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Selective Laser Sintering Adaptation Tools for Cost Effective Fabrication of Biomedical Prototypes

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Abstract

Purpose – In recent years, Selective Laser Sintering (SLS) has been used in the biomedical field, including building small-scaled biomedical devices such as tissue engineering scaffolds and drug delivery devices. A compact adaptation system for the SLS is needed to obtain a more effective and efficient way of sintering small-scale prototypes so as to reduce powder wastage. Limitations of available smaller-scale adaptation devices include the need of additional electrical supplies for the device. This paper reports the development of such a system to be mounted at the SLS part bed without any additional energy supply.

Design/methodology/approach – The compact adaptation device works on the concept of transferring the motion of the SLS part bed onto the part bed of the compact adaptation device. The device is an integrated attachment that is fixed onto the building platform of the SLS. The gear system of the device lifts the powder supply bed at both sides of the device simultaneously when the part bed at the center of the device is lowered. To further increase powder saving, an improved powder delivery system named alternative supply mechanism (ASM) is mounted on top of the roller to be coupled together with the compact adaptation device.

Findings – Powder saving up to 6.5 times compared to using full build version of the Sinterstation 2500 has been achieved by using the compact adaptation device. Furthermore, powder wastage has been reduced by 84% when using the ASM compared to the compact adaptation device alone.

Originality/value – The paper demonstrates the development and viability of adaptation devices for SLS to significantly reduce powder consumption by using solely mechanical means to build small parts without using external power supply.

Keywords – selective laser sintering, efficient powder supply, tissue engineering scaffold, drug delivery system.

Paper type – Research paper

1. Introduction

Rapid prototyping (RP) is an innovative layer-by-layer manufacturing process that is used to fabricate three-dimensional (3D) objects directly from computer aided design (CAD) data source (Chua *et al.*, 2003c). They offer many advantages in several diverse applications compared to classical subtractive fabrication methods such as milling or turning. They have the ability to deposit or build up material only where it is required to produce the finished parts. In addition, parts with great complexity in shape can be achieved.

In recent years, many RP systems have been used in biomedical applications, especially in tissue engineering (Cheah *et al.*, 2002, Yang *et al.*, 2002, Leong *et al.*, 2003, Yeong *et al.*, 2004, Hutmacher *et al.*, 2004, Gibson *et al.*, 2006). They included Selective Laser sintering (SLS) (Tan *et al.*, 2005, Williams *et al.*, 2005, Wiria *et al.*, 2007), Fused Deposition Modeling (FDM) (Too *et al.*, 2002, Zein *et al.*, 2002), 3-Dimensional Printing (3DP) (Lam *et al.*, 2002, Seitz *et al.*, 2005), 3D Bioplotting (Landers *et al.*, 2002a, Landers *et al.*, 2002b, Pfister *et al.*, 2004), and ModelMaker II (MMII) (Sachlos *et al.*, 2003, Yeong *et al.*, 2006). One of the requirements of tissue engineering (TE) scaffolds is the existence of interconnected porous network to allow cell movement, as well as exchanges of nutrient and metabolic waste (Hutmacher, 2000, Zeltinger *et al.*, 2001). Control over the macroscopic organization of multiple cell types is also needed in a TE scaffold. SLS, a powder-based RP system with broad range of usable materials, has been shown to be capable of constructing porous polymer scaffolds with complex internal architectures and surface chemistries to provide temporary support to the growing tissues (Cheah *et al.*, 2004, Chua *et al.*, 2003a, Chua *et al.*, 2003b, Low *et al.*, 2001, Tan *et al.*, 2005, Wiria *et al.*, 2007, Hollister *et al.*, 2005, Williams *et al.*, 2005, Bucklen *et al.*, 2008).

The SLS process begins as the roller spreads thermoplastic powder over the surface of the part bed. The piston in the part bed moves down one layer thickness to accommodate the new layer of powder. This layer of powder comes from the powder delivery system whereby one of the pistons moves upwards incrementally to supply a measured quantity

of powder for each layer. The CO₂ laser beam is then traced over the surface of this tightly compacted powder to selectively melt and bond it to form a layer of the object. The part bed is then lowered one layer thickness with the other piston supplying the powder to the part bed. The process is repeated until the entire object is fabricated.

