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Automated Extraction of 3D Printed Parts from Unfused PA12 Powder using a One-Shot 3D Printed Compliant Gripper*

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Abstract—Automated individual part extraction from powder based 3D printers has the potential to save time and cost compared with fully manual part extraction, or part sorting following automated bulk separation of parts and unfused powder. This work details the development of a novel one-shot 3D printed compliant gripping mechanism, able to extract individual solid parts from unfused PA12 powder. It was found that the unfused powder causes grip slip and instability as well as an increase in the perceived object width. A new toothed digit geometry was created, able to reduce the duration of the instability, and localised vibration was shown to eliminate the initial period of increased strain. A combination of toothed geometry and localised vibration showed a relative strain output on the gripper almost identical to that of the same grasp with no powder present. This allows individual solid parts to be extracted from unfused powder in a known pose, ready for automation of subsequent post-processing steps.

Index Terms—Additive Manufacturing, Compliant Joints and Mechanisms, Grasping

I. INTRODUCTION

S 3D printing continues to become more popular for high A volume manufacturing, the desire for automation also increases, with the goal of reducing manufacturing time and cost. SmileDirectClub currently produces 40,000 individual dental molds a day across 60 HP Multi Jet Fusion (MJF) powder based 3D printers [1]. Without automation, each one of these molds must be manually extracted from the printer before any post-processing can begin. Machines such as the HP Automatic Unpacking Station [2] allow small-to-medium sized 3D printed parts such as dental molds to be separated from the loose unfused powder which surrounds them at the end of the 3D printing process using a combination of vibration, vacuum, and air blasting. Although this machine, and similar ones for other powder processes, do successfully separate the printed parts from the loose unfused powder, they are not a perfect automated extraction solution. For some parts, such as 'green' state parts (3D printed metal

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powder parts before sintering) and delicate polymer parts, these machines may damage or destroy the parts during the automatic unpacking. The current methods are also not ideal for automating subsequent part handling or post-processing steps, as all of the 3D printed parts end up in an unknown pose. Automatically extracting the 3D printed parts directly from the unfused powder whilst their pose is still known could allow for time and cost to be saved, as the individual parts would not need to be sorted from a pile before subsequent handling.

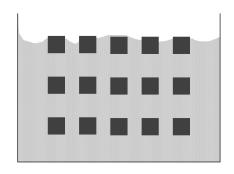


Fig. 1. MJF Printed Parts Suspended in Unfused Powder After Initial Vacuum

Figure 1 illustrates a cross-section of solid printed parts suspended in the unfused powder at the end of the MJF process, after an initial vacuum, but before manual extraction. In order to extract the 3D printed parts in a known pose, an individual extraction method would be more suitable, closer to that of the current manual extraction process. However, unlike conventional gripping tasks, issues arise when attempting to grasp an object surrounded by unfused powder. Although the theoretical pose of the object is known, conventional optical or tactile sensors which are commonly used in gripping applications make it difficult or impossible to distinguish between the object and the surrounding powder, as most current automatic gripping applications involve clean objects surrounded by air. This makes closed loop control of the gripping process difficult.

Although physical interactions between powders and other granular materials is common in many natural and man-made processes [3], there are still many gaps in our understanding of the statics and dynamics of these interactions. Kang *et al.* states, "A canonical problem in the field is the modelling of the penetration dynamics of a large object within a granular material made of much smaller, but macroscopic particles"[4].

Since no existing literature has been found on using a gripper to extract objects from a powder, more low-level research must be gathered on the individual steps in the gripping process. Another issue is that as the unfused powder is not solid or rigidly attached to the object, it can move and cause instability during extraction. When a load is transmitted through granular media the stress is not applied uniformly, it is applied along heavily stressed chains of particles (Figure 2) [5][6]. As the loading direction changes, there is a rapid reselection of this relatively sparse network of contact forces, which can result in instability [7]. As long as there is some amount of powder between the gripper and the part, there is a risk of this instability causing the part to slip as it is extracted.

As an object moves through a granular medium, a region of particles in front of the object becomes 'jammed', caused by a build up of a network of force chains [8]. Albert *et al.* showed that the drag force of an object moving through granular media is heavily dependant on the size of the object (both the frontal area and length) and much less dependant on the actual shape [9]. Changing the shape of the intruder moving through granular media was found to have an effect on the drag force an order of magnitude less than an equivalent change in shape for an object moving in a fluid. No literature was found on the interaction of two solid objects, such as a gripper and object to be gripped, with powder in between them.

