Flexible Object Handling in Additive Manufacturing with Service Robotics

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***Abstract*—The focus of this paper is the flexible handling of printed objects; specifically looking at the unloading process of a 3D printed object from the printer's build plate.**

To design functioning universal gripper fingers 150.000 models were analyzed, in order to calculate an appropriate range of dimensions. To determine the exact position, orientation and dimensions of the printed object a simple but effective algorithm analyzes the GCode file provided by the printer. Based on this information a detachment-strategy is chosen, which is a combination out of one or more of four basic movements. Upon receiving this information the robot executes the unloading process. Furthermore, five different gripper finger approaches and designs are examined and tested with an industrial gripper on a lightweight robot. The presented flexible handling approach provides the first step towards an economical way of handling printed objects from the build plate, reducing the non-value adding time of 3D printing. The proposed concept is not bound to the fused filament fabrication (FFF) technique, but can be applied universally to any 3D printing process by means of minor adjustments to the presented designs.

***Keywords*-Flexible Handling, Additive Manufacturing, 3D Printing, Automation, Robotics, Grasping, Machine Unloading, Service Robotics, Fused Filament Fabrication**

I. Introduction

Additive manufacturing, especially 3D printing, is increasingly used in research and product development processes across many industries. Only used in rapid prototyping processes at the beginning, this advanced production process is currently used for functional prototypes and even individual product series [1]. Since the expiration of the patents of multiple kinds of additive manufacturing techniques such as fused filament fabrication (FFF), stereolithography (SLA) or selective laser sintering (SLS) the amount of available printers has increased drastically. Not only are huge companies able to afford one of the machines, but also the smaller companies with just a few employees. There is a lot of research going on in the field of material science to increase the range of printable materials.

Nevertheless, there are still a lot of challenges before additive manufacturing is widely used as a common production technique and can rival injection molding. As there is currently almost no automation implemented in 3D printing processes, a lot of work has to be done manually by workers, as visualized in Fig. 2. When considering the workers health, there is a need for innovative improvements with an increased automation in the process chain. The printing stock and the production process is unhealthy and can even be toxic, especially if you come in contact with it on a daily basis [2]–[4].

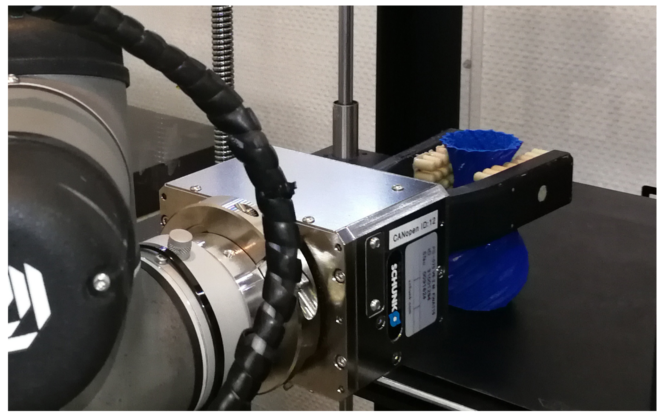


Figure 1. Using a service robot and an industrial gripper with flexible, custom gripper fingers to detach a printed object from the built plate of a printer.

The different printing techniques stayed almost the same for the last few years, but there were great improvements in the field of lightweight robotic hardware. Robots and their components are getting cheaper and at the same time the programming and controlling has improved. For example, this is partially due to Open-Source frameworks like Robot Operating System (ROS) [5]. This enables robotics to now be affordable even for small-use cases.

In this paper we combined 3D printing and service robotics to implement a flexible approach in automating the unloading of FFF printers. A printer waiting to be unloaded increases the non-value-adding time, leading to less prints in a given timeframe. This costs energy as well as delaying the printing schedule unnecessarily.

