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# NOVEL ONE-DEGREE OF FREEDOM HELIX MACHINE ARCHITECTURE FOR ADDITIVE MANUFACTURING

Additive manufacturing has been relying on conventional machinery architecture. Conventionally, the architecture used is a Cartesian set-up. The *X-Y-Z* axis move independently to move the tool on the *X-Y* plan and increment the *Z*-axis when the layer is finished. The machine architecture in this paper simplifies the design by constraining the machine to have solely one-degree of freedom. One degree of freedom is also known as a helix linkage. If individually controlled tools are placed all along the rotating arm, then this movement allows an opportunity to deposit material in a single sweeping motion. To increase furthermore the output, multiple arms can be added at a fixed angle. Finally, because of the predictive motion, multiple helix machines can be synchronized to create collaboratively a bigger part. This type of manufacturing process has potential applications in binder jetting, material jetting, and selective laser sintering.

## 1. INTRODUCTION

There are seven types of additive manufacturing (AM) techniques, Direct Energy Deposition, Fused Filament Fabrication, DLP/SLA, Laser Powder Bed Fusion, Material Jetting, Binder Jetting, Sheet Lamination. All of those processes rely on the deposition (or selective curing) of a layer before incrementing to the next one. This repeated process yields a final part. Some of those processes work with different sorts of matter: liquids, resins, binders, powders, and solids (such as filament).

Most of those processes use a machine that moves the tool in an *X-Y* plane, individually controlled to create a layer. Then, another individually controlled axe moves the *Z*-axis as to increment to the next layer. Many manufacturers have opted for a Cartesian style machine, with which the axis are in a combination of series and parallel configuration. An individual motor controls each axis, as it is easier to program. Another type of machinery used in the *fused filament fabrication* (FFF) is the delta style machine. In this case the axis are all in parallel of the *Z*-axis. They are all also individually controlled. The synchronization of those motors moves the tool to the correct *XYZ* coordinate. Other architectures are possible, some

have only one motor for the *Z* axis, some two, and even four motors (one in each corner of the build plate). The *X*-axis can be doubled as to have two individually controlled tool. Serial machine can be *X* on top of *Y*, on top of *Z*; or *Z* individually, *X* on top of *Z*. The *core XY* uses two belts to move the *XY* axis. Other exotic architectures of machines have been tried for *fused filament fabrication*, such as Scara and polar architecture.

A machine is nothing without its tool. Most processes use one tool to deposit material (or remove in case of milling). However, binder jetting, material jetting, laser sintering, and direct light processing (DLP) are similar as the tool is essentially an array of smaller "tools". Binder jetting and material jetting both use an array of cartridges that you would find in a 2D printer to print paper. The tool, the cartridge, has multiple orifices out of which material (binder or resin) comes out and is selectively placed and cured. The cartridges can be stacked to increase the deposited surface area. Direct light processing displays (DLP) light selectively across an area. The tool is the projector and the sub tools are the individually controlled pixels. Laser sintering is somewhat analogous, as one or multiple lasers beams move across a plan to selectively cure, sinter, or melt the material. It is classified with the other mentioned technologies, as the laser can move quick enough that it comports as an array of smaller tools.

Another key similitude with those technologies is that they all rely on the previously deposited layer, as material cannot be printed in mid-air. Binder jetting deposits continuously unbounded powder and the tool selectively binds them by jetting binder. The unbounded powder is used as support. Material jetting either deposits the wanted material or a support material; support is constantly jetted. DLP cured material is helped with the uncured resin; in some cases support needs to be cure along with the part. Finally, the selective laser sintering/melting relies on the non-bounded powder.

This novel machine architecture is capable of using the previously cited processes. Throughout this paper a focus in done on binder jetting of binder on sand to create sand molds for a sand casting application. The key concepts regarding the machine kinematics and the tool have been patented [1, 2].

## 2. CASTING

For mold making, there are two types of techniques depending on the desired casted part resolution. Lost wax casting is superior in terms details, but molds tend to be for "smaller" parts. Sand casting, is less precise as the sand is rough and the pattern used for the mold can deviate with time and humidity. If a surface needs to be functional, then milling the surface of the casted part to the correct specification is a must.

