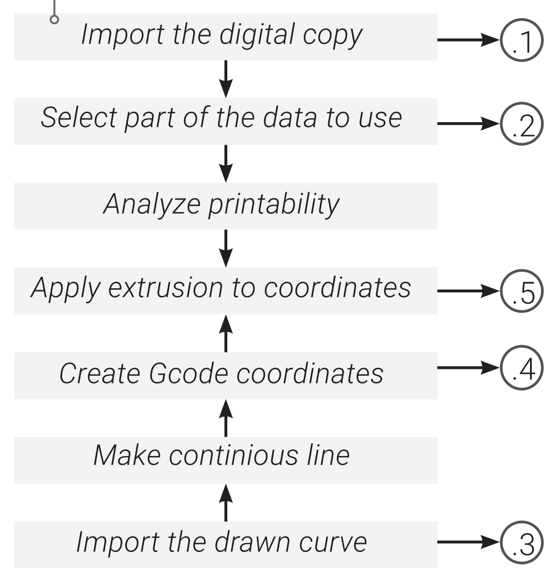
This simple selection of the data is thus problematic. Normally the calculated extrusion is quite accurate, but if you have a gap somewhere the total amount of plastic is inadequate. One failsafe was designed to aid the designer in the process, a rolling mean filter was applied to the generated g-code, if this rolling mean would go below a calibrated minimum value, the corresponding value would be increased to the minimum extrusion rate. Applying the rolling mean over 100 values means that retractions are still valid however making larger gaps is being blocked by the function.

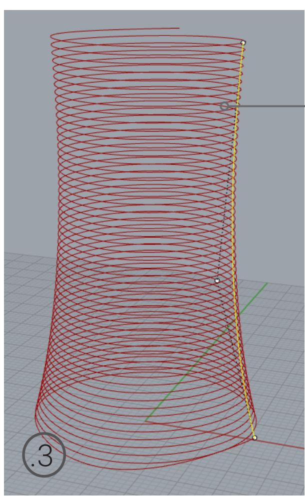
When choosing larger sample sizes, for instance a couple of layers, this was not as evident. Because in your sample data the layer-to-layer intricacies are captured and translated to the new geometry, the general structure of the 3D print is like the sample.