The presented paper proposes a handling approach for a flexible unloading process of an FFF printer. In order to accomplish this challenge multiple things are required: a robot, gripper, gripper fingers, nondestructive detachment-strategies, and knowledge about the printed object itself. In this paper we focus on the knowledge, strategies, and the design of the gripper fingers, as the robotic hardware is independent. After an exploration of the current state

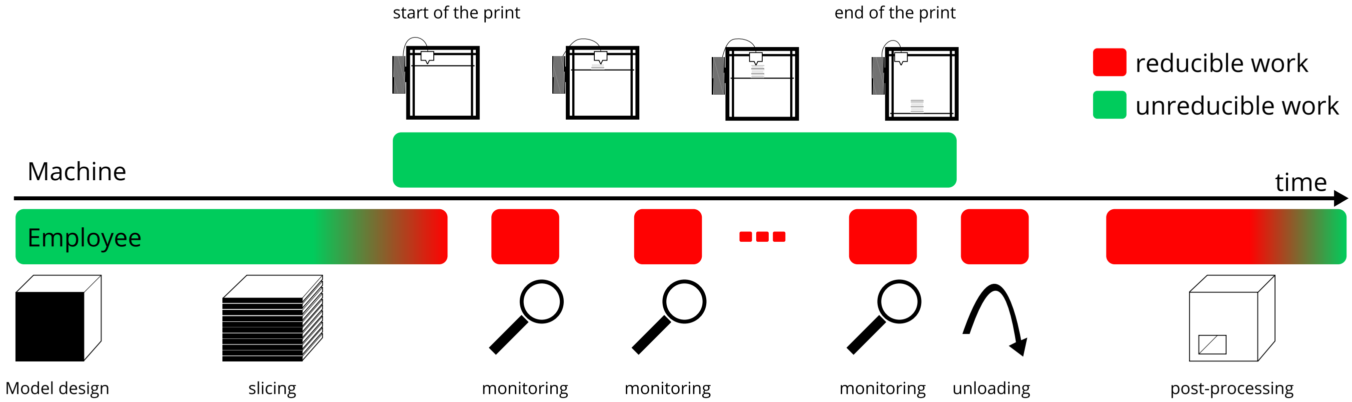


Figure 2. Overview of the manual work during the printing process and if it is or is not potentially reducible. Currently, there is a lot of manual work needed especially during and after the printing process.

of the art, several thousand 3D models from Thingiverse [6] were evaluated in order to get data about the average measurements of 3D models particularly designed for printing. Furthermore several strategies for detaching the object are explained and evaluated. To get the width and position of the currently printed object, the GCode is automatically analyzed and this information is processed to control the robot.

Previous work has mainly focused on the possibilities and trends in additive manufacturing. But current processes and solutions are unsatisfactory and need a lot of manual work. We believe that we have found a possibility to automate the handling of printed objects, which helps to reduce the workload and health threats.

II. State of the Art

The additive manufacturing process, today known as 3D printing, was developed and patented in the 1980s by Charles W. Hull [7]. In this process, called stereolithography (SLA), the cross section of the desired object is produced layer by layer from a UV light sensitive resin, which is cured using a Laser. Increasing the distance between build plate and resin, the next layer of resin is applied and cured. This cycle is repeated until the object has been completed. Once completed, the printed object can go through post-treatment in order to achieve the desired mechanical and optical properties. This 3D printing technique is widely used in dental applications as well as use cases where small, highly detailed objects are required, due to the high resolution and flexible mechanical properties it enables.

Two years after the development of the SLA process, the selective laser sintering (SLS) process was developed by Dr. Carl Deckard and Dr. Joe Beaman [8]. SLS functions along similar principles as SLA, yet a powder is used, instead of a resin, which is molten via a laser, binding the material together.

