Intent-Based Material Extrusion 3D Printing:
Moving from process-driven to intent-driven 3D printing

Appendices
Additive Manufacturing (AM) including the generally known 3D printing, is viewed to be a disruptive manufacturing principle. In additive manufacturing, parts are gradually built by adding material, typically in layers, through digitally controlled systems (Tempelman, Eyben & Shercliff, 2014). This enables the production of parts without the need of expensive moulds and other process specific tooling.

Both the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) laid down standardizations and terminologies to describe different AM technologies. Generally, seven AM technologies can be distinguished: powder bed fusion, vat photo-polymerization, material jetting, material extrusion, sheet lamination, binder jetting and directed energy deposition and sheet lamination (ISO 17296-2, 2015):

**Powder bed fusion**
This principle is also described by the terms ‘direct metal laser sintering’ and more commonly as ‘selective laser sintering’ (SLS). In this process, a layer of powder is repeatedly deposited on top of the previous layer and selectively fused using thermal energy (Tempelman, Eyben & Shercliff, 2014).

**Vat photo-polymerization**
Vat photo-polymerization, also referred to as stereolithography (SLA) uses a liquid photopolymer that is selectively exposed to ultraviolet light to cure the photopolymer on a layer-by-layer basis (Tempelman, Eyben & Shercliff, 2014).

**Material jetting**
In material jetting, small plastic droplets are deposited on and cured by high intensity UV-light in order to form an object (Tempelman, Eyben & Shercliff, 2014).

**Material extrusion**
Plastic is extruded through a heated nozzle to form layers of material which fuse together by cooling in ambient air (Tempelman, Eyben & Shercliff, 2014).

**Sheet lamination**
Sheet lamination builds a model by stacking sheets of plastic or paper on top of each other, connected by an adhesive, and cut to shape via a laser or cutter (Tempelman, Eyben & Shercliff, 2014).

**Binder jetting**
Binder jetting uses a powder bed on which inkjet heads selectively deposit a bonding liquid. The powder is deposited in layers every time the previous layer has bonded (Tempelman, Eyben & Shercliff, 2014).

**Directed energy deposition**
Directed energy deposition is similar to material extrusion, but the deposited plastic powder is fused locally on the part after being extruded rather than extruding already molten plastic (Tempelman, Eyben & Shercliff, 2014).
The concept of affordance is often used in the context of Human-Computer Interaction (HCI). However, within the HCI community people adhere to different interpretations of the concept of affordance, mainly due to two widespread interpretations of the word.

The term affordance was introduced by James J. Gibson in his book Ecological Approach to Visual Perception (Gibson, 1979) but later became popular when Donald Norman introduced his interpretation in the book The Psychology of Everyday Things (Norman, 1988). While their definitions of affordance appear to be similar, there are important differences between their interpretations.

Gibson’s theory of affordance
According to McGrenere and Ho (2000), “Gibson intended an affordance to mean an action possibility available in the environment to an individual, independent of the individual's ability to perceive this possibility.” Moreover, he claimed affordances have three fundamental properties:

1. An affordance exists relative to the action capabilities of a particular actor (e.g. doorway might be high enough to enable one small person to walk through, but that does not mean that every person (including tall people) can walk through.
2. The existence of an affordance is independent of the actor’s ability to perceive it (e.g. a person might be able to open the door, but might not realise this because there is no door handle or sign to inform the user of this action possibility)
3. The affordance does not change as the needs and goals of the actor change (e.g. whether or not a person wants to go through the doorway, he or she might still be able to do so).

However, McGrenere & Ho (2000) note that the definition of affordance by Gibson is incomplete because there are two additional properties of affordances that he implies, but not directly states: 4. An affordance is binary (i.e. it either exists or it does not exist). 5. “Affordances can be nested when an action possibility is composed of one or more action possibilities” (McGrenere & Ho, 2000) (e.g. the affordance of being able to consume an apple also nests the affordances of biting and swallowing the apple).