The SLS system used in this article, Sinterstation 2500, is capable of producing objects measuring up to 300 x 350 x 380 mm. The size of the two powder cartridges is 280 x 330 x 380 mm. Depending on the size of the parts built, a typical building process requires powder supply of minimum one third of the power cartridge volume. Therefore, the original Sinterstation 2500 is not material-efficient in building small scale prototypes used for biomedical devices such as scaffolds and drug delivery devices (DDD). Each of these devices is commonly sized less than 30 x 30 x 30 mm. Hence, this work was carried out to find a more effective and efficient way of sintering small-scale prototype. With the existence of the compact adaptation device, both small-scale (with the compact adaptation device) and large-scale parts (without the compact adaptation device) can be built efficiently using the Sinterstation 2500.

A compact part bed and powder delivery adaptation device was manufactured to allow the usage of small amount of biomaterial powder for building small-scale parts using the Sinterstation 2500. The main criteria of the adaptation device are it should be able to process small amount of material, it should function using mechanical means in sync with the original Sinterstation without the need of extra electrical supply and it should be mounted onto the building platform of the original SLS. Other criteria are low cost and simplicity for manufacturing, minimum maintenance and long life for the usage, interchangeable parts for ease of part replacement, structure stability and rigidity, safe and ease of use.

To provide for more efficient powder delivery system, the development of SLS adaptation devices has been reported in the literature. An example of them is a custom-made miniature sintering platform that was installed in Sinterstation 2000, which consisted of a miniature build cylinder and two powder supply chambers that were driven

by two additional stepping motors beneath the miniature sintering platform (Lee, MPhil thesis 2006, Zhou *et al.*, 2007, Zhou *et al.*, 2008). However, the need for additional power supply to drive the powder chambers is a disadvantage of this system, as this approach would require a number of additional electrical elements, such as wiring, batteries, ballast, etc. Another example is a device that consists of a spacer and a feed piston, meant to be placed inside the Sinterstation 2000 powder cartridge. The outer wall of the spacer was fitted onto the cartridge wall, reducing the volume of the cartridge, while the feed piston was fitted onto the spacer inner wall and was connected to the Sinterstation cartridge piston and moved together with the cartridge piston to raise the powder level (Muylaert and Low, 2006). This device needs to be installed in both powder cartridges, posing inconvenience and hassle. The mounting, setting-up and adjustment of more than a single device would result in longer time consumption. Therefore, a compact adaptation system for SLS that works mechanically without the need for additional power supply is needed. This paper reports the development of such a system, which is also simpler due to the mounting of only one device in one location, which is at the Sinterstation part bed.

2. Compact Adaptation Device Process

The compact adaptation device is designed to be a one-piece attachment that is fixed onto the building platform of the original Sinterstation (refer to Figure 1). It works on the concept of lifting the powder supply bed at both sides simultaneously. The gear mechanism of the device's powder cartridges is designed in such a manner that they move in sync with the movement of the build platform of the original Sinterstation. A rack and pinion concept is used to transmit the motion of the part bed into the opposite motion of the modified supply beds. As such, this meets the criteria of having the compact adaptation device to work solely on mechanical means without additional electrical supply. This section details the process to setup the compact adaptation device on the Sinterstation 2500 and steps to use the device.

Figure 1. Schematic diagram of the compact adaptation device

2.1. Setting up Compact Adaptation Device System

The mini adaptation device is mounted on the Sinterstation 2500. Figure 2 shows the steps to setup the device.

Figure 2. Setup steps of compact adaptation device for Sinterstation 2500: (a) lowering down original part bed after placement of adaptation device, (b) clamping and securing all locking nuts, (c) lowering down piston to roller level whilst providing a clearance distance.

Before mounting, the prototype is set to be at its lowest height. The prototype is then placed on the original part bed and tightened onto it with two screws. The original part bed is then lowered down from the upper limit position (Figure 2(a)). The piston should be lowered down such that the top plate flushes with the surface table. The four clamping mechanisms are tightened against the cylinder walls and secured by the locking nuts to the final position of the clamping plates (Figure 2(b)). The clamping mechanisms are equipped with rubber fender to protect the Sinterstation part bed wall from damage.

