A FLEXIBLE RAPID PROTOTYPING CELL

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Abstract

Rapid prototyping systems have demonstrated high flexibility in terms of creating complex geometry parts. Improvements in accuracy and material properties enable rapid prototyping to become a widely used and important part of the product development process. Further applications and further improved performance can be achieved by combining rapid prototyping machines with conventional machine tools to form flexible manufacturing cells. One way to form such a cell is to integrate with industrial robotics. This paper will describe work carried out using an ABB IRB 1400 industrial robot in conjunction with a DTM Sinterstation 2000 to form a Flexible Rapid Prototyping Cell.

Keywords: Rapid Prototyping (RP), Selective Laser Sintering (SLS), Surface Finishing, Robot.

1. INTRODUCTION

Industrial robots play an important role in automated manufacturing systems. In such systems, materials processing machines are linked together by industrial robots and automated guided vehicles. It is logical to consider Rapid Prototyping (RP) as part of a longer process chain, which makes use of RP's speed and ability to create complex geometry. Robots are capable of integrating with conventional RP machines to produce flexible manufacturing cells [1]. Such cells could be regarded as Flexible Rapid Prototyping Cells (FRPCs).

The purpose of an FRPC is to achieve further automation in prototype manufacturing. Rapid prototyping machines are highly flexible in terms of creating complex geometry. In many cases prototypes built by RP machines have to go through a series of post-processes before they can be delivered to the customers. In the case of DTM's Selective Laser Sintering (SLS) process, the most important post-processes are prototype removal, prototype handling, waste material handling and surface finishing of prototype. The handling of finished parts as well as unused materials have to be carried out manually. Due to variations in the SLS process and geometry related issues, tolerances within the prototype will vary and human errors in post-processing may also result in poor overall accuracy. Furthermore, the amount of manual effort spent on post-processing restricts the usefulness of RP technology. Because of the wide range of purposes for RP parts and the geometrical complexity, most RP post-processing must be performed manually.

Rapid prototyping machines are not designed to work automatically with other specified working platforms. However, re-engineering a rapid prototyping machine so that it was capable of working with a robot would be a relatively trivial task in many cases. Some robot configurations are specifically designed to mimic human arms (revolute coordinate systems) and as such can carry out many of the complex handling tasks normally restricted to manual operations. This paper will go on to discuss modifications that can incorporated to solve some of the problems in the SLS process. Previously manual tasks can be facilitated by the integration of a robot arm on SLS RP technology. Experiments were focus on a DTM Sinterstation 2000 and ABB IRB 1400 industrial robot.

2. BRIEF REVIEW ON SLS POST-PROCESSES

After a prototype is built in the SLS machine, it has to go through a series of post-processes, which are usually carried out manually. First the powder cake must be transferred from the SLS machine to the Rough Break Out (RBO) station. The RBO station assists with sorting out parts from loose powder and collecting unused powder. Prototypes are then moved to an abrasive-blasting machine where powder that sticks on the prototype surface is removed. Powder trapped in tight corners and holes is not easily removed by this method and manual cleaning of the part is often required. Coating and infiltration can help improve the surface quality, which is normally achieved by dipping the prototype into a polymer resin solution and then drying it. Finishing the prototype to the required roughness is usually achieved by using abrasive paper. Finally primers, paints and other surface coatings are applied if required.

3. HANDLING OF PARTS

To obtain parts from the SLS machines automatically would not be a difficult task, if all that is required is simple transport of the whole powder cake to the RBO station and separation of the prototypes and powder. However if it were necessary to carry out other automated tasks, then it would be useful to have some method for maintaining registration of position and orientation of the prototype. Using a support system can solve this problem. Many existing RP machines use supports to fix parts to the build platform, maintaining position and orientation relative to the platform. Examples include Stereolithography (SLA) and Fused Deposition Modeling (FDM). SLS does not normally require supports because unsintered powder surrounds the prototype, giving it an advantage over other processes. However when sorting out SLS prototypes from the powder cake, powder must fall away and parts will shift in relative position. Using a robot arm to catch the prototype at this time would require sophisticated detecting devices and control units. Even so, the robot may be able to detect and clamp the part, but may not be able to maintain registration on the position and orientation.