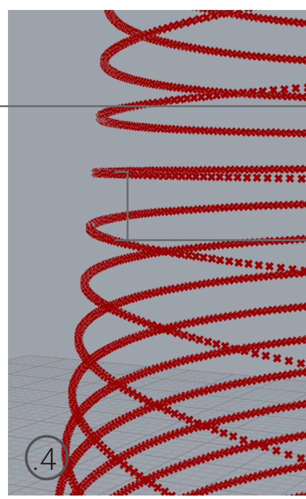




10.0; Overview of the grasshopper script





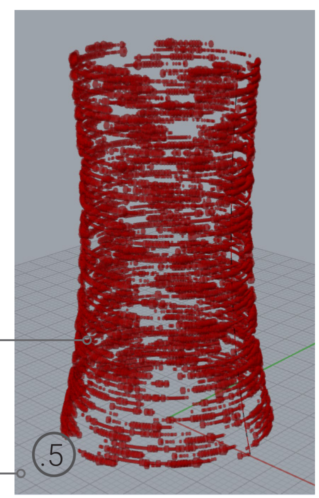


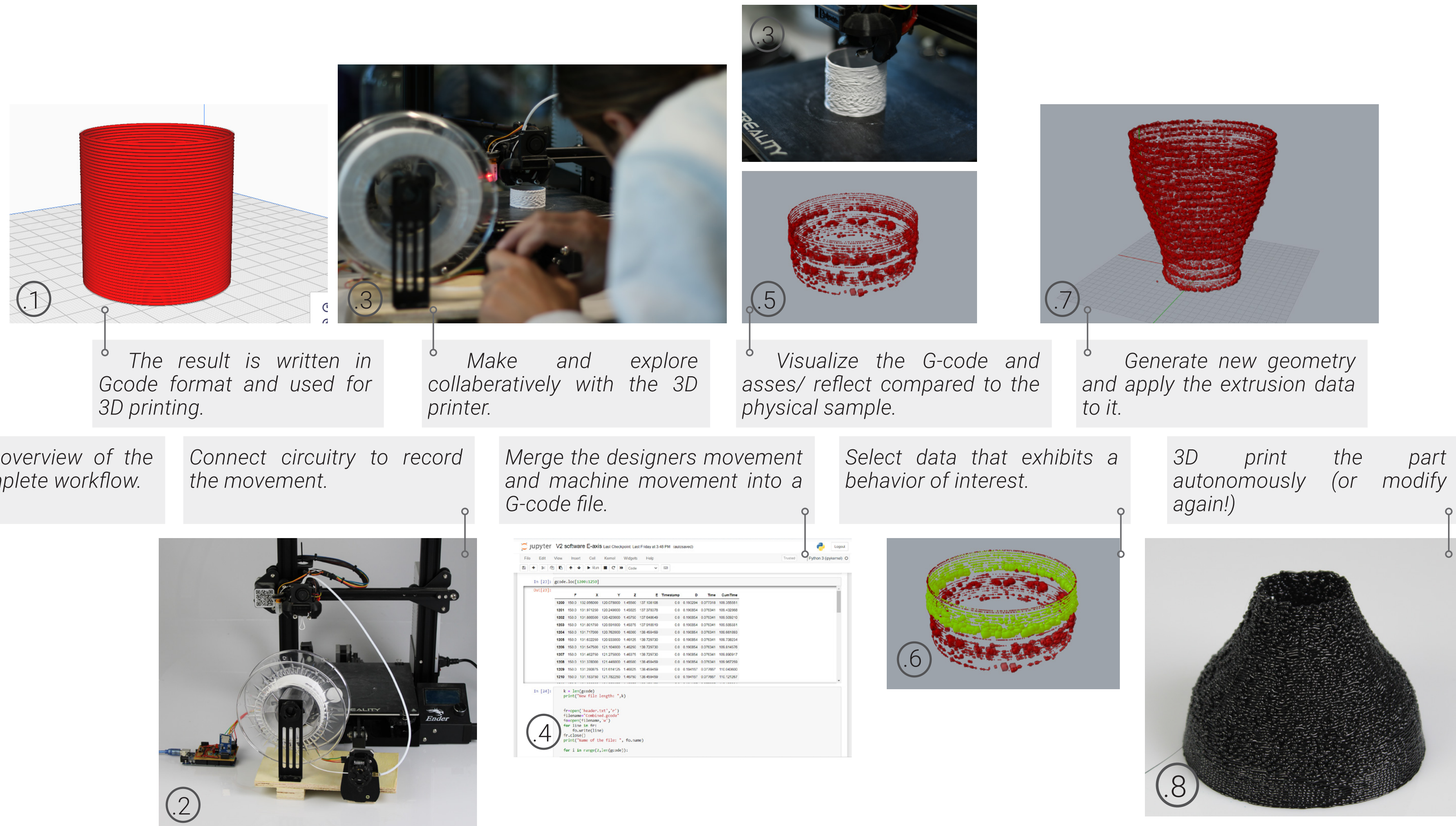
Base curve is revolved arround the origin axis.

Just as the sample data 1mm layer height and 0.2mm resolution

The selected data is repeated along the pattern.

The result is written in Gcode format and used for 3D printing





11; overview of the complete workflow.