Sand casting is traditionally uses wood patterns made by a CNC milling machine. To make the most basic part, two halves are needed to make the mold. Two halved because you need to remove the patterns. The pattern is put inside a box and sand with binder is then packed. Depending on the binder used, the solidification is either done by heat, $CO_2$, or with time. The process is repeated for each half and then they are assembled. The mold is most of the time a parallelepiped shape. Finally, the alloy is poured inside the mold.

In spite of those points, sand casting is very common process to make large cheap parts of different alloys. A review was made in 2018 by Le Néel and al. which analyses the current

state of the art of manufacturing techniques used for sand molds with additive manufacturing [3]. It was found that few researchers focus on the opportunities that binder jetting sand molds offer for sand casting application. Because of this, it is a process that still needs further investigation.

Additive manufacturing removes the need of a patter. The mold can be directly printed. AM can offer not only the optimization of the part itself, but also the mold. An example of the optimization was done via reducing the thickness of the mold. Furthermore, Le Néel and al. proposed a novel design to reduce the thickness of the mold to a shell with a variable thickness [4]. This methodology is important for sand casting for multiple reasons. First, it reduces the amount of material required, therefore less binder is used which leads to less material needing to be recycled. Secondly, reducing the volume of the mold increases the available volume in the printer. Increasing the number of parts made per batch, increases the throughput, therefore making the part cheaper.

Design for foundry is a complex subject. Molds have to take into account the flow of molten liquid alloy within the mold. The mold has to: sustain erosion, degas, evenly flow, and especially cool evenly. Additive manufacturing can increase the reliability of the cast by homogenizing the cooling. It has been proposed to deposit different material composition; materials with drastic thermal properties at specific locations via the help of additive manufacturing [5]. Knowing and adjusting the local properties is a key advantage.

Additive manufacturing techniques, such as FFF have been known to have anisotropic mechanical properties; therefore part orientation must be taken into account when designing a part [6]. Binder jetting has the advantage of having isotropic properties as the binder flow relatively evenly through the sand. The property makes it easier to design a mold to withstand casting requirements. Matsi et al. Have show cased the importance of rapid prototyping for product development with the help of 3D printing technologies [7]. Two technologies were compared, a fused filament fabrication (FFF) from Stratasys and a binder jetting from Zprint (later bought by 3DSystems). The inkjet method was faster and cheaper, but the quality was lower than FFF process.

In the proposed machine architecture, the tool's precision depends on the nozzles specifications and the properties of sand deposited. The tolerances of the part will depend on the powder fineness and the resolution of the binder jetting tool.

The complexity of robot is ever increasing. To increase the reachability of a 6-axis robot, some are mounted on linear axis. This redundancy is complex to manage, as multiple solutions are acceptable. Walther and al. proposed a tool path planning to solve this issue [8]. The proposed machine limits the number of axis as to reduce the complexity.

## 3. MACHINE ARCHITECTURE

### 3.1. STATE OF THE ART

A few methods for adding granular substrate are commonly used in additive printing. There is the double chamber method. This method, illustrated Fig. 1, consists of having a chamber filled with unbounded granular substrate and another that is the printing chamber. After laying material and selectively printing on it, the printing chamber goes down.