To ensure smooth distribution of the powder during operation, the powder surface at the two supply cylinder has to be installed evenly. The piston is then lowered to provide a clearance before the parts are built. (Figure 2(c)). The roller is then used to spread the protruded powder cake from the powder supply to cover the part bed. The powder bed is not always covered with powder at the first instance. It helps to lower the piston in increments identical to the layer thickness whilst spreading some powder feedstock with the roller. Sintering operation has to be done in the working range that will not cause the base of the prototype to collide with the Sinterstation part platform.

2.2. Fabricating SLS Parts

Building parts with the devices mounted on the Sinterstation requires that the parts to be laid within a more stringent volume, which is within the 80 by 100 mm area, with 70 mm height. Parameters such as layer thickness, part bed temperature, scan speed and laser

power can be inputted through the normal procedure of inputting the Sinterstation parameters.

The powder that has not been used during sintering requires sieving to ensure that there is no powder agglomeration that will interfere in the smooth application of the powder layering.

3. Validation of Sintering Process using Compact Adaptation Device

To verify the workability and viability of the compact adaptation device, the prototype is tested with powders that are used in the current SLS system. The powder selected for testing is poly- ϵ -caprolactone (PCL), which is supplied by Solvay Interlox (USA). PCL has a low melting temperature of 60°C. It does not need other outer sources of heating apart from the laser, as the laser alone is sufficient to bring the temperature of the powder to its melting point.

There are three steps to validate the sintering process using the mini-SLS kit, which will be detailed in sections 3.1-3.3.

3.1. Fabrication of Cylindrical Structure with 15-layer Thickness or Less.

The initial prototype tested was a small cylinder of diameter 16mm and 2mm thickness. The layer thickness was set to 0.15 mm (0.006 in). The part cylinder and the part bed heater are set at 60°C and 30°C respectively. Laser power is set to 2W. Scan speed is set to 2540 mm/s.

As observed, PCL powder experiences a high adherence caused by static electricity of the metallic roller, hence there is a problem with the powder “sticking” onto the roller and disrupting the distribution of powder evenly, forming tracks on the powder bed. It was also observed that the roller accumulated more and more powder if it was not cleaned up. Since the build was relatively short, it was not tedious to clean the roller after spreading two to three layers. However, it was foreseen that this problem would affect the

automation process in building for parts with higher thickness. Figure 3 shows the part obtained from the experiment.

Figure 3. Sintering part of first testing using PCL powder.

The problem of powder sticking onto the roller was solved by changing the powder compacting method in the supply cartridges. The powder supply should be less compacted (less packing density), during the preparation process. If the powder supply were too hard compacted, more powder would stick together/agglomerate, and hence more powder would stick onto the roller.

It can be seen that the sintered powder packs the area very evenly. The only drawback is the need to clean up the roller after sintering two to three layers. Nevertheless, this drawback is due to the powder characteristic and not the prototype mechanism as the sintered part appeared well built without any distortion as if being built using the normal full SLS system.

3.2. Fabrication of Cylindrical Structure with Thickness More than 15-Layer

As the first experiment was successful, the prototype was next used to fabricate a drug delivery device (DDD). The specimen has an outer diameter and inner diameter of 24 and 16 mm, respectively. The specimen was 10 mm thick and layer thickness was again set to 0.15mm, thus giving a total of 66 layers. Laser power intensity was 3W for the inner cylinder and 4W for the outer ring. Cylinder and the part bed heater were both set to 60 °C and 30 °C respectively. Scan speed was set to 5080 mm/s. The cylinder heater was also disabled. The DDD outer ring was sintered using higher laser power to achieve a denser region, which acted as ‘diffusion barrier’ to prevent drug initial burst and to control the diffusion rate. These settings were based on previous work (Leong *et al.*, 2007). The successfully built DDD specimen is shown in Figure 4.

Figure 4. DDD specimen fabricated using compact adaptation device

Care has to be taken to control the cylinder and part bed temperatures. This is because powder supply, together with the part bed cylinders, is placed inside the part bed. As such, heater settings may affect and change the powder properties.