Another two years later, in the late 1980s, S. Scott Crump developed and patented the fused deposition modeling (FDM) 3D printing technique [9]. Since the term FDM was also protected by his company, Stratasys, various names have been formed for this process, including the widely known name: fused filament fabrication (FFF). In this additive manufacturing process, the object is also produced in layers, however, a thermoplastic material and a heated extruder are used. The material, called filament, is conveyed through a heated nozzle, upon which it softens and can be applied to the build plate. The distance between the nozzle and the build plate is increased, and the next cross-section of the object is applied. As the FDM technique has a much simpler principle and build, this process was highly sought after.Due to the expiration of the FDM patent in 2009 and the development of the open-sourced replicating rapid-prototyper (RepRap) [10], [11], FFF 3D printers, along with the knowledge of how to manufacture these printers, became widespread. Enabling printing with a wide variety of materials infused in a thermoplastic binder, FFF 3D printers are the most common, readily available additive manufacturing devices found in a large number of industrial and private settings today. The approach presented in this paper was developed and tested using the FFF additive manufacturing technique, to which it is however, not restricted. Since the FFF 3D printer, there have been many more developments in additive manufacturing, including the introduction of multiple different techniques to produce 3D objects. Almost all of these however, still demand a great deal of knowledge, supervision, and post-processing from the supervising employee. As described in Fig. 2, the worker is needed in multiple stages of the 3D printing process chain. These include the model design, slicing with optimal parameters, monitoring of the actual print process, as well as unloading and post-processing of the object. Due to the toxicity of the materials used during this manufacturing process, it is thus necessary to automate as many processes of 3D printing as possible. In order to further advance the capabilities and efficiency of 3D printing through automation, many producers of 3D printers are starting to research and refine this process. Amongst these are the 3D printing giants Stratasys Ltd. (with the Continues Build Demonstrator), Formlabs (with Form Cell), and Digital Metal (with the ”no-hand” production line) [12]. The Continues Build Demonstrator was designed, as the name states, for continual printing without the downtime of waiting on an employee. To enable this, Stratasys developed an FDM 3D printer fashioned with a conveyor belt as a build plate [13]. A clear plastic film is placed on the conveyor, upon which the object is printed. Once the print has completed, the film is conveyed towards the front edge of the build plate until the printed object is no longer within the build volume. Afterward, it is cut, causing the printed object upon the film to fall into a collection bin, clearing the build volume of the 3D printer and enabling the next print job to begin.

With the project Form Cell, Formlabs has also designed a 3D printer which can be automated [14]. Similar to the approach chosen by Stratasys, Formlabs has implemented a removable build plate in order to increase the production efficiency and reduce the hourly machine rate. This is implemented with their trademark SLA 3D printer and an industrial robot arm. This arm is used to remove the build plate of finished prints from their fixture and transport them to the next post-processing station. Thus, it is possible to expand the cell's capacity as desired.

The metal 3D printing giant from the Sweden, Hgans Group Digital Metal, has also announced an automated additive manufacturing process chain [15]. With the use of an industrial robot arm, the 3D printers are supplied with a metal powder filled build box to begin the production. As the binder jetting process finishes, the robot prepares to remove the build box and transport it to various post-treatment stations including: powder removal, debinding of the plastic, and sintering. Upon removal of the build box, a new build box with the desired material can be placed in the 3D printer, enabling very little machine downtime.

Another company which has joined the automation of 3D printing movement is the 2017 startup Voodoo Manufacturing. Their goal is to use 3D printing to rival injection molding of smaller quantities. In order to enable this, Voodoo Manufacturing has started Project Skywalker, in which an industrial robot arm removes the finished print from the build volume for multiple 3D printers [16]. This is done by use of a removable build plate, which is extracted from the printer upon completion of a print job, using the robot arm. Having been removed from the build volume, the build plate, along with the hereupon printed object, are placed upon a conveyor to be transported to post-processing. A new build plate is set in the printer and the next print job can be started.

There are many other companies pursuing 3D print automation including 3D Systems with its product, Figure 4 [17], which is based upon the same principles as Formlabs's Form Cell. Most of these, however, have the same approach to the automated removal of the 3D printed object by removing the entire build plate. With this approach the printer build volume is cleared, and a new print job can be tasked, reducing the printer downtime significantly. In these cases another built plate is inserted which could lead to problems like calibration errors. Through the removal of the build plate, the post processing and supervision required by an employee has not been reduced as the printed material needs to be removed from the build plate by hand. Therefore, the only benefit of the above mentioned approaches, besides that of Digital Metal, is the reduction of printing costs and the downtime of the printer.