Afterwards, the unbounded chamber goes up and the recoater lays a specific quantity of material on the printing chamber as to repeat the cycle until the part is fully printed. To ensure that the required quantity of material is deposited an overflow bin is present at the end of the path of the recoater. All the excess powder is pushed in that compartment to be evacuated at the end of the build. This unbound powder goes in the recycling process as per with the remaining powder in the printing and unbound chambers. The process can be further improved by creating a symmetry in the design. The recoater used in the EOS Formiga P110, as show with Fig. 2, can recoat back and forth reducing the recoating cycle time.
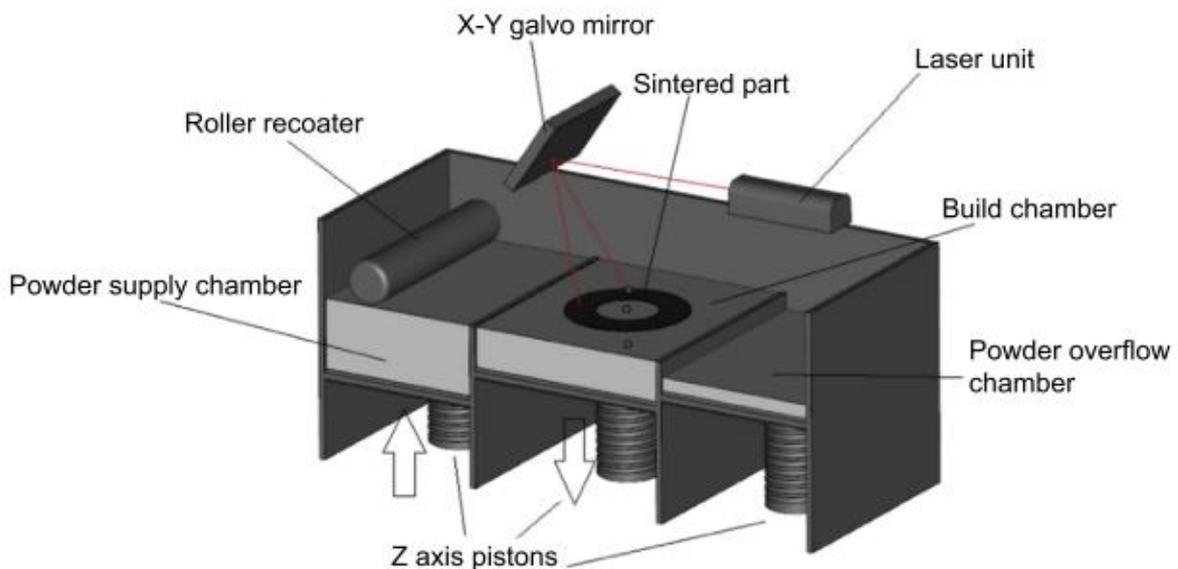
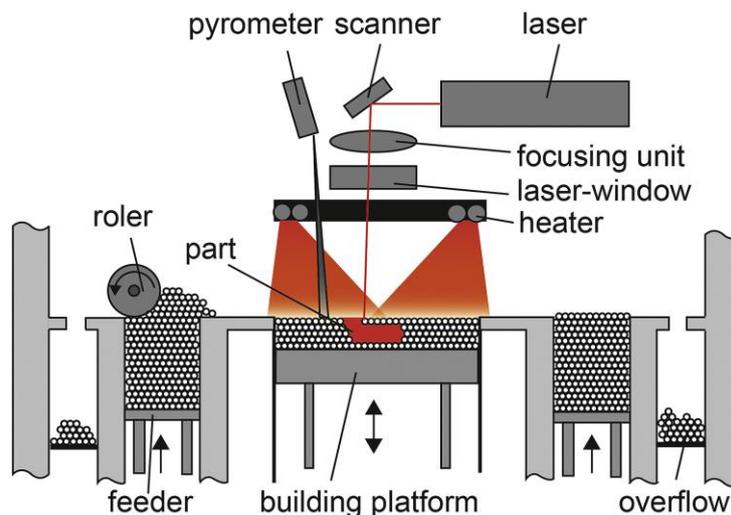Fig. 1. Double chamber design with overflow bin [9]

Fig. 2. Double double chamber design with overflow bins [10]

Realizer GmbH, now bought by DMG Mori, had a machine called the Realizer 50 [11]. This machine had a novel kinematics for a SLM printer. As show with Fig. 3, the machine

had: 1) a **rotational** movement called a "wiper system" to deposit metallic powder, 2) a **linear** movement with the circular build platform. The sintering, or melting, is achieved by the laser and x-y scanner. It can be noted that the two systems are decoupled. Although decoupled they work in a synchronous manner as to deposit material at the right time and move the platform at another via electronics.
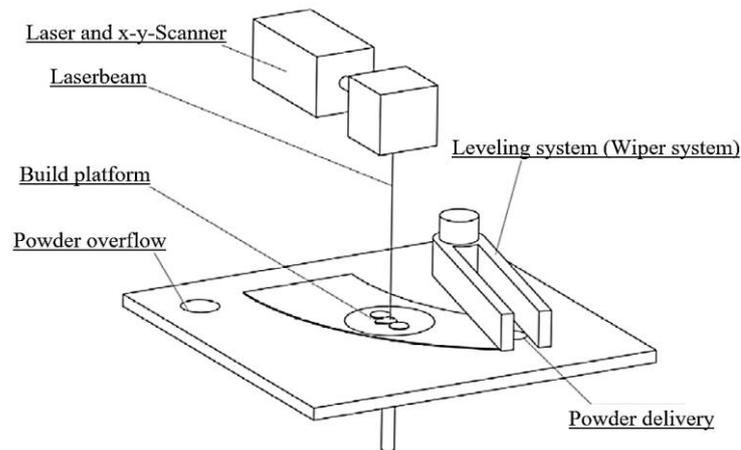