Norman’s theory of affordance
Norman’s definition of affordance is somewhat different from the definition of Gibson. Norman states: “…the term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used.” (Norman, 1988, p.9)

This definition implies that according to Norman, an individual's perception plays a role in determining whether or not an affordance exists. Thus, according to Norman, an affordance only exists when an individual is able to perceive it, whereas Gibson views the existence of the affordance and the perception of it to be independent (McGenere & Ho, 2000). As a result of this distinction, Norman’s affordance is dependent on the knowledge and past experiences of the individual perceiving it, whereas Gibson’s affordance is not. However, in both cases, the perception of the affordance is dependent on an individual’s knowledge and past experiences.

Another important difference is that for Norman there is no actor as a frame of reference, i.e. the affordance is tied to the object, not to the actor. The frame of reference for Gibson is the action capabilities of the actor, whereas for Norman, it is the mental and perceptual capabilities of the actor.
Constructing a working definition for affordance
In order to construct a working definition for affordance, well-argued decisions have to be made to choose between opposing aspects of the two interpretations. To recap, these opposing aspects are:

**Gibson** An affordance is independent on an individuals' ability to perceive it.
**Norman** An affordance is dependent on an individual's ability to perceive it.

**Gibson** An affordance either exists or does not exist.
**Norman** An affordance exists in varying degrees.

**Gibson** The action possibilities are relative to an actors' action capabilities.
**Norman** The action possibilities are relative to the mental and perceptual capabilities of an actor.

In the following sections, a well-argued decision between the interpretations is made for each of the differences.

Binary vs varying
In the last section, the decision was made to make a distinction between the existence of the affordance and the perception of the affordance. This decision implies that the existence of the affordance is binary. However, one can still argue whether the perception of the affordance should be assessed in a binary fashion or in varying degrees. In order to make decisions in the design process, it is beneficial to be able to assess the level of usability of the affordance. In order to make clear distinctions, it is beneficial to be able to differentiate between action possibilities that are easy to accomplish, and action possibilities that are hardly usable. However, when using a binary assessment strategy, the only differentiation between categories of affordance would be whether the action possibility is usable or not usable. Therefore, no distinction can be made between action possibilities that are barely usable, and action capabilities that are barely usable, since both would fall under the category of “usable”. Thus, Norman’s interpretation of varying degrees of affordance is more beneficial in this design process.

Action capabilities relative to the actor’s action capabilities or to the actor’s mental and perceptual capabilities
Since the decision was made to distinguish between the existence of affordance and the perception of the affordance, no decision needs to be made here. Due to this distinction, the existence of an affordance is relative to an actor’s action capabilities and the perception of the affordance is relative to an actor’s mental and perceptual capabilities.
Working definition of affordance
The previous argumentation leads towards the following working definition of an affordance:
An affordance is an action possibility available in the environment to an individual, independent of the individual's ability to perceive this possibility. (Gibson, 1979)
According to the working definition affordances have the following fundamental properties:
1. An affordance exists relative to the action capabilities of a particular actor.
2. The existence of an affordance is independent of the actor's ability to perceive it.
3. The existence of an affordance is binary.
4. The perception of the affordance exists relative to the mental and perceptual capabilities of the actor.
5. The perception of an affordance can exist in varying degrees.
6. The affordance does not change as the needs and goals of the actor change.
7. Affordances can be nested when an action possibility is composed of one or more action possibilities.
Intention is a term that is widely discussed in philosophy. Philosophers are intrigued by the meaning of intent since it is used in different senses of the word.

Philosophers identify three guises of intention (Setiya, 2018): intention for the future, intention with which someone acts (Davidson 1963, pp. 5–8) and intentional action. Moreover, philosophers make a distinction between future-directed- and present-directed intentions ((Bratman, 1984), (Searle, 1983), (Velleman & Bratman, 1991)) Future-directed intentions guide an agents’ planning and constrain their adoption of other intentions (Velleman & Bratman, 1991). Present-directed intentions have a causal function in producing behaviour (Searle, 1983). By combining these two views, the following forms of intention can be distinguished:

1. **Intention for the future** (future-directed) (e.g. I intent to 3D-print this model by the end of the week) Form: I intent to do A at some point in the future.