Next to the immense progresses in 3D printing, there is also currently a lot of research in the field of robotics, especially in terms of collaboration [18]–[20]. Presently, robots are already widely used and offer great opportunities for future applications, especially in cooperation with humans [21]; cleaning robots like the Roombas are just the beginning. A future application in the household could, for example, be a cooking robot similar to the proposed BratwurstBot [22] that is already in the field.

The approach introduced in this paper reduces the needed nonproductive time by automating the unloading process in a way that the printed object is detached from the build plate and removed from the printer. Furthermore, an automated post-processing becomes possible. This approach provides a solution that can be added to almost any FFF 3D printers and, by means of minor adjustments, most other 3D printing technologies. Thus, it is possible to use the approach in a production environment with multiple 3D printers and 3D print techniques to reduce the overall production cost, time, and the needed human supervision.

In this paper the presented concept uses an industrial robot arm equipped with a universal gripper finger design to enable the automated removal of a wide variety of 3D printed objects of all shapes and sizes. In addition, the gripping of objects is executed without the need of a machine vision system, as an algorithm is used to calculate the optimal gripping position and removal strategy for each printed object based upon their GCode data. These removal strategies are generated from basic translations and rotations to minimize the possiblity of damaging the object. This enables an efficient automated removal of 3D print objects from a vast variety of 3D printer models, including most 3D printing techniques.

III. APPROACH

The goal of this paper is to present an innovative concept that will reduce employee risk, tooling costs, and further increase the process efficiency. To realize this, a variety of components are required: knowledge about the printed object, a flexible handling opportunity,and a detachment-strategy. This section analyzes several thousand 3D models, proposes five gripper finger designs, as well as a set of basis movements for detaching the object from the build plate.

A. Analysis of 3D printed parts

In order to develop a suitable flexible gripper finger design some information about the printed objects is required. That is why around 150.000 3D objects from the online community Thingiverse [6] were analyzed. The dimensions of these STL 3D objects were determined and stored using the free software ADMesh. To determine the distribution of the object widths, a histogram of each dimension (x, y, z) was plotted. The density and cumulative distribution were approximated using standard distribution functions with minimal deviation from the real values, as the given distributions require different approximations.

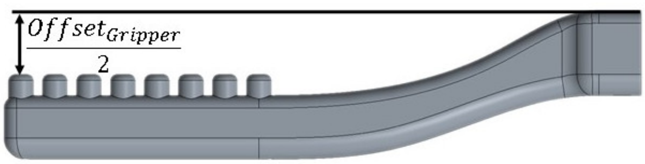


Figure 3. The gripper offset describes the spacial difference between the power intake and the force application.

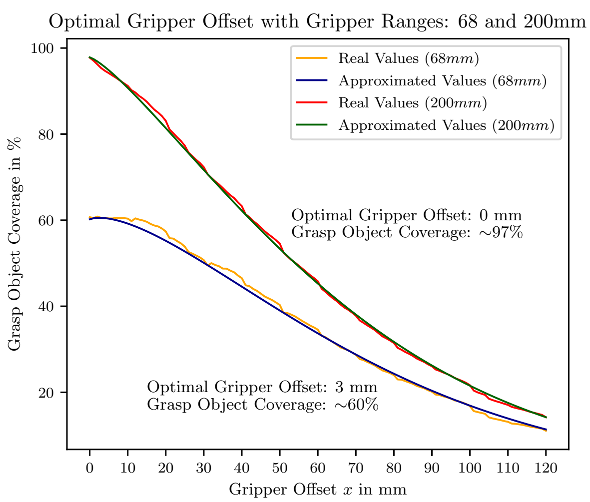


Figure 4. This graph depicts the gripper range of 68 and 200mm, resulting in a 60% and 97% grasp object coverage of the analyzed data.

This was done in order to estimate the most common dimensions, enabling an efficient range of graspable objects. The distribution includes around 5% of the objects available through Thinigverse; however, an increase of the percentage simply shifts the distribution further to the y-axis.