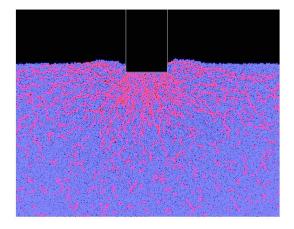


Fig. 2. Force Chains Under Flat Intruder (pink colours are part of the force chain, blue ones are not) [5]

For non-magnetic, irregular, solid objects surrounded by powder which is intended for re-use, options for gripper types are limited to those which directly make contact with, or physically grasp, the object. Common configurations include parallel or claw grippers, actuated electronically or pneumatically. Whilst conventional manufacturing may be suitable in some cases, 3D printing allows more complex geometry to be created, allowing the gripping mechanism and digit geometry to be tailored to the task of extracting objects from unfused powder, as well as the possibility to more easily modify or tailor individual grippers to specific types of 3D printed parts needing extraction.

3D printing the types of mechanisms used in conventional grippers in a one-shot process without the need for assembly

post-manufacturing is possible, but successful joint performance can easily be affected depending on the surface finish or excess material (such as unfused powder) still present after printing. Cuellar et al. details a series of joints for non-assembly 3D print fabrication, but highlighted unfused powder as having the potential to increase friction and lead to poor joint performance [10]. Cali et al. found that creating non-assembly joints using 3D printing required many careful design decisions such as creating holes or sockets in joints to allow excess material to be removed, with many calibration models needing to be printed for each joint size[11]. As almost every 3D printing process manufactures parts in parallel layers, curved surfaces in the CAD model are approximated by individual steps. This results in a 'staircase effect' on any surface which is not exactly parallel or perpendicular to the layers, which can have a negative effect on the performance of joints and faces which require tight tolerances [12][13]. Many 3D printing guides and services recommend a gap of around 0.5mm for interlocking or print-in-place parts. A gap of this size on every joint of a conventional gripping mechanism could lead to large errors and backlash at the tips. The rated backlash of many industrial grippers is an order of magnitude smaller than this gap at around 0.05mm [14].

One of the benefits to 3D printing gripping devices, is the ability to produce complex geometries which would be difficult to create using more conventional manufacturing methods. This also allows backlash to be reduced or eliminated, by removing interconnecting joints that are made of separate parts. Figure 3 shows a single piece gripping mechanism which features two coils to allow rotation of the digits[15]. The mechanism is actuated using a double effect pneumatic cylinder. This means a simple linear input motion is transferred into an opposing gripping motion, using a single 3D printed part with no joints or assembly, apart from the connection to the actuator. Blanes et al. focuses on grippers for food handling applications, and notes that the surface finish and excess material remaining in and around parts, due to the powder based printing process, was not ideal[15]. This gives an insight to some of the issues that could be faced when developing grippers using the MJF process, especially if they are to be used without going through post-processing steps such as cleaning and polishing.

Many compliant grippers fall within the category of 'soft robotics' which experience large deformations to achieve the desired movement, often controlled using integrated pneumatic actuators [16]. Whilst these soft grippers are good at grasping a wide range of object shapes and sizes, they often need to be assembled of many individual components, made from different materials [17]. Integrating some form of onboard sensing can also be more challenging for compliant grippers. Xu *et al.* [18] and Reddy *et al.* [19] both utilise vision-based systems to track deformation across a compliant gripper to help calculate applied forces, following some form of finite element analysis. Although vision-based methods are not suitable for a gripper buried or covered in powder, strain gauges can also be used to measure the deformation of compliant elements [20], which pose a greater suitability for a powder application.

In industrial applications, vibration is used to help increase

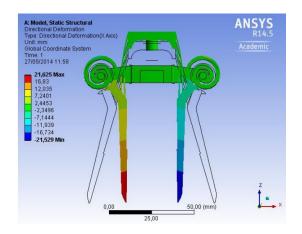


Fig. 3. Angular Gripper Mechanism [15] (MDPI open access)

the bulk density of powders and increase uniformity [21]. Dunst *et al.* showed that vibration can be used to increase the flowability of powders and separate agglomerates by reducing the internal friction forces[22]. Wu *et al.* [23], Matsusaka *et al.* [24] and Killmann and Tomas [25] showed that vibrating a powder delivery tube allowed for a more consistent and higher flow rate through the nozzle. Vibration is also used in the HP Automatic Unpacking Station to help separate the solid objects from unfused powder by allowing them to move more easily though the unfused powder. At this scale however it causes the pose of the object to become unknown, as the entire build volume is vibrated at once. This is not ideal for delicate objects, as separate objects could collide with each other within the powder, even if they were initially separate.