2. **Intention with which someone acts** (future-directed) (e.g. I am setting these parameters in Cura because I intent to make a flexible 3D-printed structure or I am using .2 layer height because I intent to rapidly iterate my model) Form: I am performing A because I intent to do B because I intent to do C ... because I intent to do Z.

3. **Intentional action** (present-directed) (e.g. I am doing something intentionally with no particular reason) Form: I intent to do A right now for no particular reason

Having distinguished the different guises of intention, it is not hard to argue that the “intention with which someone acts” is the most interesting form of intention to consider in the design process due to its causal relationships between goal and the required action(s) to accomplish that goal. Both intention for the future, and intentional action fail to attribute any reasoning as to why someone would pursue a certain goal. The only distinction between the two is that the first is future-directed, whereas the latter is present-directed. Therefore, from now on, the word “intention” will be used in the sense of “intention with which someone acts”.

### A working definition of intent

Having attached a meaning to the words intention and affordance it is now possible to define the relationship between the two. In intention (i.e. I am doing A because I intent to do B), A is an action that has a causal relationship with the action or goal B. Since an affordance is defined as ‘an action possibility available in the environment to an individual independent of the individual’s ability to perceive this possibility’, one could argue that intent represents a subset of actions from all available action possibilities, in the environment (i.e. affordances). In this case intent would be defined as:

‘An intent is a representation of a combination of affordances that an actor or multiple actors may perform in order to achieve a goal.’

However, the previously mentioned definition of intent does not work in cases where the user intents to achieve a goal while the required affordances are not present in the environment. In order to include the possibility of not being able to meet a user’s intent, it should be defined as:

‘An intent is a representation of a combination of actions that an actor or multiple actors may perform in order to achieve a goal.’

In this case, if all the required actions to achieve a goal are afforded (i.e. available in the environment as action possibilities), the user’s intent can be met. How well the user will be able to meet his or her intent is dependent on the signifiers in the environment (i.e. the usability). If not, affordances (i.e. utility) should be added to the environment.

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**Appendix C - Definition of intent**

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in order to enable the user to meet his or her intentions.

It is important to note that according to this definition, an actor or multiple actors may perform a combination of actions. The word may implies that there could be multiple action sets to achieve a goal, and therefore, some actions may or may not be performed depending on the route the user chooses to take towards accomplishing his or her goal. Moreover, these actions may be performed by a single actor or multiple actors, since some actions may be performed by the user, while other might be performed by the printer or other actors.
Introduction
Ultimaker B.V. (hereafter Ultimaker) is a Dutch 3D printer company which was founded in 2011. Currently their product line includes the Ultimaker 3 (see figure above), Ultimaker 2(+) (and their extended versions), and the Ultimaker Original+. Combined with these 3D printers Ultimaker sells a variety of 3D printing filaments and provides an open source slicing software called Cura.

Ultimaker is continuously improving the print quality, reliability and user experience of their Fused Deposition Modeling (FDM) 3D printers. Examples of recent improvements are dual-extrusion, swappable print cores, active bed levelling, software-material interaction through NFC and water-soluble and breakaway support material.

Ultimaker can, apart from Computer Aided Design, completely control the 3D-printing workflow through their products ranging from slicing software to materials and hardware. This context introduces a lot of possibilities to improve the user experience. One aspect of the user experience Ultimaker would like to investigate is the user-machine interaction, specifically: the possibility of adapting the 3D printed output based on user intent.

Problem definition
Over the past years of developing Fused Deposition Modeling (FDM) 3D printers, much of the focus has been on making the printing more accurate and reliable. Developments such as variable layer height, multi-material printing and soluble support have brought more options for the user to explore when 3D printing objects. However, these developments have mainly focused on the affordances of the FDM 3D printer (i.e. the action possibilities made available to the user). However, the plentiful options available to the user are not yet translated into easy to understand options to match user intentions (i.e. representations of a set of actions of the affordances in the 3D-printing workflow (see figure on next page) may take to achieve the user’s goals).