Fig. 3. Realizer 50 desktop SLM machine kinematics [11]

The Realizer 50, like the Formiga P110 move the recoater with a rotation. This reduces the complexity of the machine. The arm does not need linear guides, nor lubrication. Furthermore, stepper motors can use novel drivers that eliminates the need for end stops and position can be known trusted in an open loop using back-EMF [12]. The proposed design couples the rotational and linear movements by a mechanical linkage. This design simplifies the electronic system design and ensures a perfect synchronized movement of the tool.

Another approach to constrain the movement to a rotation and a linear translation is to use a 6-axis robot. Trials have been conducted with a TX90 as by Staubli, show in Fig. 4. The cost of the robot and the complexity was not reinforcement of the developpement of a helix architecture. The robot approach is carried out by Viricast3D and ExOne [13, 14].



Fig. 4. Staubli TX90 6 axis robot with the sand deposition tool

This design was experimented because the robot is a polyvalent machine. The tool path could be confirmed with a high degree of freedom machine. The 6 axis robot can easily replicate the linear movement in the Z axis as to increment the layer; but it cannot do a full 360° rotation. However, it can achieve at ± 180°. This kinematics was a good proof of concept to see how the tool and the deposited sand would behave. Additionally, the tool can just be changed at the 6th axis, at the "wrist" location.

It is evident that to achieve a continuous rotation a custom machine has to be designed and prototype.

### 3.2. ADDITIVE MACHINE WITH ONE-DEGREE OF FREEDOM

A holistic approach in the machine design is taken. Firstly, a focus is made on the additive manufacturing machine with a binder jetting tool. Secondly, the sand hopper design associated with such machine is discussed.

Binder jetting AM machine binds material by the jetting of binder. The cartridge that jets the material have a resolution commonly presented in dots per inches (DPI). Using the metric system, it is referred as dots per mm (DPMM). The developed machine uses cartridges with 128 channels across 64.5 mm. Therefore, it has a 1.98 DPMM (spacing of 0.508 mm per dots). The cartridges are stackable. The first prototype is being conceived with 10 cartridges. The projected material line is 645 mm. The material is jetted on a layer of sand that is deposited via a hopper. A recoater lays the sand flat at a specific layer height.

The novel machine design is based on the concept of the *helical joint* (helix linkage or screw joint). A helical joint is a mechanism that has only one degree of freedom (1-DOF). A DOF is the number of independent parameter that define its configuration. Yet, with 1-DOF the helical joint can achieve a rotation and a translation. It should be a 2 DOF because of the two movements. But because the translation is proportional to the rotation, the mechanism is considered 1-DOF. This mechanism is often seen with nut-bolt linkage, Fig. 5.
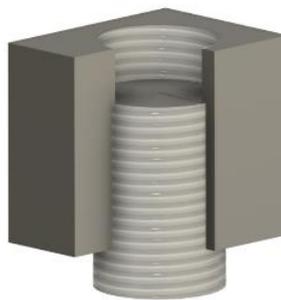


Fig. 5. Helical joint

To illustrate the concept with a nut and bolt, the nut is fixed compared to the ground and the bolt will be in rotation. If a motor rotates the bolt, then the bolt will not only rotate, but move up or down. In the demonstrated case the bolt goes up. An arm is attached to the bolt as to off-set the movement.

A tool comprised of a single cartridge is the simplest design is attached at the extremity of the rotating arm. This configuration is not advantageous because it will result in a annular deposition which is represented by Fig. 6.