Explorative workflow overview

The explorative workflow is highlighted in fig 11. And consists of a few steps, first an explorative shape must be chosen and sliced in normal CAD/CAM tools, this shape does not contain the specific design intention but acts as a mere base to work from. This generated G-code is started with the stepper motor aimed for exploration is connected to the measuring circuitry (in the example the extrusion axis). The print can then be made, the designer and printer work together to create the final geometry. This results in the physical part, which contains the research intention. Next to this the recording and the G-code used are put through the python script. This results in a digital representation of the explorative physical 3D print. This G-code is loaded into grasshopper and visualized. Lastly the designer can use data of the digital representation and apply it to new geometry which can be 3D printed without designers' involvement.

This explorative workflow consists of two final parts, the explorative sample (fig 11.3) and the appropriated sample (fig 11.8) and borrows parts from the standardized digital fabrication workflow. In the discussion we will dive into the specific changes we propose.

WORKSHOP

To explore the opportunities of the designed workflow a workshop was prepared with five participants: three experts in the field; Troy Nachtigall, Koen van Os and Jori van der Kolk, as well as two students Industrial design (undergrad and graduate school). The workshop consisted of three main activities:

1, make a sample by manually moving the extrusion axis. A vase mode print of a cylinder of 50mm by 20mm and 1mm layer height was used. During the process the participants were asked to think aloud while collaborating. After this there was a reflective discussion on the outcomes and insights.

2, Reflect on the data and process. Here the data generated with the first step was assessed and a part was chosen to explore further in a small sample print.

3, Print a small design. The chosen data was used to inform the small premade vase design and was reflected on by the participants.

The goal of the workshop was to extract experiences from experienced 3D printing enthusiasts, mostly to generate a discussion on workflow and not on specific interactions, the general discussion was led by the previous steps but a broad set of pre-prepared questions allowed for in-depth exploration of ideas and concepts.

Workshop outcomes

The main outcomes and comments of participants are highlighted on the following page, we will reflect first on general outcomes and conclusions of the three steps. After which we will highlight specific in situ-comments (fig 13).

In process

The resulting samples can be seen in fig 13, and the interviews were analyzed and assessed. Interesting was the prior knowledge all participants applied to their printing. All participants started with "A nice thick line, to make the print stick well", the manual control allowed them to do this, after this all the participants first tried to get used to the extrusion amount, how fast they had to turn the wheel to create a certain wall thickness.

After this 3 out of 5 participants attempted to make holes in the print, "because that is normally hard to achieve", moreover these participants applied "retraction" to reduce stringing.

Two participants noted that they got a sense of rhythm when making textures, the sounds of the steppers and the hand movement afforded them to make very regular patterns, participant 5 noted that they did not need to pay much attention when in this rhythm.

All participants noted that it was very interesting to be so close to the printer extruding material, two out of five noted the force feedback provided by the backpressure of the nozzle, and the instant response of rotating the knob and material coming out. Three participants noted that the material was very humid, thus popping and noted that being this close very quickly empowers you to analyze the materials performance.

Reflecting on the data

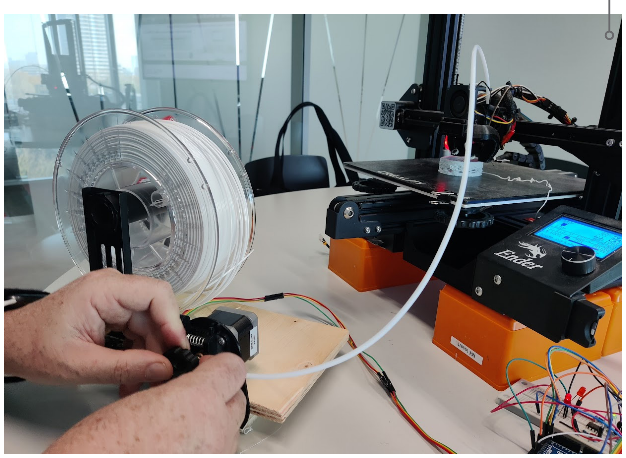
When asked about the final print the consensus was that it was super difficult to visualize the 3D printed part. Looking at the data it was clear that there was quite a big translation from the physical part to the digital visualization. All participants (except P1 and P2 because the recording failed), noted that they could see how the data was captured. However, it was also noted that the translation from the data to the physical part is not trivial. For P5 for instance the hole at the top was visible, and the pulsating pattern, however the raw data looks very lumpy instead of the smooth pattern in the print.