Currently, users of FDM 3D printers are presented with a multitude of affordances, ranging from interchangeable print cores (hardware), different materials (materials), and print settings (software), of which most are hidden at default to avoid misuse. This has created a knowledge gap between users who can take advantage of all these affordances and those who can’t. Intent-based 3D printing could result in a better printing experience and 3D prints that better match the user’s goal by taking the user’s
goals into consideration during the entire printing workflow. Ultimaker has focused on implementing user-friendly solutions in the final stages of the workflow, but these solutions are not related back to the user’s goals and vice-versa: the user intent is not yet considered in the creation of parts.

Examples of different user intentions are: dimensionally accurate printing and printing for physical properties. The first is an example of increasing accuracy, which has been one of the primary goals of FDM 3D printer manufacturers. However, the latter is an example of a different goal. Instead of focusing on printing a shape to be dimensionally accurate, the user is interested in printing objects with specific physical behaviour. The second example shows how the user’s intent might not merely focus on printing accurately, and therefore, print settings, material and hardware are tuned for satisfying a different goal. It is interesting to investigate and map different user intents in the context of FDM technology (hardware, software and material) and to develop means for the user to realise their intentions more easily.
Assignment
The goal of this project is to identify different user intentions in the context of FDM 3D printing. Subsequently, these intentions will be translated into easy to understand tasks for the 3D printer and the context in which it is used to perform. Identifying the user’s iterative design process and changing print settings to make increasingly detailed parts can positively affect the user experience. Apart from rapid prototypes, functional parts produced by engineers also differ in required properties for aesthetic models made by designers and architects. Through implementing user feedback, the system can learn a user’s goals and meet their intended 3D-printed outcome more effectively.

The project starts with an analysis of different user intents by means of knowledge in the fields of user-machine interaction, human-computer interaction, design methodology, human-in-the-loop systems and cyber-physical systems. At the end of this phase, one or multiple intent-based workflows will be chosen to be improved.

The end result of the project will be a prototype which depicts how the intent-based printing is achieved. This prototype is likely to be a combination of software (a Cura plugin) and hardware (additional sensors and actuators that enable feedback on the end result). Additionally, 3D printed models realized with the intent-based printing are part of the prototype to depict the new design capabilities enabled by intent-based printing. The exact implementation of the intent-based printing is dependent on the user intents found in the analysis phase and which critical, compelling intents are solvable within the time-frame of the project.
1. **Build plate** The build plate provides a straight surface of borosilicate glass for the print to stick to. The build plate is heated by a Printer Circuit Board (PCB) heater to improve build plate adhesion.

2. **Print head** The print head consists of the dual print cores and cooling fans. The print head moves across the build surface in order to print the model on a layer-by-layer basis.

3. **Knurled nuts** The knurled nuts on the bottom of the build plate assembly enable manual levelling of the build plate.

4. **Build plate clamps** The build plate clamps hold the glass build plate in place during printing.

5. **Push/rotate button** The push/rotate button is used to navigate the user interface and confirm selections.

6. **Display** The display shows the user interface of the 3D printer’s firmware

7. **USB port** The USB port enables users to print models directly from a flash drive.

8. **Feeder 2** The feeder pushes filament through the bowden tube and the nozzle.

9. **Bowden tubes** These low-friction tubes guide the filament from the feeder motors towards the nozzle.

10. **Feeder 1** The feeder pushes filament through the bowden tube and the nozzle.

11. **Ethernet port** The ethernet port enables the 3D printer to communicate over an internet connection.

12. **Double spool holder** The spool holder holds the filament in place to be fed to the feeder motors. The holder has NFC tags to detect the loaded materials.

13. **Cable cover** The cable cover is used to hide cluttering cables from sight.

14. **Power socket and cable** The place where the power brick is connected to the printer.

15. **Power switch** Turns the power ON and OFF.
Appendix F - Print cores

First introduced in the Ultimaker 3, the print core enables users to quickly change hot-ends in order to achieve a higher uptime and more flexibility. Before the print core concept was introduced, changing the hot end of the 3D printer required disassembly of the print head. However, the nozzle could be changed by using a wrench. After the nozzle was changed, it needed to be properly (heat) tightened in order to avoid leaking. This was a very tedious and time-consuming process. Print cores use pre-assembled hot-end sub-assemblies that make changing a hot-end a plug-and-play process.