It is thus evident, that the most common dimensions are below $80mm$, as is shown in Fig. 6 through 8. Furthermore, the minimal required gripper offset for a given range was determined as shown in Fig. 4. The gripper offset is the distance between both grip surfaces when the gripper is completely closed (see Fig. 3). To grasp even small objects from the build plate, the offset should be as small as possible. With an offset of $0mm$ and a range of $140mm$, more than 90% of the objects can be grasped (see Fig. 6).

B. Design of the gripper fingers

Proper gripper fingers are required, to be able to grasp and detach 3D printed objects from the build plate of a printer. The gripper needs to support a range of $140mm$ to grasp more than 90% of all analyzed parts and have an abrasion-resistant gripping surface in order to reduce wear and increase the gripper life-span.

(a) 3D printed burling gripper finger. Offset: 10mm, coverage: $\sim 58\%$

(b) Cast burling gripper finger. Offset: 20mm, coverage: $\sim 45\%$

(c) Air-cushioned gripper finger. Offset: -10mm, coverage: $\sim 56\%$

(d) Polyurethane foam damped gripper finger. Offset: 0mm, coverage: $\sim 63\%$

(e) Tong-gripper. Offset: 0mm, coverage: $\sim 97\%$

Figure 5. Designed and evaluated gripper fingers having different gripping ranges, as well as different flexible grip surfaces.

The gripper fingers also need to be adaptable to the 3D printed object, enclosing it as much as possible, in order to transfer the required detachment-force across a wide surface area, reducing the stress on the object. This prevents damage to the printed objects during the unloading process, also enabling the unloading of fragile objects. With the

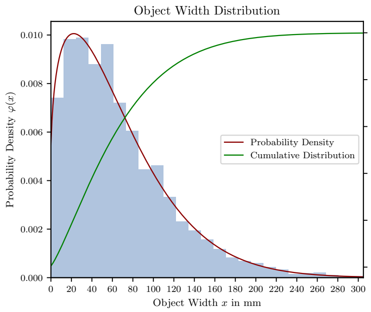


Figure 6. Object width distribution in x dimension

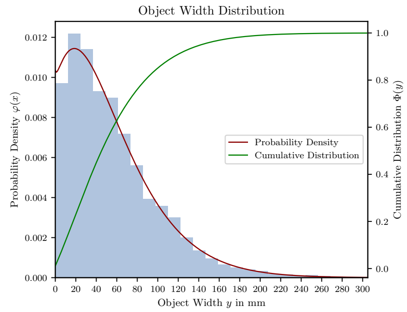


Figure 7. Object width distribution in y dimension

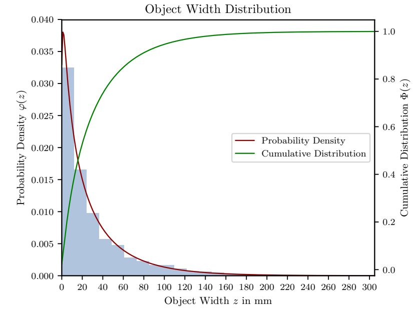


Figure 8. Object width distribution in z dimension

above mentioned criteria, five gripper finger designs where implemented and tested in order to reduce the costs and effort of a 3D printing production.

The gripper finger displayed in Fig. 5a is made up of a PLA base and a thermoplastic polyurethane burling gripping surface. The burling structure enables a good force induction, but not over a large surface, as the printed flexible material prohibits a versatile adaptation of the burling profile.

Hence, the same gripper was tested with the burling structure comprised of a cast elastomer resin, as seen in Fig. 5b. This enabled a far greater degree of adaptation and allowed the successful removal of multiple 3D printed objects.

To further increase the adaptability of the gripping surface an air cushioned gripper finger design was pursued, see Fig. 5c. This design proved to be too adaptable, prohibiting a proper force transfer to the object, ultimately causing the detaching process to fail. With an adaptation of the used elastomer material and cushion design, a viable solution is plausible. However, the estimated costs and poor efficiency of the air-cushion design brought about the need for a new and improved design.