3.3. Fabrication of Tissue Engineering Scaffold Model.

A further step to test the feasibility of the SLS kit was carried out by building a TE scaffold model. A truncated octahedron scaffold of strut diameter 0.28 mm was built. The overall scaffold dimensions were 35 x 35 x 35mm with four unit cells at x-, y- and z-axes. The laser power was set at 5W, layer thickness at 0.15mm and scan speed at 5080 mm/s. The part bed temperature was set at 30°C and all other heaters were turned off. These settings had higher laser power than those in section 3.1 and 3.2 to give more rigidity to the thin struts of the scaffold structure, as the higher the laser power, the denser and hence more rigid the part is.

The sintered scaffold and its CAD model are shown in Figure 5. The sintered structure shows good consistency on its shape and size with respect to its CAD model.

Figure 5. Truncated Octahedron TE scaffold: (a) CAD model, (b) prototype model built using mini-SLS

This sintering trial once again showed that the compact adaptation device was able to build parts that were similar to that of a normal full build. Another value-add of using this device is that less powder is needed, thus making the device a cost-saving tool for fabrication of small medical devices. This will be further discussed in the next section.

4. Estimation of Powder Reduction

Estimation was carried out to compare the volume of powder needed for a single layer to build the part on both the normal Sinterstation full build and the compact adaptation device. The powder savings of using the compact adaptation device is approximated to be 6.5 times than that if using a normal Sinterstation full build. The calculation results are shown in Table 1.

Table 1. Comparison of powder usage between full build and compact adaptation device.

It can be seen that the volume of powder used in the compact adaptation device is 15% that of the amount used in the normal full build (or a reduction of 85%). Therefore, it is summarized that although the SLS kit works on the concept of lifting the supply bed simultaneously, its usage of powder is by far superior to that of the full build.

The successful fabrication of the DDD devices and particularly the scaffolds has ascertained the feasibility of the compact adaptation device prototype. With the use of this device on the DTM Sinterstation 2500 system, the SLS process can now sinter small physical models up to a volume of 80mm by 100mm by 70mm without having to fill up the large supply cartridges with powders. This will greatly improve the build preparation speed, due to the smaller building area of the compact adaptation device, as compared to the Sinterstation full build. The cost of fabricating small parts could also be lowered due to the powder savings and the compact adaptation device is safer for users to operate. The introduction of the compact adaptation device not only cuts down time in build preparation time (refer to Table 2), it also saves large volumes of powder from degenerating and going to waste in using the full build. A compact adaptation device uses approximately 6.5 times less powder than the full build. This is in line with the findings of other works using modified SLS system to fabricate relatively small-scale structures (Zhou *et al.*, 2008).

Table 2. Comparison of preparation time between full build and compact adaptation device.

Another advantage of the compact adaptation device is that it runs purely by mechanical means. With the use of simple gear systems, it transmits the part piston movement into an opposite motion to both the powder supply beds simultaneously. Hence, it does not need any additional means of power source.

An attachment feature, which is the alternative supply mechanism or ASM in short, will be described to improve this basic prototype. These features were further developed based on powder usage and wastage considerations.

Investigation is carried out to review the efficiency of the compact adaptation device in terms of powder usage and powder wastage. The powder wastage is mainly due to the mechanisms designed to supply the powder. The current mechanism of the rack and pinion drive system constrains both the supply cartridges to move up concurrently when the Sinterstation part bed is lowered, ‘oversupplying’ powder to fill in the part bed. Nevertheless, only powder from one cartridge is used to fill the part bed, while the powder from the other cartridge is not used and is swept away by the roller.

Although the first prototype is able to produce the desired sintered parts, the simultaneous movement of the supply cartridges will always result in a supply that is considered redundant. Excess powder contributes to untidiness to the system, which will require thorough cleaning by the user. Figure 6 shows the excess powder that is swept away to the sides of the part bed, and drops to the bottom of the kit and sticks on the Sinterstation part bed wall.

Figure 6. Powder wastage: (a) at the sides of the part bed, (b) at the bottom of the part bed and (c) on the Sinterstation part bed wall

This excess powder is difficult to recover as the excess powder has high possibility of being contaminated and hence is likely to be disposed.