3.1 Support Structures

The role of the support is to link the object with the part piston. As a result, the relative position and orientation between the part and the part piston is always known. The primary function of SLA and FDM supports is to maintain the position during the build time and prevent the collapse of overhanging structures. Since the purpose of the SLS supports is different, they will have different design concepts. The supports used in SLS for the FRPC would have the following requirements:

1. Maintain the part's relative position and orientation to the part piston.
2. Provide a means for the robot arm to clamp the part accurately.

3.2 Fixture

In this project, a fixture system was designed to fulfill the above requirements. Fig3.1a shows the components of the fixture system. The fixture system consists of a platform, a handle for the robot, and a base. The base is bolted to the Sinterstation part piston. The platform and the handle are fixed together to form a single part, and there is no relative movement between the two. There are pinholes under the handle, which mate with the pins above the base. Once the handle is fitted, only upward movement is allowed.

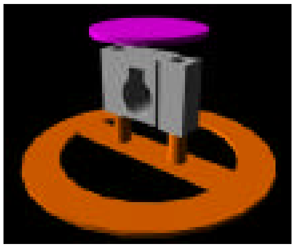

Fig 3.1a

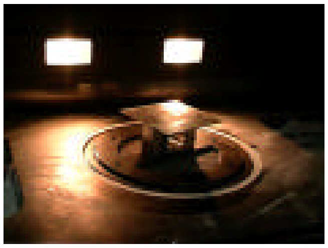

Fig 3.1b

Fig 3.1a, CAD drawing of the fixture system showing the platform (top piece), handle (middle), and the Pin (bottom). Fig 3.1b, the fixture is installed inside the Sinterstation 2000.

Before building the parts, the fixture system is installed into the machine. The machine startup process is mostly the same as usual, except the level of the part piston is adjusted until the platform surface of the fixture system is level with the build plane. The inclination and the flatness of the platform should be carefully adjusted since any part of the platform higher than the lowest level of the roller will result in build failure. However no part of the platform can be too low, because if this happens the first layer of powder above the platform will be too thick to penetrate by laser and the part will not adhere to the platform.

Experiments have been carried out to prove that it is possible to start sintering on such a platform. Figs 3.2a and 3.2b show blocks attached to a platform. In order to achieve this, the piston level has to be adjusted precisely. Furthermore different laser powers and scanning speeds have been tested. For the DTM Sinterstation 2000 used, laser power was set to 14 (about 9W), having normal scanning speed, when Duraform is used. This is higher than the normal laser power used for Duraform, which is around 7W.

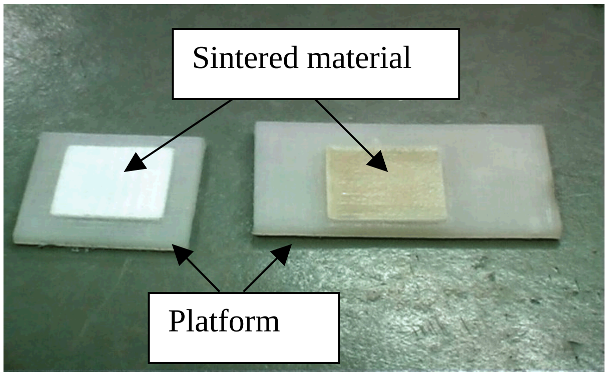

Fig 3.2a

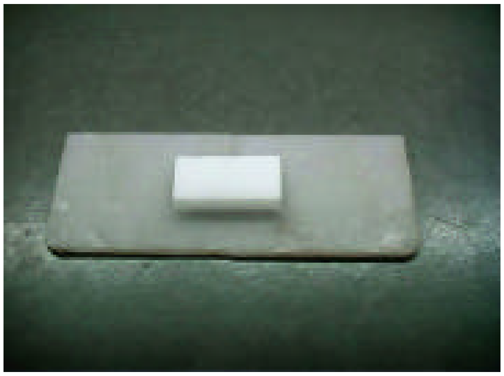

Fig 3.2b

The function of sintering the first layer of powder above the platform is to build a support structure between the parts and the platform. This structure provides a rigid linkage between the part and base. Fig 3.3a to 3.3e show the sequence of operations.