This improvement was realized by exchanging the air-cushion with a polyurethane-foam. As portrayed in Fig. 5d, the gripping surface is further covered by an abrasion-resistant material in order to increase the gripper life-span . This design proved to be very successful, as the foam provides an adaptable surface, which is able to transfer the required force over a large surface, reducing object stress during unloading.

Lastly, the gripper range was increased in the tong-gripper design shown in Fig. 5e. With this design the range increased from 60%, with a gripper range of $68mm$, to 97%, with a range of $200mm$. This range of $200mm$ was primarily chosen in order to increase the gripper reach, enabling the grasping of printed objects from any position within the build volume. The gripping surface was constructed using the same cast elastomer resin, but in the form of a concave tire profile. With the added bonus of an increased gripper range and the new gripping surface profile, the tong-gripper exceeded the desired criteria.

The gripper designs were tested against each other, with the polyurethane-foam finger and the tong-gripper performing the best. However, these developed designs are prototypes and thus need to be further optimized and manufactured from a more stiff, lightweight material such as Aluminum.

C. *Strategies for detaching the object from the build plate*

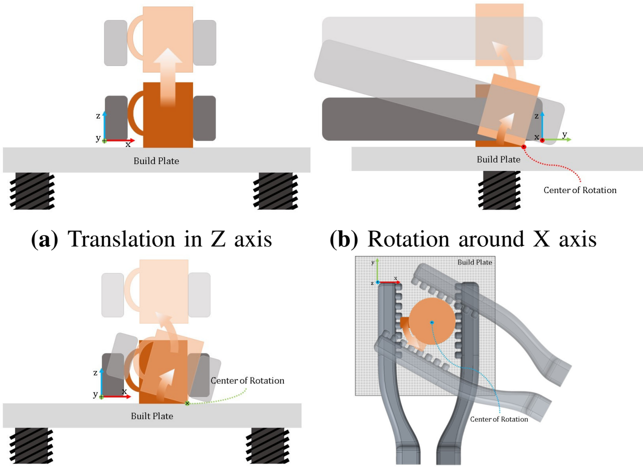
By applying the molten filament onto the build plate the material bonds together with the plate, due to the rough surface on a microscopic scale. To detach the finished object these bonding forces have to be overcome. An optimized strategy for detaching the object from the build plate of the printer has several advantages. Firstly, the object receives less harm as the stress is reduced during the removal process. This is required to provide a nondestructive detachment. Secondly, the robotic hardware is also treated with care as the forces and torques are decreased.

Three translation axes (X, Y and Z) and three rotations (around X, Y or Z axis), as well as a combination of these, can be performed to detach the object. An employee would always make use of the height of the object in order to generate leverage forces while rotating around either the X or Y axis. After some tests, this method was also implemented in combination with a translation in Z axis. As some models can be fragile, the rotation is executed over one of its edges to avoid damaging the object.

The adhesion forces between the build plate and the object can exceed the robot's load capacity, hindering a successful object removal when the wrong strategy is used. The right strategy, however, makes use of leverage forces and torques, which reduces the maximum force needed to be exerted by the robot.

IV. EXPERIMENTS AND RESULTS

We used innovative techniques to determine the necessary detachment-forces to accurately evaluate and model the detachment-strategies. To choose an optimal strategy that is



(a) Translation in Z axis **(b)** Rotation around X axis

(c) Rotation around Y axis **(d)** Rotation around Z axis

Figure 9. The four basic elements for generating the object detachment-strategies: Executing a translation in Z axis (a) a rotation around one of the axis X (b), Y (c) or Z (d).

used for the current object, an analysis of the given GCode is implemented. After the analysis the utilized hard- and software is described briefly and a life-span test is executed with the promising gripper finger approaches.

A. Detachment Force Analysis

In order to determine an estimate of the required detachment-force needed to detach a printed object, with a given surface area, from a build plate, an analysis was conducted similar to that of Teliskova et al. [23]. As portrayed in Fig. 10, five objects were printed upon the build plate. These were detached from the build plate with the use of a force-gauge and a vertical and horizontal pull. The worst-case scenario of a vertical detachment from the build plate is displayed in Fig. 10 showing multiple positions and varying surface areas. At one thousand millimeters squared, only position three was further pursued as the build volume of the selected printer was too small for all five positions and the other positions exhibited a decline of required forces. Upon analysis it can be said that this is due to the uneven build plate, which is not perfectly parallel to the nozzle plane. Minute differences cause the adhesion forces to change, mostly decreasing, due to an improper binding of the material to the build plate. Therefore the presented trend-line should only be used to estimate an approximate required detachment-force, in N, for the worst-case scenario of a vertical pull.