5. Alternative Supply Mechanism (ASM)

To achieve precise powder deposition and minimized powder wastage, an alternative supply mechanism (ASM) was developed. The ASM acts as the powder supplier for the compact adaptation device that is mounted on the Sinterstation part bed. Therefore, the usage of the ASM is coupled with the compact adaptation device as the part bed. The uniqueness of this ASM lies in its location when mounted inside the Sinterstation. The

ASM device is mounted on top of the roller. Thus, the powder supply for the compact adaptation device comes from the top. The ASM consists of a main frame and its triggering mechanism. The main frame is mounted on top of Sinterstation roller, while the triggering mechanism is comprised of a pair of triggering hinges to trigger the opening of the powder depository tray.

5.1. Setting Up the Alternative Supply Mechanism (ASM)

The ASM should be used in couple with the compact adaptation device kit. The setup of the compact adaptation device kit is the same as described in section 2.1. However, these cartridges should be left empty without powder and a metal top plate is used to cover them. The ASM is mounted on the SLS roller, while the triggering mechanism is mounted into the location of the SLS swing gate.

5.2. Powder Deposition Mechanism of the Alternative Supply Mechanism (ASM)

In ASM, the powder deposition is carried out by sliding the powder depository plate upon activation of the triggering linkage. Figure 7 shows the triggering process, where the ASM is moving from left to right (the red arrows indicate the ASM movement). In Figure 7(a) the ASM is about to be activated by the triggering mechanism. Figure 7(b) shows the powder deposition process, where the powder depository plate slides opens due to the movement of the linkage when it strikes the triggering mechanism. A slot is machined on the powder depository plate and acts as a measuring cup to deposit a fixed amount of powder. When the plate slides open, the slot is exposed, thus pushing and dropping the required powder.

Figure 7. Schematic diagram of the ASM: (a) The ASM just before activated by the triggering mechanism, (b) the activated ASM with open powder depository plate

The ASM consists of two powder cartridges, one on the left and the other one on the right of the roller. To ensure that only one cartridge deposits powder at a time, the triggering mechanism utilizes a standard hinge that is attached onto two pieces of metal blocks with a gap/slot in between them (refer to Figure 8 (a)). The block arrows indicate the ASM

movement. The blocks allow only outward flipping action of the hinge to occur (refer to Figure 8 (b & c)). There are two of these trigger mechanism stationed at the original swing gates location. These two hinges are offset at a distance such that only one linkage will make contact with the hinge (refer to Figure 8 (d)). Figure 8 (d) shows how this triggering mechanism works. When the roller starts to move from the left, the right linkage of the ASM will make contact with the left hinge. The blocks prevent the hinge from flipping inward and thus, the right linkage is pushed to slide open the powder depository plate. The ASM carries on the motion where the left linkage will pass the right hinge without activating the mechanism. When the roller moves to the right to supply the second layer of powder, the ASM left linkage will make contact with the right hinge. Here the blocks prevent the inward flipping and thus, hitting the left linkage to open the powder depository plate. The ASM continues to travel to the right where the left linkage passes the right hinge without activating the powder feeding mechanism.

Figure 8. Working mechanism of the ASM when attached to the compact adaptation device: (a) The components of the triggering mechanism, (b) activated triggering linkage, (c) inactivated triggering linkage where the hinge flip outward to give way to the linkage and (d) top view of the ASM movement (red arrows indicate the direction of the movement).

5.3. Sintering Result

The ASM was then tested for the functionality of its mechanism, its ability to be used for different types of powder, and the stability of the fabricated parts. Thus, specimens were built using two types of powder, namely poly- ϵ -caprolactone (PCL) and poly(vinyl alcohol) (PVA) powder so as to validate the system. Table 3 lists the SLS parameters setting used to fabricate the PCL and PVA samples.

Table 3. SLS parameters setting for PCL and PVA powder

5.3.1. Sintering of Poly- ϵ -Caprolactone (PCL)

A PCL disc specimen of diameter 45mm and 3mm thickness was fabricated to observe the integrity among the sintered layers. Figure 9(a) and (b) shows that the accuracy of the specimen was attained and no shifting between layers occurred. A further fabrication was carried out to ascertain the feasibility of the ASM system. A scaffold with truncated octahedron unit cells having strut diameter 0.28mm and overall scaffold dimensions of 20 x 20 x 20mm was fabricated using the ASM (refer to Figure 9(c)). The scaffold built shows good regularity of shape and sizes. With the fabrication of such an intricate scaffold, the ASM has been successfully shown that it is a feasible means of supplying more precise amount of powder to build relatively small parts.