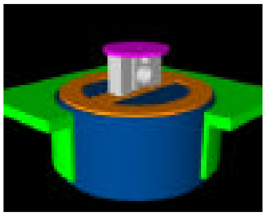

Fig3.3a

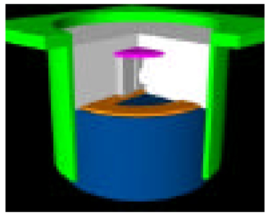

Fig3.3b

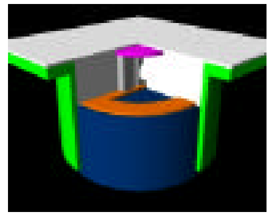

Fig3.3c

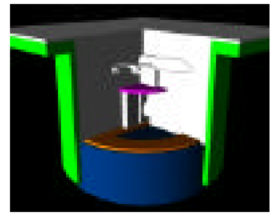

Fig3.3d

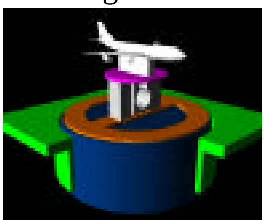

Fig3.3e

Setup the fixture as shown in Fig 3.3a, and then immerse the system in the powder as shown in Fig 3.3b. Control the layer thickness above the platform. Start building in the chamber. Finally the part is built with the support attached to the platform (Fig 3.3e).

4. REMOVAL OF WASTE MATERIAL

Two strategies are applied to remove the material from parts. The first approach is used to remove large amounts of unused powder for recycling. Installing a built-in vacuum cleaning system into the SLS machine is an obvious solution. The only problem would be to redesign the build chamber to reduce the effect of contaminating structures inside the chamber. This process aims to remove up to 80% of the unused powder.

The following section shows an example of how to redesign the part piston, based on the concept of pipe installation. Fig 4.1 shows that the pipes are installed to surround the part cylinder. These pipes are connected to filters and a suction device. The system is constructed to suck the powder whilst the part piston is rising. Fig 4.2 shows the operation of the system. By using this built-in design it will be very difficult to upgrade the existing equipment, but the concept can also be realised by using an external device. Fig 4.3 shows the structure of the external device. Because several kinds of powder can be used in the SLS machine, changing the external device eliminates the problem caused by contamination of powder inside the pipes.

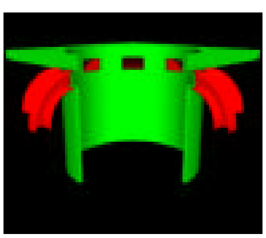

Fig4.1

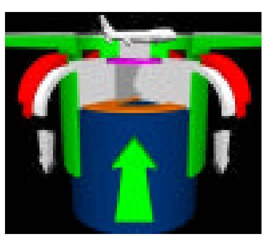

Fig4.2

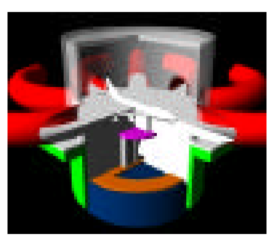

Fig4.3

Fig4.3 shows a transparent shell with pipes connected as an external device. The working principle is similar to the one shown in Fig4.2

Using this system, it may be difficult to remove the powder close to the parts' surface. This will be done after the parts and the fixture have been taken out of the Sinterstation. Development of a brushing machine to clean the parts in all directions is one possible solution for further removal of powder. The idea of using sand blasting is also possible by installing a nozzle onto the robot arm. A further possibility would be to use centrifugal force by rotating the part at high speed, so that the powder on the parts' surface will eventually detach.

5. REMOVAL OF PARTS FROM THE MACHINE

There are occasions when it is not necessary to use a part fixture within the Sinterstation. If we simply want to collect the parts, and do not care about their position and orientation after they have been taken out, then the support and fixture system mentioned before is not required. However by doing this, registration of position and orientation will be lost. So, as far as possible, a fixture should be included as standard equipment of an FRPC and a support must be built unless the geometry of the part is too difficult to have supports under it.

Recall the procedure used so far. After using the vacuum cleaner to extract most of the powder for recycling, the fixture and the parts would be taken out by using a suitably equipped robot arm or other transporting device. Another advantage of using a fixture is therefore the elimination of the need to design grippers for clamping different kinds of parts.