B. GCode Analysis - Getting the object's position

Regarding the different proposed detachment-strategies, the robot has to be aware of the object's position. This is usually set by the user during the slicing process as well as the scale of the object itself. Combined with the added support structures, the printed object's dimensions differ

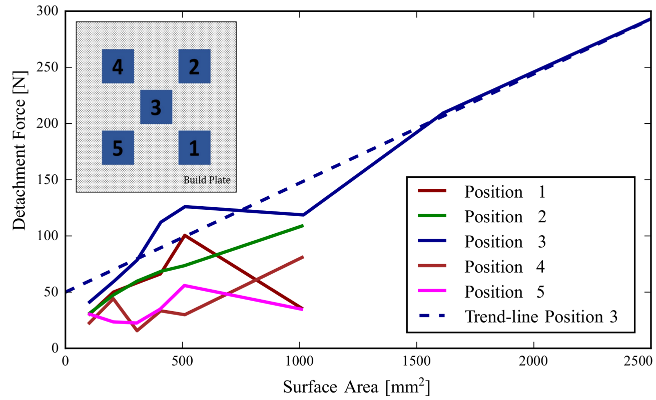


Figure 10. The evaluation of the detachment force was based on the position and contact surface area between the object and the build plate, to estimate the unloading behavior in future detachments (as described with the Trend-line Position 3).

from the designed object. To determine the real position and dimensions on the build plate an algorithm analyzes the GCode of the printing job. GCode is the most widely used numerical control programming language [24]. It is used to control the printer, containing all necessary parameters and movements to manufacture the object.

For each layer the algorithm checks the paths of the print head to calculate the position on the build plate as well as the dimensions in X, Y and Z. Once the position and orientation has been determined, the algorithm further calculates the required grasping position, as well as opening and closing gripper widths, in order to ensure an optimized removal of the 3D printed part. This is done to reduce stress on the involved parts, making the unloading process as efficient as possible. With the determined information, the object can be removed from the build volume of the printer using an optimized detachment-strategy using inverse kinematics, as described in the section III-C.

C. Sticking everything together

In order to apply the concept and use the designed gripper fingers we utilized a Universal Robots UR5, with a maximal 5kg payload, in combination with a Schunk PG 70-Plus gripper, with $68mm$ of grasping range. Both of these are controlled with the Robot Operating System. This system was chosen, because it is one of the most rapid ways to set up a demonstrator. As the maximum payload of the robot arm is 5kg and the gripper weighs around 1.5kg with accessories, there are only 3.5kg left for handling the printed objects.

Most of the printed objects are small and light, but to detach the object from the build plate the torque of the arm is needed. In a state machine the software periodically checks the current state of the printer over an interface. When the job is done, the GCode analysis algorithm downloads the GCode from the printer backend and calculates the position as well as the dimensions of the object. Now the grasping position is known and the robot can start to detach the object. For this the gripper is set to the specific opening width. Afterwards, the robot moves inside the build volume of the printer. When reaching its final goal the gripper closes and gets in contact with the object. A check, whether the gripper is closed and has an object between its gripper fingers, determines if the robot should start to execute its detachment-strategy. If so, it is executed and the object is detached from the build plate; checked for successful detachment by assuring that the object is within the gripper fingers; and upon a successful detachment, automatically placed at a defined area.