The bricks represent the deposited sand. The sand is laid all along the tool path. To fabricate the part, the binder is jetted at the correct spot, Fig. 7. Once the final height is reached, the unbound sand can be removed to reveal the final part (bounded sand) as illustrated with Fig. 8.
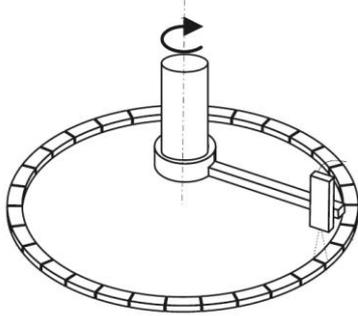
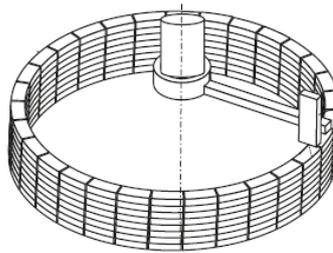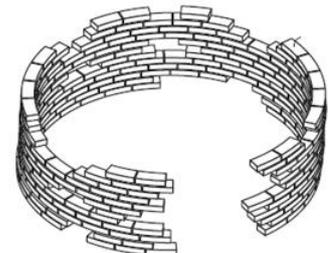| | | |
|---|---|---|
| Fig. 6. Deposition of the first layer | Fig. 7. Deposition of the entire part, sand and binder | Fig. 8. Unbounded sand removed |

The tool can be duplicated all across the rotating arm as to deposit material all across its length. Parts that are more voluminous can then be achieved with such design. To even the load and also to increase productivity, the arms can be multiplied as to have 2 or more arms. Fig. 9 illustrates a configuration with 4 arms.
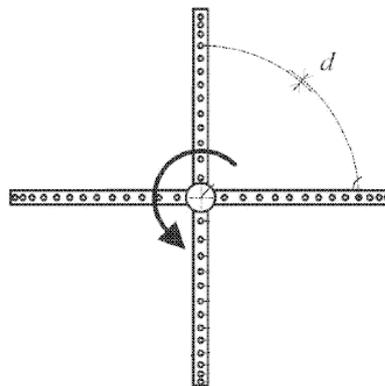
Fig. 9. Configuration with 4 arms

The rotating arm can either be fixed on the ground, Fig. 10, or be fixed at the ceiling, Fig. 11. Fixing on the ground may be the simplest solution, yet it imposes to have a shaft go through the manufactured part. Therefore, it may not be that advantageous. The solution to fix the robot at the "ceiling" may be a better solution. The difficulty is how to attach the robot. An enveloping structure around the machine may be sufficient to hold the 1-DOF machine. Nevertheless, a machine fixed to the ground with the helical axis going through may be useful in certain cases. For example, a propeller can have through hole in the middle as seen with and . In that case the machine is not a constraint.
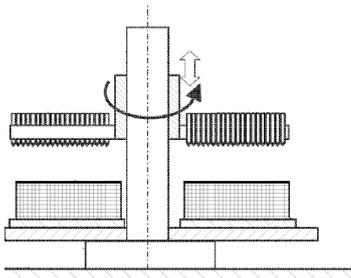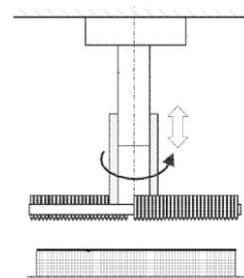
Fig. 10. One-DOF fixed on the ground



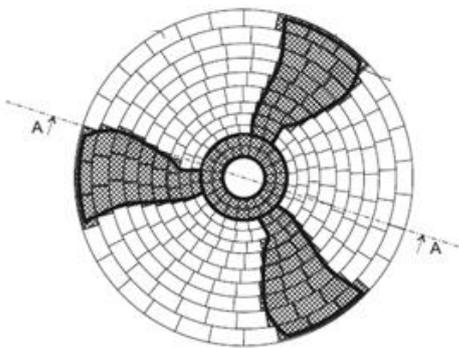Fig. 11. One-DOF fixed at the ceiling



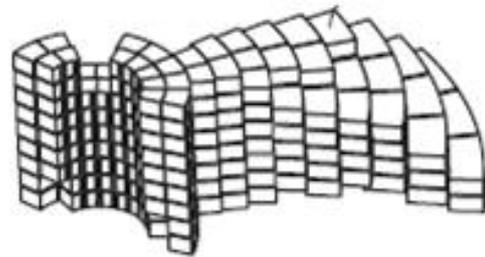Fig. 12. Illustration of a more complex part (black is bounded sand)

A-A



Fig. 13. Part removed from the loose sand

A conventional 3D printer manufactures a flat *XY* surface and then increments in the *Z*-axis. It should be noted that the machine does not move like a regular 3D printer. This architecture is always going up, it could be said it is a true 3D printer and not a 2.5D printer. The proposal of multiple arms and the fact that it is always moving will affect the slicing algorithm. The model slicing is a topic not discussed in this paper.