From this literature review, there are no studies on gripping or extracting solid objects, covered or buried in powder. This is likely due to the relatively recent application of powder based 3D printers being used for high volume manufacturing, which gives a use case for the research but also simplifies some of the issues, such as the fact that the pose of the object is already known. The aim of this paper is to create a one-shot 3D printable gripping mechanism, suitable for extracting 3D printed solid objects from within unfused PA12 powder. As the literature highlighted poor performance of 3D printed joints compared with conventional manufacturing techniques, the gripper mechanism will be based on 3D printed compliant elements. The size of the gripper digits should also be minimised to reduce the drag force present when moving through the powder. This gripper will be used to help gain an understanding of how unfused powder affects the gripping process, and what techniques can be used to improve the extraction performance.

II. 3D PRINTED COMPLIANT GRIPPER

A custom gripper (Figure 4) was designed specifically for use in an application where powder is present, with geometry that could be easily modified, and with 3D printing in mind. The geometry is designed to produce a symmetric gripping motion using compliant elements, from a simple vertical input motion when mounted to a rigid base. Relatively large distributed compliance flexible regions were chosen over smaller concentrated 'living hinges' to ensure that the deformation stayed within the elastic region during operation. The structure was designed with open spaces between the thin compliant elements, and a relatively small tip area, for minimal resistance when interacting with powder, and to reduce spaces where powder can become stuck.

The gripper is mounted to a fixture on the end of the robot arm, where a linear actuator connects to the input tab. As the input tab is pushed, the compliant elements flex, causing the gripper to open. Pulling the tab causes the gripper to close, allowing objects to be grasped. A BF350-3AA strain gauge is adhered to one of the compliant elements to measure the strain as the object is gripped. This strain gauge is connected to a HX711 amplifier, along with an un-stressed gauge for temperature compensation. For a given input displacement, a higher strain in this region indicates a larger object width whilst gripping. When actuated with no object in the grip, the change in strain in this region is negligible compared to the change in strain when an object is gripped. As the mechanism is compliant, the tips are able to align with the sides of the object being grasped to provide good contact.

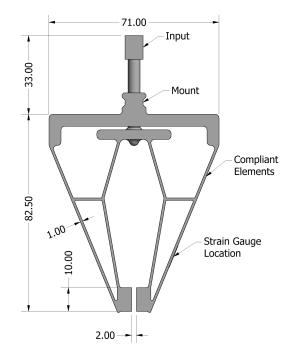


Fig. 4. Gripper Overview

Figure 5 shows a basic schematic for the gripping system. An Arduino Mega is used to control an Actuonix P16-P linear actuator through a LN298 DC motor controller. The HX711 analog-to-digital converter is connected to the stressed and unstressed strain gauges, as well as the Arduino, which logged the data.

III. GRIPPER FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) was used as part of the gripper design process, to understand the relationship between a chosen input displacement, and the resulting output displacement and motion of the compliant mechanism. Figure

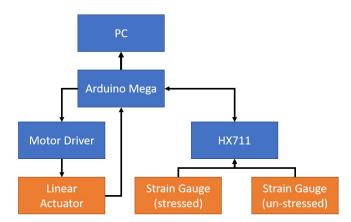


Fig. 5. Gripping System Schematic

6 shows the deformation of a compliant gripping mechanism in ANSYS 2019 R2, using a transient structural simulation. In this case, the gripper mechanism is constrained at the gripper mount, and a 2mm input displacement is applied to the input tab in the -Y direction. This causes the gripper to deform from its relaxed state, to the open state. As the compliant gripper mechanism is actuated using an input displacement and not an input force, the deformation should be consistent for any material that acts isotropically in the plane of deformation, whilst it is still in the elastic region. A stiffer material will experience a higher level of stress in the compliant regions, but the output deformation at the tips will be the same as that for a less stiff material. The simulations shown use PA12 as the material, but the deformation results were found to be the same for a series of isotropic materials.