Figure 9. Sintered PCL specimens: (a) front view of the PCL disc, (b) side view of the PCL disc, (c) truncated octahedron unit cells.

5.3.2. Sintering of Poly(Vinyl Alcohol) (PVA)

A PVA rectangular block with dimension of 12.7 x 12.7 x 25.4 mm was fabricated (refer to Figure 10). It was observed that the layers of the PVA part were successfully sintered, although some shifting occurred at the first few layers. This could be due to the large temperature gradient between the sintered part and the surrounding powder. This caused the sintered layer warped and shifted when the roller rolled over it. It was indicated by the time of 45 minutes required to heat up the PVA powder to reach 65°C using the feed heater. It was suggested that the slow heating was due to the poor heat conductivity of the PVA powder (~2W/mK) (Wiria, PhD thesis 2007).

Figure 10. Sintered PVA specimen

5.4. Estimation of Powder Wastage and Precise Powder Amount

The powder quantity supplied by the cartridges of the compact adaptation device was calculated and compared to the precise powder supply of the ASM in this section. This is carried out to quantify the efficiency of the ASM.

The dimensions of the compact adaptation device part bed and cartridges are shown in Fig. 11. The powder layer thickness is set at 0.15mm.

Figure 11. Dimensions of the part bed and powder cartridges of the compact adaptation device kit

Volume of powder required by the part bed per layer:

$$\begin{aligned}
 &= \text{part bed cross-sectional area} \times \text{powder layer thickness} \\
 &= 80 \text{ mm} \times 100 \text{ mm} \times 0.1524 \text{ mm} = 1.2192 \times 10^{-6} \text{ m}^3 \dots\dots\dots (a)
 \end{aligned}$$

Volume of powder supplied from the cartridges per layer:

$$\begin{aligned}
 &= 2 \text{ cartridges} \times \text{gear ratio} \times \text{cartridge cross-sectional area} \times \text{powder layer thickness} \\
 &= 2 \times 1.2 \times 99\text{mm} \times 100\text{mm} \times 0.1524\text{mm} = 3.621 \times 10^{-6} \text{ m}^3 \dots\dots\dots (b)
 \end{aligned}$$

Volume of powder wastage per layer:

$$= a - b = 2.4018 \times 10^{-6} \text{ m}^3 \text{ (which is 66\% of the total powder supplied)}$$

As mentioned, to increase the efficiency of the process, the powder depository plate was designed to contain a fixed amount of powder before it was deposited onto the part bed. The size of the slot on the measuring cup was essential to reduce powder wastage. When the powder layer thickness was set to 0.15mm, the part bed will require a volume of $1.2192 \times 10^{-6} \text{ m}^3$ powder. To ensure that the powder from the powder depository plate was sufficient to cover the part bed fully, an estimated powder supply factor of 1.3 was used as a conservative gauge. Therefore the slot was designed to contain powder with volume of $1.6 \times 10^{-6} \text{ m}^3$, which has reduced the powder wastage by 84%.

The cost of powder wastage was also evaluated for two types of powder that were used in the tissue scaffold fabrication, namely PCL and PVA. Table 4 shows the specification of PCL and PVA powder used, while Table 5 lists down the comparison between the compact adaptation device and the ASM in terms of powder efficiency.

Table 4. Biomaterial powder specification and cost of powder wastage when using the compact adaptation device.

Table 5. Comparison between compact adaptation device and ASM in terms of powder efficiency.

6. Conclusion

New attachment devices for the Sinterstation2500, namely the compact adaptation device and alternative supply mechanism (ASM), have been successfully developed to increase the efficiency of powder usage. Powder used was only 15% that of using full build version of the Sinterstation 2500 when the compact adaptation device was used. With the use of pure mechanical means, the ASM was able to supply powder one layer at a time. Compared to the compact adaptation device, the powder wastage from the supply side has been reduced by another 84% when using the ASM. With much a more efficient powder usage, researchers can now economically fabricate parts and reduce time required for powder preparation when performing experiments on sintering biomaterials. Besides, the ASM has eliminated the backlash problem that was faced when using the compact adaptation device. The fabrication of PVA rectangular block and PCL complex scaffold has verified the feasibility and workability of the ASM.