To put this concept through its paces, a prototype as seen in Fig. 14 has been built. The machine uses the upside down configuration. There are no middle pillar.



Fig. 14. A 200 mm diameter x 600 mm prototype 1 dof machine

The is only one motor at the top spinning a threaded rod. Attached to the rod are two rotating arms dispensing sand and ink. Four rods guided with bearing are added to the platform to increase the stability. This version uses an Arduino microcontroller as a stepper driver. The inkjets are controlled by dedicated hardware and software.

### 3.3. THROUGHPUT CALCULATION OF HELIX ARCHITECTURE WITH BINDER JETTING TOOLS

The proposed machine architecture throughput can be calculated via the following method. The arm's length will define the build volume (capability), but also the maximum rotational speed (limit). The selected tool, the cartridges are also important as they define the maximum binder content deposition. The highest need is at the extremity of the arm as the angular rotation is the highest. The layer height is a variable, yet it is linked to the binder deposition rate. Layer height will be set as constant as to have repeatable quality.

Fixed variables:
- The machine:
  - Diameter: 650 mm,
  - Number of arms: 1.
- The tool cartridges:
  - Drop volume 80 pico liter,
  - Drop frequency 30 kHz,
  - Printing length 65 mm,
  - Dots per mm 1.96 dots/mm.
- Print parameters:
  - Binder/sand ratio 12%.

The maximum single nozzle volume output can be calculated:

$$\text{Eq(1) Volume binder} = \text{frequency} \times \text{drop volume}$$

With unit conversion this brings the output at 2.4 mm³/s. The machine maximum output is limited directly by this value. The maximum theoretical throughput with 100% tool efficiency would be calculated with:

$$\text{Eq(2) Maximum theoretical throughput} =$$
$$\text{volume binder/ratio binder} \times \text{number of nozzles} \times \text{number of cartridges}$$

With units adjustment this equals to 92.2 l/h. The machine moves in a circular pattern, therefor the nozzles in the middle do not need to jet binder at 100% of capability. The real maximum theoretical throughput can be calculated via this equation:

$$\text{Eq(3) Real maximum theoretical throughput} = \text{diameter} \times \text{layer height} \times \text{rotation}$$

All those variables are known expect for the rotational speed. The rotational speed is linked to the maximum throughput of the most outward nozzle. The rotation speed can be calculated with:

$$\text{Eq(4) Rotational speed} = \text{maximum theoretical throughput/(layer height} \times \text{distance between nozzles} \times \text{machine radius)}$$

The rotational speed is 0.31 radian/seconds or with units conversions 2.94 RPM. This value can be plugged back into Eq(3) to obtain the real maximum theoretical throughput of 23.9 l/h.

To increase further the output, either the cartridges need to be changed to higher throughput, or more arms need to be added to increase the number of tools. The increase of number of arms it linear, 2 arms = 47.8 l/h, 4 arms 95.6 l/h. The next limiting factor to consider is the volume in the machine to put all the tools. The current prototype is being built with two arms.

### 3.4. COMPARATIVE THROUGHPUT OF PROPOSED ARCHITECTURE VS. CURRENT STATE OF THE ART

The current state of the arm with available information to compare build volumes is expressed in the following table.

| Manufacturer | Machine | Volume (mm × mm × mm) | Price (k-USD) | Build rate (l/h) |
|---|---|---|---|---|
| Voxeljet [15] | VX1300 X [16] | 1 280 × 680 × 500 | Unknown | 179 |
| Voxeljet [15] | VX4000 | 4 000 × 2 000 × 1 000 | 2 100 | 144 |
| Voxeljet [15] | VX2000 | 2 000 × 1 000 × 1 000 | 950 – 2 000 | 21–58 |
| Voxeljet [15] | VX1000 | 1 000 × 600 × 500 | 840 – 1 000 | 9–43 |
| Voxeljet [15] | VXC800 | 850 × 500 × ∞ | 735 | 12 |
| Voxeljet [15] | VX500 | 500 × 400 × 300 | 445 – 505 | 4–7 |
| Voxeljet [15] | VX200 | 300 × 200 × 150 | 150 - 260 | 0,6–2 |
| ExOne [14] | S-Max Pro | 1 800 × 1 000 × 700 (400) | Unknown | 145 |
| ExOne [14] | S-Max | 1 800 × 1 000 × 700 | Unknown | 125 |
| ExOne [14] | S-Max Flex | 1 900 × 1 000 × 1 000 | Unknown | 115 |
| ExOne [14] | S-Print | 800 × 500 × 400 | unknown | 40 |

The proposed machine has a build volume of diameter 650 mm with height of 650 mm. The build rate is rounded to 48 l/h. The prototype is comparable with machines worth $800 000 and $2 000 000.