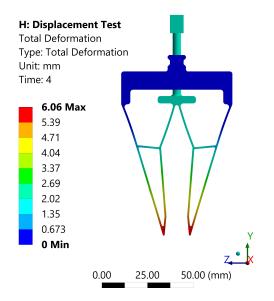


Fig. 6. Gripper FEA Deformation

Figure 7 shows the relationship between the input and output displacement of the compliant gripper. The output displacement is measured as the horizontal movement of one of the gripper tips, meaning that the largest object which can be grasped is approximately twice the output displacement of a single tip, or around 12mm in this series of tests. Although the output displacement of the tips is not perfectly parallel, the rotation is relatively small (under 5 degrees for a 6mm displacement of the tip). For the FEA, the data is plotted from a transient simulation which translates the input tab of the gripper vertically by 2mm. The directional displacement in the Z-axis (shown in Figure 6) is measured from a single element located at the lower gripping tip of the gripper. This is compared to a series of measurements taken from a 3D printed gripper. The five discrete experimental points were measured though the creation of five 'input displacement blocks' which moves the gripper input to a specific position to allow the output displacement to be measured using digital calipers. Both the FEA and 3D printed gripper show a linear relationship between the input and output displacement within the range tested, with the gradient being 2.8449 for the FEA and 2.8858 for the 3D printed gripper, a difference of 1.4%. This shows that the simulated mechanism is a good representation of the actual 3D printed gripper.

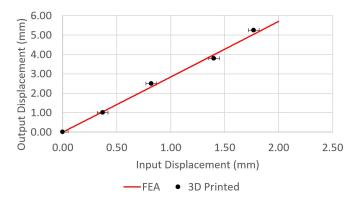


Fig. 7. Input vs Output Displacement for FEA and 3D Printed Gripper

IV. TEST SETUP

To test object extraction from powder, a 30x30x30mm cube with a 24x15x5mm tab on the top face was 3D printed using the HP MJF process in PA12. As the gripper digits are smaller than the object tab which is to be gripped, full contact between the gripper and object is made during the grasp. This clean object was then placed into a tray and covered in unfused virgin PA12 powder (Figure 8). Virgin PA12 powder was chosen, as opposed to powder which had already been used for printing, as although the flowability of recycled powder is lower, it has also been shown to be less consistent [26], and the powder recycle rate is not always fixed which could affect results. Galati et al. showed that the molecular structure, shape, and surface of the used/recycled powder is unaltered compared to the virgin powder [27]. A UR5 robot arm [28] with the custom 3D printed compliant gripper was used to reach into the powder to extract the object. Once lifted, the robot arm moves to the side before releasing the object. As the location of the object within the powder is known, extracting it using the gripper and robot arm is automated, requiring no manual input from the user other than to start the test. Throughout the test, the strain output is logged by the Arduino for later analysis

on a PC. Figure 9 shows the physical test setup used. One of the 3D printed grippers is shown in Figure 10, mounted to the end of the actuation unit. The wires from the strain gauges are mounted fairly loosely to prevent them from being pulled during operation, and they attach to the HX711 board just out of frame above the gripper.



Fig. 8. Object in PA12 Powder

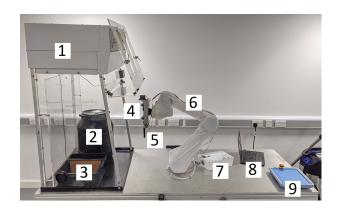


Fig. 9. Test Rig. 1: Fume/Particle Cabinet. 2: Powder Storage. 3: Test Tray. 4: Actuator. 5: Gripper. 6: Robot Arm. 7: Gripper/Actuator Controller. 8: Laptop. 9: Robot Control Pendant

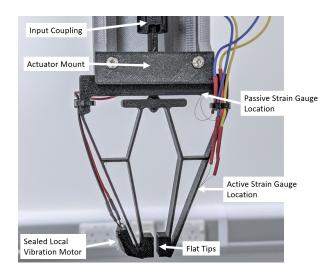


Fig. 10. 3D Printed Gripper

V. STANDARD GRIP TEST RESULTS

Figure 11 shows the strain output from gripping the object with no powder present. It can be seen that the strain rises just

before 10 seconds as the object is gripped, where it remains almost unchanged until it is released. The small rise in strain at around 20 seconds is due to a horizontal movement of the robot arm as part of the object extraction path, causing a slight change in the reaction force and an increase in strain on one side of the gripper. The test was carried out six times, with each showing a similar output, both in the overall trend and scale of the strain output. As the strain gauges are not calibrated to show microstrain, the strain output for this graph, and the ones which follow, are scaled relative to the average of this test with no powder present. This is done by dividing the raw strain output for each test by the raw strain output during the grasp test outside of any powder.