The parts and the fixture are taken out and placed on another working platform. In this working area, cleaning and finishing of parts will be carried out. The fixture would be used to register the position of the part in the work area.

6. PARTS FINISHING

6.1 The part accuracy

There are four major elements that may affect the part accuracy. The CAD model approximation, distortion caused during building, stair-step effect on curved surfaces, and surface roughness resulting from the process used [2].

CAD model approximation errors are differences between the desired model geometry and model geometry obtained by the RP machine. The popular STL file format uses triangular facets to approximate the actual model. When dealing with straight lines and planes, the error is small, but if STL is used to approximate curved or freeform surfaces the tessellation process can generate larger errors. Increasing the mesh density can minimize this problem, but the file size will become larger since the number of triangles required representing the surface is increased [3].

Distortions are changes of geometry during or after the building process. Curling, Glazing and Bonus-Z are common problems in SLS machines [4]. These problems are reducing as a result of improvement in properties of new materials.

Stair-step is a problem faced by most RP machines. Since nearly all RP machines use the concept of layering, if the layer thickness is too high then the error is large and the resolution decreases. If the layer thickness is decreased, the errors can be reduced but the build time increases. Sometimes reorientation of building direction can help reduce the stepping problem.

6.2 Conventional parts finishing

Most SLS parts will go through a manual finishing process aimed at improving the surface quality. Abrasive papers and other additives are applied in this case. Finishing of parts can be achieved by using additive techniques and subtractive techniques. Additive techniques may include the application of coatings, protective layers or surface strengtheners. These coatings or layers may be removed after all the processes have finished or just left on the surface. Subtractive techniques may include milling, turning, drilling, polishing, blasting and grinding. All these process may cause a loss of material. Also it is worth mentioning that both additive and subtractive methods can be applied in a selective area or over the entire surface.

6.3 Robot finishing

Most SLS prototypes have a need of surface polishing and finishing in post-processing to improve the surface quality [5]. The geometric sensitivity of robots provides sufficient potential for performing finishing tasks. When compared with CNC, robot arms usually have larger work envelopes and more degrees of freedom, which enable them to tackle tasks that require complex geometrical manipulation. The tasks here are similar to those used in robot sculpting and finishing [6]. Besides milling and grinding, the robot arm can also act as a device for applying coating in selected regions.

Experiments have been carried out to investigate the effects of coating and the robot finishing process on surface roughness of the prototypes. Prototypes made of nylon composite have been used. The procedure was to apply coating on the prototype's surface, and then tools held by the robot arm finished the surface. The coating material used was a cyanoacrylate based adhesive. The tools used were modified grinding tools with spring-loaded mounting. Coating material infiltrated into the porous structure of the surface. Voids on the surface were blocked and the surface hardness increased. Durometer Type D was used to measure the hardness of the surface and it was recorded that after applying the coating the hardness increased from 62 to 75. These characteristics help achieve lower surface roughness after finishing since hard and brittle surfaces can attain better surface quality after finishing than soft and tough ones.

It should be noted that if voids appear on the surface, the roughness will increase. Fig 6.1 shows the cross-section of a specimen finished without applying coating. Voids appear on the surface. Fig 6.2 shows the cross-section of a specimen coated with adhesive. Voids on the surface are occupied by the adhesive. It can be seen that application of the adhesive reduces the number of voids appearing at the surface after finishing.