**Material support**
Print cores are available with three different nozzle sizes: 0.25 mm, 0.4 mm and 0.8 mm in diameter. Not all sizes are able to print all materials.

**Material combinations**
Printable materials are not only limited by the used nozzle size, but also by material combinations used when printing with a dual nozzle configuration. Some material combinations are not supported due to differences in process parameters.

**Types of print cores**
The print cores come in an AA and a BB variant. The BB variant is intended for printing PVA material, since this material requires different nozzle design to achieve sufficient material flow.
This appendix presents most of the filaments sold by Ultimaker.

**Polylactic acid (PLA)**
PLA is the most popular 3DP material due to its ease of printing at low temperatures and reliable printing results. It is the ideal material to use when creating concept models, presentation pieces or visual aids. PLA is not particularly strong. Due to its brittleness (over time) it is not advised for producing functional and mechanical parts. (Ultimaker, 2018d)

**Acrylonitrile butadiene styrene (ABS)**
ABS, unlike PLA, has excellent mechanical properties and can therefore be used for components that require toughness and durability. Moreover, it has a thermal resistance of up to 85 degrees Celsius, which also makes it suitable in contexts with higher than room-temperature. However, printing ABS requires more higher print- and build plate temperatures. Moreover, it is advised to print ABS in an enclosed volume in order to maintain a warm, controlled environment which combats the increased chance of warping. Additionally, printing ABS emits the highest amount of ultrafine fine particles compared to other 3DP filaments. Therefore, an enclosure is not only advised for better printing results, but also for maintaining healthy work environments. A HEPA filter can be used in order to filter the fine particles. (Ultimaker, 2018e)

**Co-polyester (CPE)**
CPE, also known as PET-G, is a popular material for printing parts with mechanical purposes. It combines the strength of ABS with high tensile strength. It has high dimensional stability and chemical resistance. It has a slightly lower temperature resistance compared to ABS; up to 70 degrees Celsius. Moreover, it is easier to print compared to ABS, since it requires lower print- and build plate temperatures and emits few ultrafine particles. (Ultimaker, 2018f)

**Polycarbonate (PC)**
PC is one of the toughest materials to 3D print. It offers high mechanical strength, temperature resistance up to 110 degrees Celsius and good UV stability. Moreover, it has great dimensional stability and has flame-retardant properties. However, like ABS and CPE(+), the high print- and build plate temperatures required make it challenging to print with this material. (Ultimaker, 2018g)

**Polyamide (Nylon)**
Nylon is material that is suitable for functional prototypes and end-use parts because of its flexibility. Nylons are both strong and flexible and are therefore suitable for creating dynamic structures with high impact resistance. Nylons are typically harder to work with due to their high humidity absorption. (Ultimaker, 2018h)

**Thermoplastic polyurethane (TPU)**
TPU is a semi-flexible rubber-like material. In addition, it is a strong material capable of withstanding high impact forces without deforming or breaking. It also has good chemical resistance. TPU is not suitable for components that are exposed to UV light or high temperatures for long periods of time. (Ultimaker, 2018i)

**Polypropylene (PP)**
PP is also flexible, but it not as flexible as TPU. However, if the part requires slight flexibility, PP might be an ideal choice due to its high toughness and fatigue resistance. Moreover, it has a low friction coefficient which makes it suitable for sliding applications. It has both good chemical- and electrical resistance and its low density which enables creation of lightweight parts. (Ultimaker, 2018j)
Polyvinyl alcohol (PVA)

PVA is not typically used for printing objects. Instead, PVA is often used as a water-dissolvable support material. This makes PVA a good support material for printing objects with large overhangs and complex geometries with hard-to-reach cavities. PVA requires different nozzle design due to its different fluid dynamics. It is great for use with PLA, Nylon and CPE. (Ultimaker, 2018k)

Breakaway

Breakaway filament is meant for easy to remove support structures. Unlike PVA, Breakaway can be removed by hand and does not need additional post-processing after removal to leave a quality finish. (Ultimaker, 2018l)