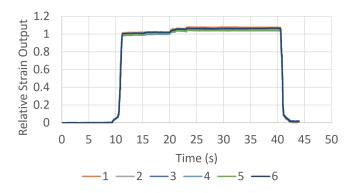


Fig. 11. Object Grip Outside of Powder

Figure 12 shows the strain output from gripping the same object but this time completely covered in unfused PA12 powder. It can be seen that there is a high initial strain output relative to the test with no powder, followed by a period where the strain slowly declines until it reaches a steady output until the object is released. The initial flat region of high strain is due to an equilibrium between the applied grasping force, and the compacting of the powder around the object before it is moved. As soon as the gripper begins to move upwards (at just after 15 seconds) to extract the object, the force chain network through the powder, between the gripper and the object, becomes unstable and the digits are able to move again. During this region where the strain output declines, unfused powder is continuously falling from between the object and the gripper as it is lifted (Figure 13), causing the part to slip, until a stable force chain network through the powder is found again. Although in these tests the object did not completely fall, it is visibly more unstable in the grasp. It should also be noted that after this period of slip, although the strain plateaus it does so at a higher level than would be expected for that object width if no powder was present. This is due to the fact that there is still some amount of powder between the object and the gripper, causing the strain output to equal that of a larger solid part. Although the overall trend is consistent for each of the six tests, the exact slip speed and behaviour during the region of instability was not consistent.

This initial test shows that although it is possible to successfully extract 3D printed solid objects from within PA12 powder with a 3D printed gripper, there is instability in the grip, and the perceived object width is much larger than expected

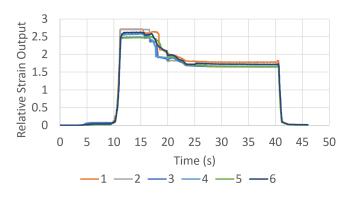


Fig. 12. Object Grip Inside of Powder



Fig. 13. Object Slipping in Grasp

(around 2.5x). Simply increasing the gripping force does not necessarily help either of these issues, and excessive gripping force is not ideal for delicate parts. The increased strain experienced by the gripper will also reduce the the fatigue life, due to an increased stress level. This means other methods of reducing the slip and perceived object width without increasing the gripping force would be most beneficial.

VI. TOOTHED GRIPPER

One way to increase the stress on the powder without increasing the overall squeezing force on the object is to reduce the contact area of the gripping face. To do this, a 'toothed' gripper was created, by adding a series of tabs extending perpendicular to the face of the gripper (Figure 14). There are four tabs on each side of the gripper, each being 0.6mm in thickness, with a depth of 5mm. This increase in stress applied to the powder should allow the digits to pass through the powder close to the side of the object more easily.

VII. TOOTHED GRIPPER TEST RESULTS

Figure 15 shows the strain output from grasping a series of object widths from 3mm to 9mm with the flat and toothed grippers. It can be seen that both follow the same trend, with an error trend that decreases as the object width and strain increases.

Figure 16 shows the strain output whilst gripping the same object as before, but with the toothed gripper. It can be seen that there is an initial rise in strain much greater than what would be expected with no powder present (2-2.3x), but this time once the object is moved there is a rapid movement

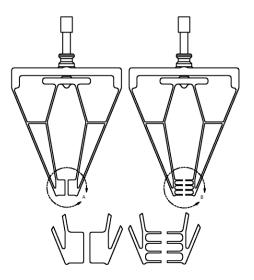


Fig. 14. Flat vs Toothed Gripper Geometry

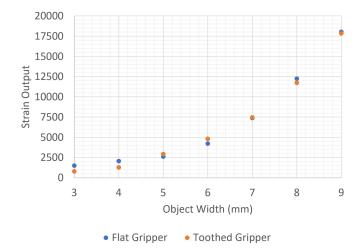


Fig. 15. Flat vs Toothed Gripper Strain Response

of the tips as the powder becomes unstable, instead of a prolonged region of gradual slip. Although the instability is not completely removed, the only time it happens is when there is a change in direction such as the object being lifted (just after 15s) or being moved to the side (at around 20s), as this causes the force chain path through the powder to become unstable, but a new one is always quickly found, unlike with the flat tips.

VIII. DIGIT VIBRATION

As shown in the HP Automatic Unpacking Station, vibration can aid in separating the unfused powder from the 3D printed objects, but it causes their pose to become unknown. Localising vibration to the tip of the gripper should allow it to move more easily through the powder immediately surrounding the object, but without a change in the pose of the object to be gripped, or those which may surround it. To achieve this, a small sealed brushed DC vibration motor (Figure 17) was mounted to the end of the digit, which can be activated during the gripping process. The vibration frequency of this motor

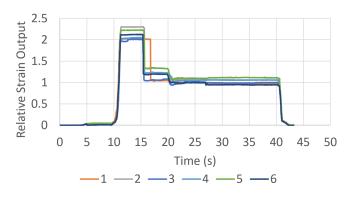


Fig. 16. Object Grip Inside of Powder with Toothed Gripper

is approximately 200Hz at 5V. For the following tests, the vibration is enabled as the gripper began to close, and disabled approximately one second after the object is gripped.