Reflecting on the final print

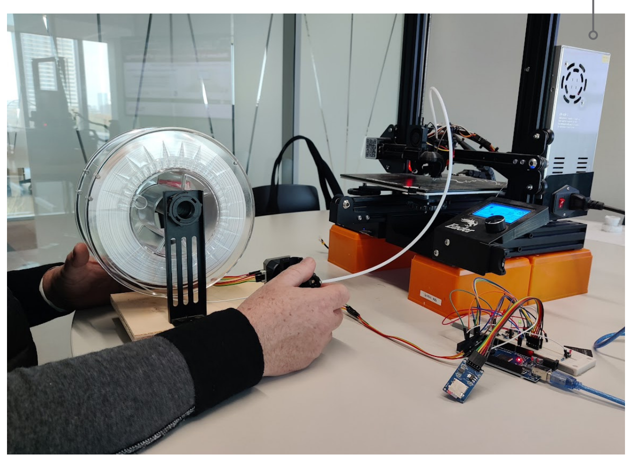
When reflecting on the final print most participants noted they could see the data coming from their explored sample. Notably one printed sample failed, and ensued a discussion on how close to the recorded part the copy should be. Where the repetition should resemble the exploration very closely. The participants reflected on the way that digital visualization was not enough to predict the outcome. However, when comparing to the physical explored sample the comparison was closer. Specifically participant 3 noted that the aesthetic of the part changed as the layer heigh increased, reducing the reproductive accuracy over time.

Participant 4 noted that he would use the manual exploration and the data generated as a base for his own coding to capture the movement, thus not using the generated data directly in new design.

12.1; Two handed control of the extruder while printing, "more control" in smooth extrusion.



12.2; Single handed control of the extruder, pre-rolling the filament to feel the nozzle pressure better.



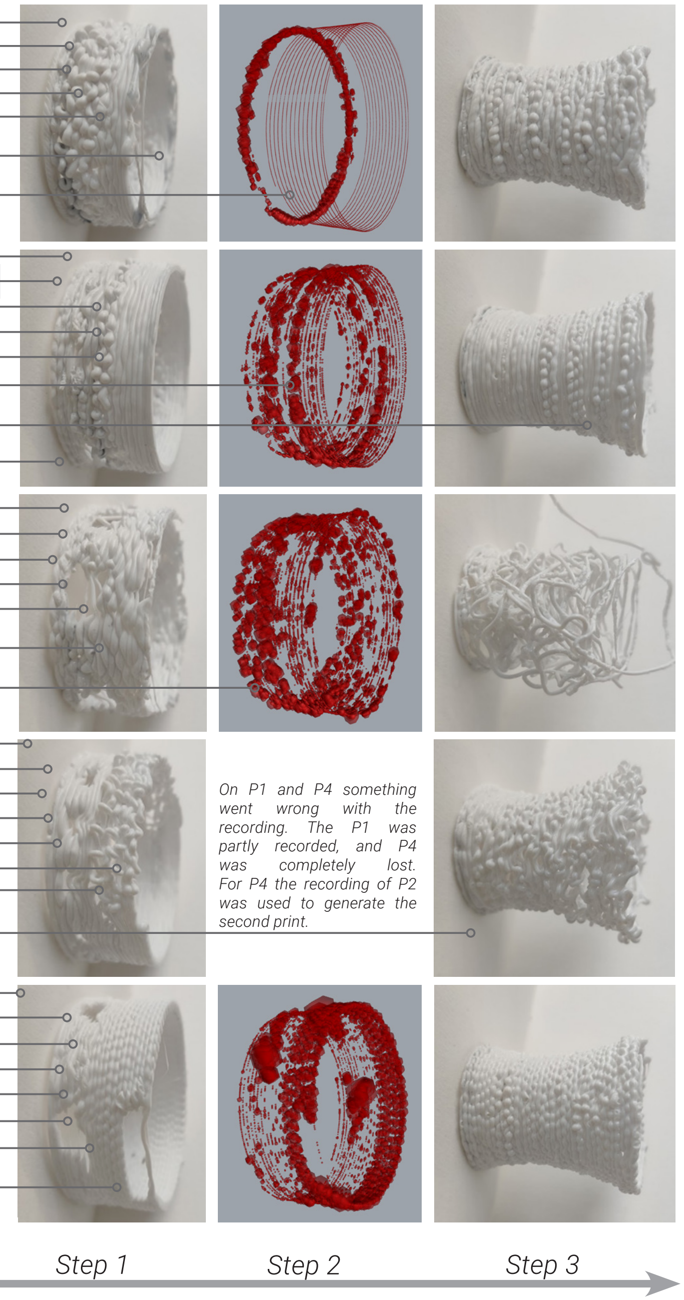
Let's get some good material flow on the first layer.
This is really manual labour.
I'll wait for a bit, I've extruded a bit too much.
I can adapt to the material quite well
I would like some additional feedback like sound.
Because you are manually doing it, it doesn't look calculated like a computer program
The code can't really visualize the plastic behavior, the rope coiling would just be floating extrusion.