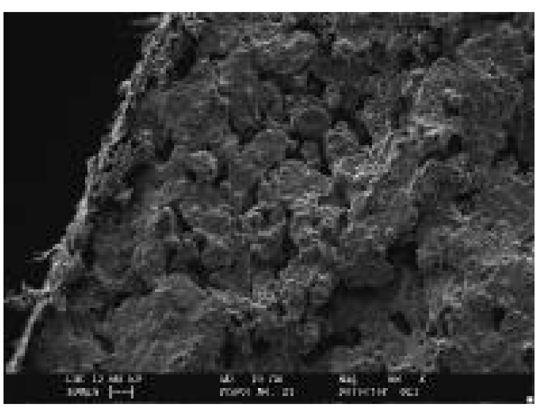

Fig 6.1

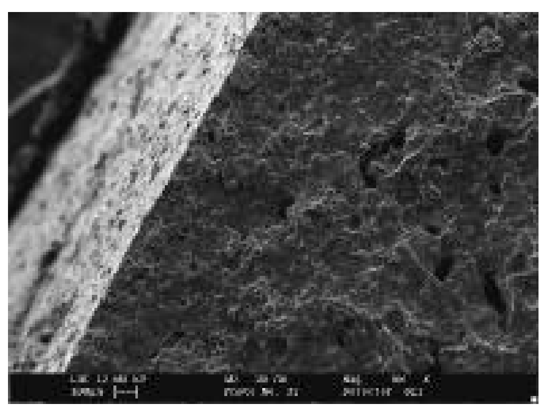

Fig6.2

After a model is designed, two kinds of files are generated for different purposes. These files are STL and Cutter Location Source File (CLSF) files. RP machines read STL files for building the prototype. CLSF files record tool paths generated by CAM software. These contain parameters like tool positions and orientations. Tool position is described by a tool center point in the

Cartesian coordinate system, while tool orientation is described by vector notation. For robot finishing, a CLSF file cannot be used directly. The robot controller has its own programming language named RAPID [7]. In RAPID, the user defines a user coordinate system and an object coordinate system to coincide with the coordinates used in CLSF file. The relative position and orientation is determined by calibration of the workpiece and the tool coordinate system is determined by calibration of the tool. RAPID uses Euler angles to describe the orientation of the tool and uses a quaternion to describe the orientation of the workpiece.

The tool path generated is translated from CLSF file to a RAPID (PRG) file. The robot has 6 degrees of freedom. 5 degrees of freedom are sufficient to determine the position and attitude of the tool [8], since the tool is rotational and its axis of rotation is along the 6^{th} axis. To finish curved surfaces with the tool axis normal them, a 5-axis robot finishing technique is required.

Fig 6.3 shows the layout of the robot finishing platform. A prototype is fixed on a fixture, which is located within the working area of the robot. The robot carries the tool, which is spring-loaded. Fig 6.4 shows the details of a spring-loaded tool. This kind of tool restricts the pressure applied to the surface. The pressure can be adjusted by changing the spring. In experiment the pressure used was between 20 and 30 kPa. Use of a spring-loaded tool also enabled better contact between the tool and the surface. This is important since it is assumed the prototype built by RP machine will have dimensional errors due to different kinds of distortions. If a rigid tool is used, the tool tip is difficult to trace over the surface. Interference and clearance may occur during the process.

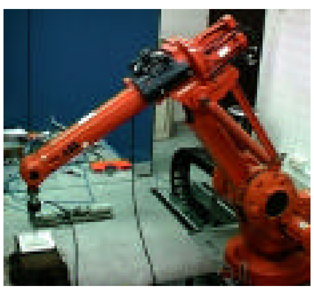

Fig6.3

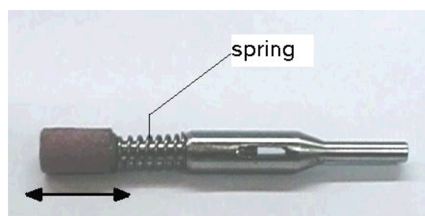

Fig6.4

7. CONCLUSIONS

A method for integrating a DTM Sinterstation 2000 with an industrial robot (ABB IRB1400) has been described. It has been found that this combination is feasible to realize a Flexible Rapid Prototyping Cell (FRPC), because most of the technologies required have already been developed. The prototype can be built using a fixture platform in order to maintain the prototype's position and orientation. Finishing of surfaces can be automated by industrial robot.

The conditions for using a fixture within the Sinterstation have been studied. This includes the design of the fixture, the process environment (part bed temperature and laser power) required and the control of part piston height.

5-axis robot finishing techniques have been studied. This includes the orientation transform function between the CLSF file and robot PRG file, because CLSF uses tool axis vector notation while PRG uses Euler angle system. The calibration of tool and workpiece has been studied as well. Furthermore the use of compliant tools has been studied.

The use coating to improve prototype surface quality has been studied. Application of cyanoacrylate based adhesive on the prototype surface is followed by abrasive finishing. Roughness is decreased when compare with abrasive finishing alone.

The combination of the SLS RP technology with robot handling and sculpting appears to be a technical problem that can be achieved. Further study will attempt to establish how much time and manual effort can be saved using this approach.

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