D. Life-span test

As 3D printing objects takes a considerable amount of time, and the designed grippers and detachment-strategies require extensive testing, an experiment setup was devised that requires less time, not having to wait for each print to finish. The goal of this setup is to test the detachment-strategies along with the gripper behaviors, such as the gripper finger wear, usability, efficiency, and life-span. The experiment was conducted by use of a ferromagnetic surface along with magnets attached to a 3D printed object, as shown in Fig. 11. In order to represent the adhesion forces, magnets of varying strength were attached to a benchmarking 3D printed object, Benchy, which was placed upon the ferromagnetic surface. The maximal force which can be overcome with each gripper setup, grippers, and detachment-strategies were thoroughly analyzed with the worst-case scenario presented above. It was determined that the setup is only acceptable as an estimation of the system behavior, during the detachment-process, as the magnets enable a translational movement upon the ferromagnetic surface, unlike the adhesions forces exhibited on the object and build plate. Furthermore, the UR5 was at its limits with the analyzed magnetic force of roughly $42N$.

To perform a life-span test and evaluate the gripper finger wear, the benchmark object with the attached magnets was placed upon the ferromagnetic surface; removed from the surface using a given detachment-strategy and gripper; and placed upon the surface once more. This process was repeated for each detachment-strategy and gripper more than two hundred times. The resulting wear of the cast burling gripper fingers is depicted in Fig. 12. With these gripper fingers the wear is minimal. The foam damped gripper fingers, however, showed great wear. In order to counteract this, a protective cover was implemented, greatly improving the gripper life-span.

Upon completion of the tests with the ferromagnetic surface, the detachment of a 3D printed object from the printer build plate was tested several times using the best gripper setup, which included the cast burling, foam-damped, and tong-grippers. These tests were executed with a variety of 3D printed objects of varying sizes and shapes. Most of the tested unloading procedures were successful, affirming the efficiency of the procedure and tested gripper fingers. Thus, this automated grasping of 3D printed parts presents one of the first successful approaches so far.

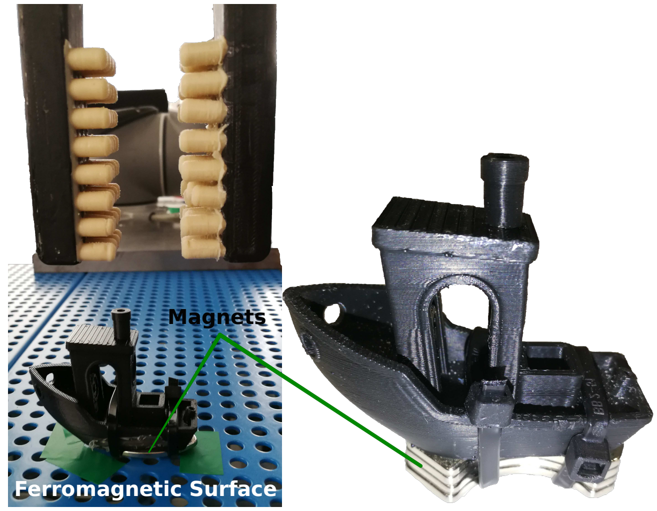


Figure 11. The adhension forces between the printed object and ferromagnetic surface are simulated by adding magnets to the 3D printed object to be able to evaluate the proposed gripper fingers and detachment-strategies with short cycle times.

(a) Burling elastomer profile before the life-span test.

(b) Burling elastomer profile after repeated usage.

Figure 12. A close up before and after the cast burling gripper finger was evaluated, showing little wear after more than 2000 use cycles.

CONCLUSIONS AND FUTURE WORKS

This paper highlights the need for automation in additive manufacturing. We have found an innovative solution for improving the way of handling printed objects by adding a service robot to the process. The possibilities of an automated unloading of the printed models, with a flexible gripper system, saves time and resources. Furthermore, the worker is unburdened as he can spend less time in the unhealthy environment. The present findings may help to improve the 3D printing process and results, by lowering the costs of prints and leading to an increase in the amount of prints within a given time. To further our research we plan to improve the algorithms to be able to handle more than one print object on the build plate.

Moreover, other manufacturing techniques such as SLS or SLA will be regarded, as they are widely used in the industry. Lastly, the robot will be placed upon a mobile platform to enable working with more than one machine. All in all there are still challenges in handling the objects, however, those are a part of our future research.

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