### 3.5. COLLABORATION OF MULTIPLE 1-DOF MACHINES

The collaboration of multiple 1-dof machines can be achieved in multiple ways. It can be seen as either:

1. Individual 1-dof machines that are temporally combined.
2. A machine with divisible regions.

The scenario would depend on the need of the user. Are parts made usually small? In this case scenario, 1 is advantageous. Or are parts usually big? In that case, scenario 2 would be beneficial. The production volume will dictate which machine is more ideal.

In high scale production, to reduce the cost of the final part a dedicated machine is often made. In this case, either solution is relevant.

In the case of scenario 1. individual 1-dof machines, the machines can be placed any-where on the shop's floor. They can be far from each other. If that is the case, then connecting the machines together on the network could be done wirelessly via ZigBee [17]. Wired connection could be detrimental as they are being moved. Manual labor is required to assemble them to a coherent large machine. The machines then would need to either have poka yokes or be self-calibrating.

In the case of a machine that has divisible regions, the machine would "split" itself if required. This design imposes a large floor space at all time to have the machine, but to have an expandable machine. Fig. 15 illustrates the collaboration of eight 1-DOF in two rows and four columns in a configuration attached at the ceiling. In contrast, Fig. 16 illustrate with the robots fixed to the ground. The pillars hinder the full potential of the synchronization. In both configurations if the machine expends, all the individual 1-DOF are accessible. In the case of three rows and three columns, with nine 1-DOF, the center machine accessibility issue. The parts made by that machine will require to be accessed after the removal of others machines' print volume. It may not be a problem is process planning is applied. In other words, the removal is of the print volume is schedule per the others. In the case of a machine failure, then it may be more problematic.
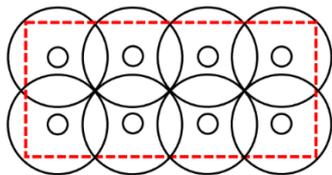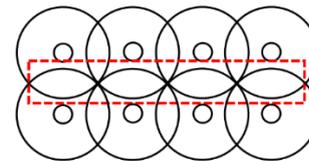
Fig. 15. Collaboration of 4 1-DOF machines

Fig. 16. Collaboration of 8 1-DOF machines

From a risk management perspective, manufacturing with multiple machines will reduce down time by increasing redundancy. If one machine is under maintenance, the other can still print. If you only have one big volume machine and it breaks down during mid print, your entire production is ruined.

### 3.6. TOOL DESIGN

From the get go, sand dispenser hopper was spotted as the weak link. The hopper needs to continuously, and reliably add material. This effect can be seen with Fig. 17, the sand stops flowing due to its angle of repose, illustrated with Fig. 18. Common machines either do not use a hopper but use the double chamber system, or they use one that has a shaking device. The shaking device ensures that the sand flow is not obstructed or that no sand is left in the chamber.

The hopper itself can shake or a device inside the hopper can loosen the sand. Either way, those methods create adverse effects. A segmentation approach was used to compart-tment each nozzle. The compartments have a specific angle and creates an unstable resting angle. The angle is slightly higher than the angle of repose of the sand. This angle depends on the sand. The parameters such has granulometry, grain shape, humidity content are all factors that influence the angle.
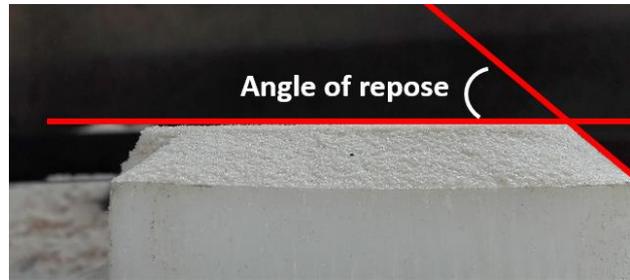
Fig. 17. Flow of sand stopped