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Figure 1. Schematic diagram of the compact adaptation device

Figure 2. Setup steps of compact adaptation device for Sinterstation 2500: (a) lowering down original part bed after placement of adaptation device, (b) clamping and securing all locking nuts, (c) lowering down piston to roller level whilst providing a clearance distance.

Figure 3. Sintering part of first testing using PCL powder.

Figure 4. DDD specimen fabricated using compact adaptation device

Figure 5. Truncated Octahedron TE scaffold: (a) CAD model, (b) prototype model built using mini-SLS

Figure 6. Powder wastage: (a) at the sides of the part bed, (b) at the bottom of the part bed and (c) on the Sinterstation part bed wall

Figure 7. Schematic diagram of the ASM: (a) The ASM just before activated by the triggering mechanism, (b) the activated ASM with open powder depository plate.

Figure 8. Working mechanism of the ASM when attached to the compact adaptation device:
 (a) The components of the triggering mechanism, (b) activated triggering linkage, (c) inactivated triggering linkage where the hinge flip outward to give way to the linkage and (d) top view of the ASM movement (red arrows indicate the direction of the movement).

Figure 9. Sintered PCL specimens: (a) front view of the PCL disc, (b) side view of the PCL disc, (c) truncated octahedron unit cells.

Figure 10. Sintered PVA specimen

Figure 11. Dimensions of the part bed and powder cartridges of the compact adaptation device kit

Table 1. Comparison of powder usage between full build and compact adaptation device.

	Full Build	Compact Adaptation Device
Supply cartridge powder area	279.4 x 330.2 mm ² (11 x 13 in ²)	99 x 100 mm ²
Supply cartridge layer thickness	0.254 mm (default value) (0.01 in)	0.006 in x 1.2 (gear ratio) (0.18288 mm)
Volume of powder supplied for 1 layer	23433.5 mm ³	3621 mm ³
<i>Powder usage on the SLS kit is approximately 15% of the normal full build.</i>		

Table 2. Comparison of preparation time between full build and compact adaptation device.

Full Build		Compact Adaptation Device	
Activity	Time Taken	Activity	Time Taken
Mounting the part bed plate	1 min	Setting up/mounting the device	2 min
Filling up powder	3 min	Filling up powder	1 min
Packing powder by shaking the powder cartridges	1 min	Packing powder by pressing using metal plate	0.5 min
Loading the cartridges onto the machine	0.5 min		
Total time taken	5.5 min	Total time taken	3.5 min

Table 3. SLS parameters setting for PCL and PVA powder

Material	Laser Power	Laser scan speed	Part heater PID	Right feed heater	Left feed heater
PCL	3.4 W	2540 mm/s	Off	Off	Off
PVA	13.4 W	2032 mm/s	65°C	65°C	65°C

Note: powder layer thickness was set to be 0.1524 mm

Table 4. Biomaterial powder specification and cost of powder wastage when using the compact adaptation device.

	PCL	PVA
Supplier	Solvay caprolactones	Sigma Aldrich
Price	SGD 84/kg	SGD 225.49/kg
Density	1.08 g/cm ³	1.26 g/cm ³

Table 5. Comparison between compact adaptation device and AAS in terms of powder efficiency.

	Compact Adaptation Device	AAS
Volume of powder supplied to part bed per layer	$3.621 \times 10^{-6} \text{ m}^3$	$1.6 \times 10^{-6} \text{ m}^3$
Volume of powder required by part bed per layer	$1.2192 \times 10^{-6} \text{ m}^3$	$1.2192 \times 10^{-6} \text{ m}^3$
Volume of powder wastage per layer	$2.4018 \times 10^{-6} \text{ m}^3$	$0.3808 \times 10^{-6} \text{ m}^3$
Cost of PCL powder wastage of a full build with 1 inch height	SGD 36.67	SGD 5.75
Cost of PVA powder wastage of a full build with 1 inch height	SGD 113.33	SGD 17.99