I need a bigger wheel to interact with.
I'm trying to figure out what the general flow is.
You have to relax to be consistent.
There is some expertise neccesary.
The audio experience is really intense and engaging.
This area really has a textile feel to it.
You could leave a personal fingerprints on plastic, and change the relationships to those plastics

I really like to print with thick lines.
The material is a bit humid.
You get a lot more feel for the process.
I'm going to make a hole in the print.
You get a lot more feel for the process.
You don't have to specify the material, just turn it on and see what happens.
You start to think, what else do I want to control directly, which means its an interesting approach.

Starts extrusion with 1 hand
Let's make the first line as clean as possible.
You very quickly see effects of your input.
Apply some retraction here and there.
With two hands you have more consistency.
I'm getting better at constant extrusion.
You can really feel the nozzle pressure.
I wouldn't use the data directly, but use it to inform the next iterations.

Participant is looking very closely at his extruded line
First get good adhesion.
I'm going to make some holes, this is normally difficult with 3D printing
Retract on edges.
Timing is quite important, it's a nice game "hit the right spot".
You feel the pressure very well
You can get into quite a consistent rithm with theese pulses.
Very low pressure when extruding over the gaps, visual cues inform the extrusion speed.



13; Workshop outcomes, P1 to P5 from top to bottom.

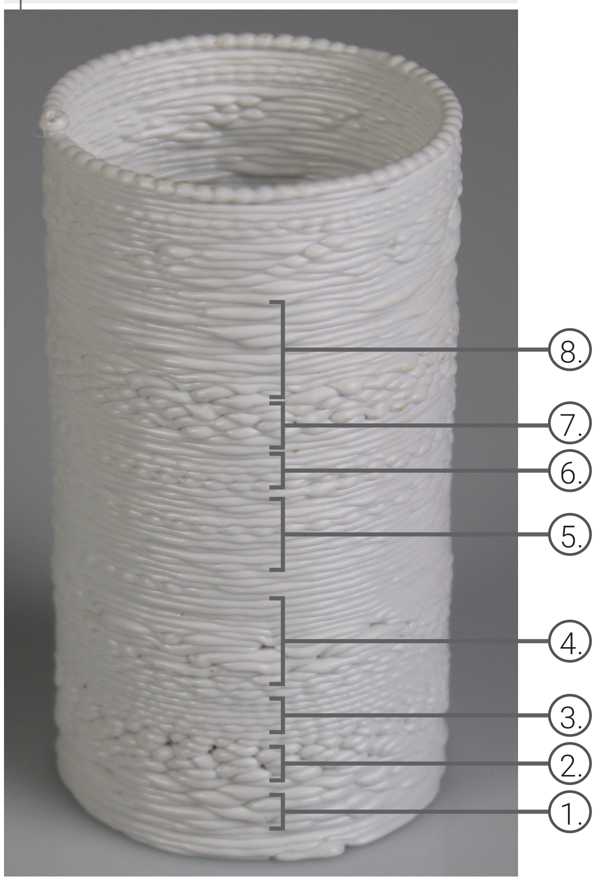
In situ comments
Reflections
Observations