Fig. 18. Angle of repose

The sand used in this experience is a silica sand HN38 ($SiO_2$) with a granulometry comprised between 50 µm and 250 µm, as illustrated with Fig. 19. The sphericity was captured via an SEM machine, Fig. 20. According to the Pettijohn scale, the sand is a 5, meaning it is angular and low sphericity [18]. The humidity of the sand was not measured, how-ever the ambient humidity was at 54%. The angle of reposed measured that day was 43°.
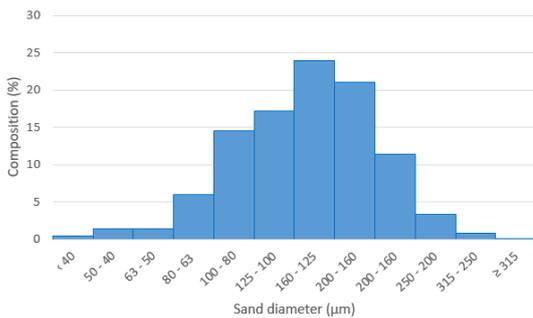


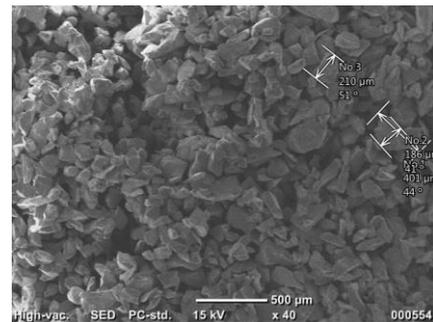Fig. 19. Refusal histogram (AFNOR)



Fig. 20. SEM capture of $SiO_2$ sand

The hopper, Fig. 21, needs to be designed with an inner angle lower than the angle of repose of sand. Each hole has its own slope as ensure the sand is unstable at all points. The educed design generates pyramids at every holes. The opening angle between the pyramid in the hopper illustrated with Fig. 22, is 30°.
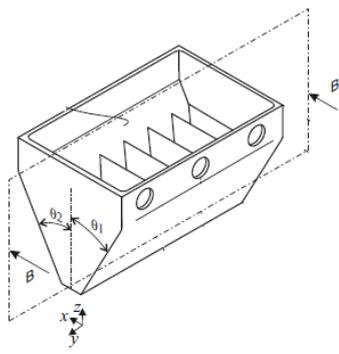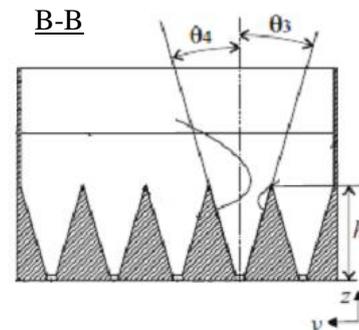


Fig. 21. Hopper design



Fig. 22. Inner hopper geometry

This part was then 3D printed with a FFF machine as to test the flow ability of the sand. The question that needs to be answered is: does all the powder flow or not? The answer is binary *yes* or *no*. The hopper is directly mounted on the jig, Fig. 23. The sand fully went through the hopper and no sand was stuck, Fig. 24.
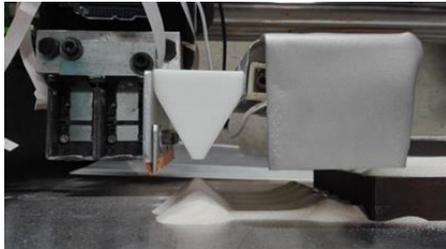


Fig. 23. Hopper mounted on the jig



Fig. 24. Hopper is empty of testing

## 4. CONCLUSION

The proposed 1-DOF machine architecture does have its simplicity, increased throughput, and flexibility. A comparative study of the estimated throughput compared to current available solutions is done.

Yet, work is not finished. A novel algorithm for helix slicing needs to be introduce as the movement of the tool is not conventional. The center of rotation of the machine is peculiar. The tangent speed is equal to zero, some sand may accumulate and the recoater needs to lay the sand correctly. Further research could be done on the tool, *how could multi-material be implemented? In this case a focus is done on binder jetting, what if we change the additive technology, what would be different with material jetting? Laser sintering? Laser melting? SLA?*

Despite those points, a simpler machine architecture dedicated for the process may be more beneficial overall.

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