Fig. 17. Mini Disc Vibration Motor

IX. DIGIT VIBRATION TEST RESULTS

Figure 18 shows the strain output from gripping the same object surrounded by PA12 powder with the flat tip gripper, but with vibration. It can be seen that vibrating the tip as the object is gripped removes the large initial rise in strain and subsequent slipping that occurred in the previous tests. There are still some slight changes in strain as the vibration is enabled and as the object is moved, but these are relatively minor compared to the large increase in strain for same test without vibration. For the gripper with flat tips, the addition of vibration did not cause the tips to move any closer to the object by the end of the test.

Figure 19 shows the strain output from an identical test, but with the toothed gripper. This setup shows the same overall trend as the flat tip gripper, but this time, the strain output does not rise higher than what would be expected when gripping the object with no powder present. This means that no slip occurs as the object is extracted, and the perceived object width is identical to that of the same object with no powder present.

Figure 20 shows the averaged strain output from each series of tests. Here it can be seen more clearly how the toothed tip geometry reduces the overall increase in relative strain output, and how the vibration reduces the initial rise and subsequent slip of the strain output. It also shows clearly how the combination of toothed geometry and vibration results in essentially the same relative strain output as when no powder

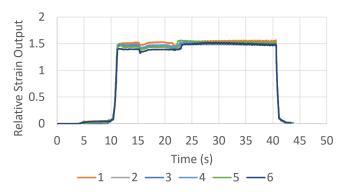


Fig. 18. Object Grip Inside of Powder with Flat Gripper and Vibration

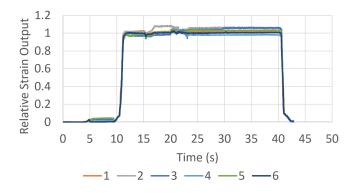


Fig. 19. Object Grip Inside of Powder with Toothed Gripper and Vibration

is present, eliminating the instability and increased perceived object size.

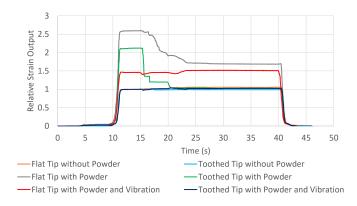


Fig. 20. Comparison of Averaged Strain Output Results

X. CONCLUSION

This research has shown that it is possible to individually extract solid 3D printed objects from within unfused PA12 powder. A novel one-shot 3D printed compliant gripper was developed, with FEA being used as part of the design process to simulate the mechanism deformation. This gripper is effective at transferring a linear input motion to a gripping motion, allowing it to reach into unfused powder and extract solid objects. It is also shown that when attempting to grip an object surrounded by unfused PA12 powder, with a standard flat digit tip, some amount of powder becomes stuck in between the digits and the object which causes the perceived object size to be larger than in reality. This powder also results in prolonged instability and slip when attempting to extract or move the solid object. To reduce or completely eliminate both the increase in perceived object size, grip instability and slip, a combination of toothed tip geometry and localised vibration can be used to allow the gripper digits to move through the unfused powder to grasp the object more closely. This increase in gripping performance allows the objects within the powder to be extracted in a known pose, allowing for easier automation of any subsequent post-processing of parts printed using powder based processes.

XI. FUTURE WORK

For this study, only virgin PA12 powder is used for surrounding the printed objects. As other studies have shown that the flowability of recycled powder lower and more inconsistent than that of virgin powder, further testing would need to be conducted to show exactly how the results shown in this paper are affected by differences in powder properties such as flowability. Further testing could also highlight the need for different tooth sizing or vibration strength to give ideal performance. Other geometry such as rounded pillars could be tested and compared to the flat horizontal toothed geometry used in this paper, to determine the best shape for moving through the powder. An enhanced control system which uses strain for closed loop control could also allow delicate objects to be gripped without applying too much force. Although this paper focuses on extracting 3D printed objects from unfused powder, the techniques developed could be applicable to other non-ideal manipulation scenarios, such as archaeology where dirty, potentially delicate, objects are extracted from the ground.

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