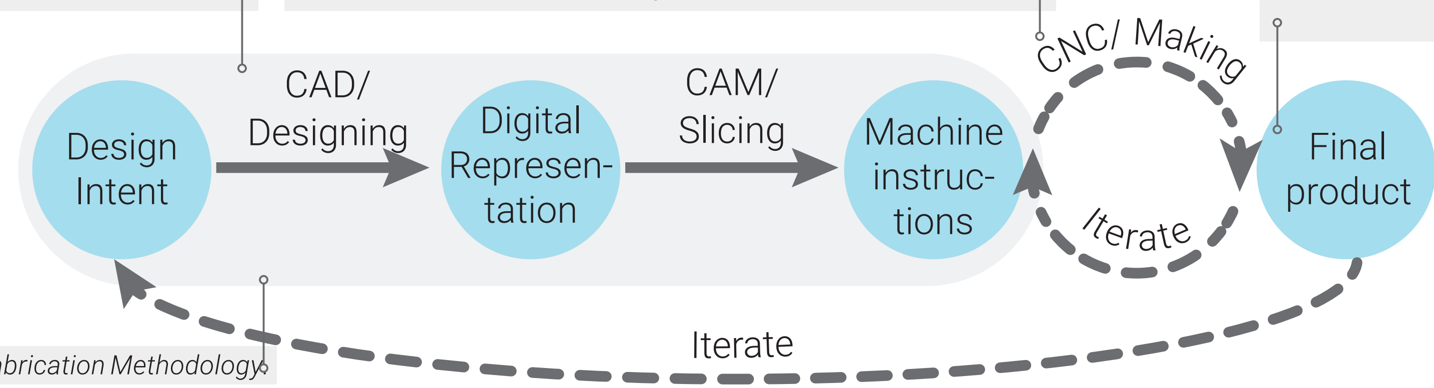
EXPRESSIVE EXEMPLAR

To explore and communicate the research richness of applying the methodology, one exploratory sample was made. The sample was based on a 50mm diameter and 100mm height cylinder, printed in vase mode with a 1mm layer height (fig 14). Printed at 5mm/s the exploration took 53 minutes. The goal of the exploration was to create different textures, from rough to smooth.

After making the sample, the physical sample was used to assess and identify interesting textures and replicated on larger 3D prints showcased in fig 14.

14; exploratory print, from this the appropriated prints were generated.





15; Collaborative Fabrication Methodology

DISCUSSION

Reflection on Methodology

As outlined before, the method to digital manufacturing is approached by a standardized linear workflow, when reflecting on this standardization at large we can highlight multiple areas where the digital materiality is far removed from the physical materiality. Throughout the process examples surfaced where it is evident that the workflow from Desing intent, Digital representation, Machine instruction and final product is not linear, and especially not arbitrary.

In contrast we propose an altered workflow where the exploration is done in collaboration with the 3D printer, in figure 14 we highlight how this process looks and annotate the differences with the standardized workflow. The main difference is the role of the initial settings, instead of predetermining all of the machine controls, we start with a standardized base and explore on top. The interaction with the machine allows us to just do what we normally would have to envision, and the continuous feedback you get from the machine allows in situ adaptation. This process is intrinsically different from the deterministic process, as we do not have to imagine what code would exhibit what behavior, and we can openly engage with the materiality of the extruded plastic.

Happy accidents

Most improvements in 3D printing are based on increasing reliability and improving accuracy when translating from digital to physical file. Next to this new printer behaviors are based on "happy accidents" which often constitute the base for new research output. Highlighted by Gourdoukis, these two are generating a paradox, the trivial manufacturing process creates new ways to engage with the materials and techniques, however it also takes away the unpredictability of these processes [5]. In other words, the effort to create a stronger standardized 3D printing paradigm inhibits these "happy accidents" from happening. Pushing the limits of the machine and code are ways to break this paradox, or by adding uncertainty within the process. The proposed workflow, however, intrinsically inserts uncertainty because of the constant interaction with a human. We cannot predetermine and rely on our motor skills to control the printer, we infuse uncertainty and chance with our hands into the process, opening the window of opportunity.

Replication of results

One of the main challenges in this research was to repeat parts of the data that were explored. The visual outcome of the exploration is dependent on the previous layer. However, when applying data to a new print the previous layers are altered. And thus, the embodiment of the code on the exploratory sample differs from the appropriated sample. In the scope of this research, the aim was to create visually reproductive explorations which was achieved in most of the explorations.

Another challenge with repetition is choosing the data and assessing printability. In explorations the designer extrudes variable amounts which is no problem because in situ compensation allows for that. However, when appropriating the exploration, it can happen that data is selected which is relatively under extruded, this will accumulate and change the outcome of the print. This can however also be taken as a new way of introducing uncertainty, however the question remains how close the appropriation has to be to the experimentation.

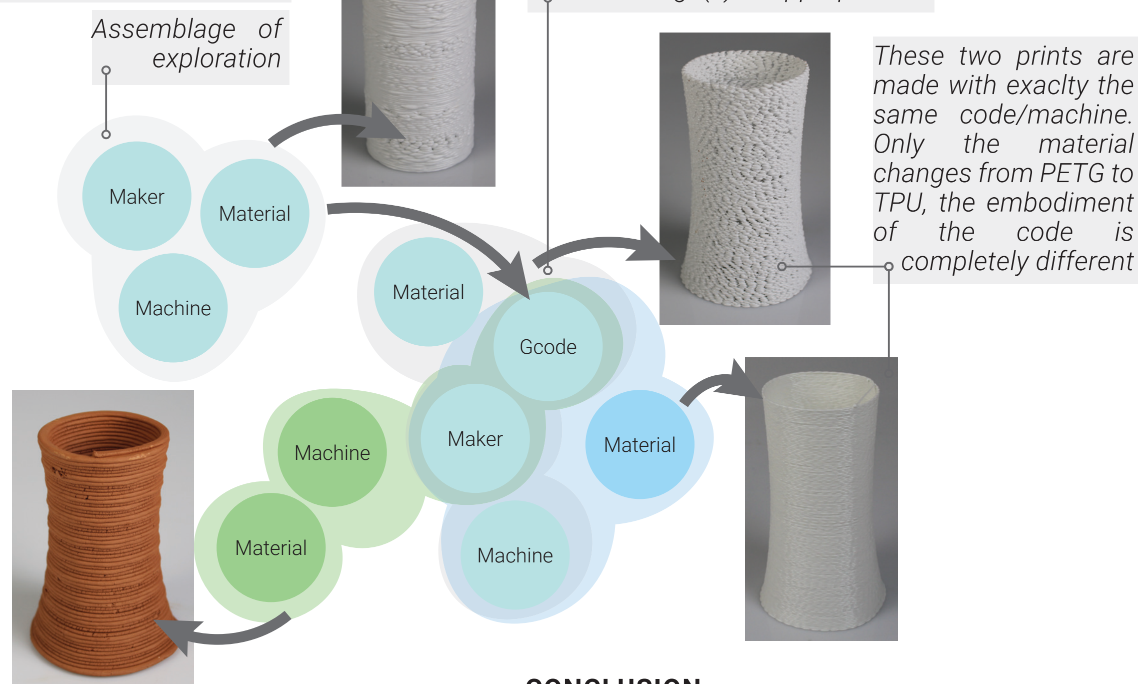
Appropriation of data

To further explore application of the G-code, samples were made by a clay 3D printer, recorded data was altered to fit this machine. The embodiment of the code is very different compared to plastic extrusion, clay printing does generally not have a very fast response to extrusion modification, which smooths the overall recorded data, and changes the expression of the data onto the print. Moreover, low extrusion creates a "pulled" clay look, which generates a different texture. To make viable clay prints, extrusion values had to be modified as well as layer heights, speeds etc. It took quite a couple of tries before the final print was made, and thus took quite some learning, the linear process of CAD/CAM was in practise reinstated.

We analyze this phenomenon from a system of assemblages (fig 16), the machine, code, designer, and material form an assemblage creating a final part. When applying our exploratory workflow we create an assemblage of exploration, with the exploratory sample and digital representation as outcomes. However, when applying that digital representation to a new print we are transposing to a different assemblage, the assemblage of appropriation. When one of the assemblage parts transposes, the embodiment of the code changes, and thus the physical properties of the final part change. When we change only the material, the embodiment of the code changes significantly. We can also compare the clay prints to this, however here the machine and material is transposed. Our preconception of the machine being a neutral entity, reproducing parts is exemplified. The hylomorphism of a different assemblage creates a different embodiment of code.

The ramifications of this are that with our methodology we capture this embodiment of code as a sort of fingerprint, and instead of guessing what it is and trying to control it, we just assume it's there and incorporate it in our process. By only looking at the final part in the exploration the in-between steps do not matter, we do not intrinsically care what the machine does and what code it uses to do it. We want to have our embodiment of that code with that material with that machine. This would mean however that for every machine and material we need to resample our explorations.

Designing instead of coding
The proposed workflow mitigates the need for advanced knowledge of CAM, while not losing the ability to produce complex G-code. The approach to reduce the users' skills necessary to make complex parts works in favour of creativity and research focussed design. However, projects like On-the-fly print and Reform step outside the FFF printing paradigm and make it impossible to design "normal" 3D prints with the tool [16, 28]. We do live in a paradigm of production with FFF 3D printers, and seamless integration with that system would potentially create a direct impact on design. We believe that the design approach of Embodied G-coding is a potential way to get more designers to create code that can be printed and put onto market.



16; Appropriation of code in different assemblages

Future work
This research was developed as proof of concept of the complete workflow, and thus choices were made to facilitate and encapsulate the full process instead of diving into every step in between. To develop the workflow and exploit it to its potential every in-between step should be researched in depth. Some work is already done, such as modes of interaction that fit the user and facilitate creative expression [29], however in this context we should explore more broadly what printer settings and what interactional displays would facilitate what kind of printing.

Moreover, at this point of the workflow there was a lot of file switching and processing before the research sample could be used to create a new sample. Next steps would contain an improved workflow with an all-in-one data editor, which communicates directly with the printer and the recording systems.

CONCLUSION

This pictorial describes the exploration of human machine collaboration in FFF 3D printing, and results in a proposed methodology for collaborative fabrication. This methodology reduces the deterministic nature of standardized digital fabrication processes and employs human machine collaboration to explore in situ.

The methodology was developed with a proof-of-concept workflow, with tools and software to facilitate the collaboration, and to ensure integration with the standardized FFF 3D printing paradigm. This workflow was tested in a workshop and highlighted the experience and reflections on applying human-machine collaboration.

Embodied G-coding aims to highlight the potential of human machine collaboration in digital manufacturing and hopes to inspire makers to incorporate embodied coding in their practices by providing a concrete workflow and tools.

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