Low-cost Machine Vision Monitoring of the SLS Process

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Abstract

During the building of a part using SLS, it is common practice to adjust the temperature parameters. It is important to control these parameters because if they are too high then part breakout is difficult. If they are too low then parts have poor material properties. One method of controlling these parameters is by observation through the process chamber window. Any adjustment can be determined by examining the colour of the cross-section in process. By using a machine vision system to determine colour variation, it is possible to calculate temperature or laser power adjustments necessary to maintain consistent part quality.

Keywords: Selective Laser Sintering, Process control, Machine vision.

Introduction

One of the major advantages of Selective Laser Sintering (SLS) process is the wide range of materials capable of being processed. The majority of parts built using SLS use the nylon-based powders since these result in relatively, strong, durable components that can be made to have the appearance of many high volume, manufactured products. Nylon, being predominantly crystalline, has a very definite melting point which means that precise control of temperatures within the SLS machine is very important. Temperature is monitored in two particular areas in the machine. Powder temperature is monitored using thermocouples at the top of the powder feed chambers and the temperature of the part-bed is monitored using an infra-red (IR) sensor. These sensors are used to control the heaters in the machine to maintain constant settings.

There are two major problems in the use of the IR sensor to measure part-bed temperature. Firstly, the part-bed does not have a uniform temperaure across the entire surface. The closer to the perimeter of the part-bed, the cooler the powder at the surface. There is also likely to be a variation between the front and the back of the part-bed due to temperature losses through the process chamber door. The single IR sensor used in the SLS machine is focused on the centre of the part-bed and can only give an average readout for the bed temperature. Because of the temperature profile of the part-bed, Fine Nylon (LNF5000) can only be effectively processed within an 8" diameter cylinder at the centre of the bed.

The second problem relates to the geometry of the part being processed in the SLS machine. The solid part in the machine is hotter than the surrounding powder. If the part being built is relatively massive (which could be defined for one layer in terms of the ratio of the melted area to the perimeter of the enclosing box) then there is a significant amount of stored energy in the part and it is sometimes necessary to reduce the feed temperatures to compensate. If this mass is in the centre of the platform then the IR sensor should be able to compensate automatically. However, parts that have some or all of the mass away from the centre may be difficult to control.

By placing a camera in such a way as to monitor the part-bed, it should be possible to obtain a localized measure of energy build up for a specific layer of a part. If this can be done accurately and effectively then it may be possible to automatically control the SLS process parameters according to the geometry of the part. The potential benefit of this is homogeneous mechanical properties or consistent part quality. This paper describes ongoing work at The University of Hong Kong using these techniques.

Use of Machine Vision with SLS

When first starting to use an SLS machine (and this is emphasized greatly during training at DTM) it is important to watch the process carefully. It is important to understand how part quality will vary according to different parameter settings. Eventually, experience takes over and after a short while it is possible to set the part build profile according to knowledge of the subtleties of the process and leave the machine to build the part automatically. However, it should be noted that even the most experienced operators may find difficulties with new geometries, requiring more than one attempt to produce an acceptable part. Since all rapid prototyping machines are designed to run unattended, it is often not until the build has finished that a fault is detected.

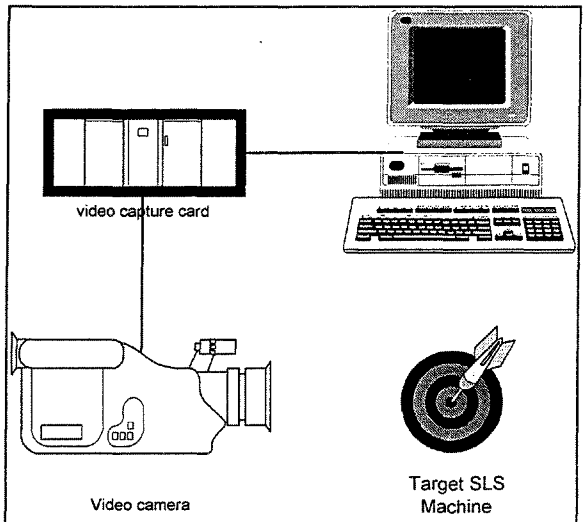

Figure 1
Hardware configuration

A machine vision system can make use of a camera placed in front of the process chamber window to see the same as the operator sees. According to the DTM materials manual [1], it is possible to observe a number of potential problems. Among these potential problems are in-build distortion (curling), short feed, ploughing, cracking and streaking. These will not always result in a bad part (except perhaps curling) and if detected in time can be adjusted to limit the effect. The most common problems are curling and short feed (critical mainly for large parts). It is suggested that machine vision can at least halt the process until manual intervention can make the decision to abort or continue (after action taken) and at best be linked into the process computer to adjust the parameters directly.

Initially, this project was approached as a final year undergraduate project and therefore it was important to minimize the cost of any additional equipment. A low cost machine vision system also has the attraction of being more practical for implementation into the existing SLS machine. The hardware configuration can be seen in figure 1. At the time, a video camera sampled through an image capture card offered the cheapest and most convenient solution.

Energy Principle

The general principle of SLS processing of nylon powders is to use the part-bed and powder heaters to raise the powder temperature close to melting point. Energy is then added to the powder from the laser in order to fully melt the powder. According to Nelson [2] the additional energy is constant for a set laser power, scan speed and scan spacing i.e.:-

$$\text{Energy density}(\text{cal/cm}^2) = \frac{P * f}{BS * SCSP}$$

Where P is laser power, BS is scan speed, SCSP is scan spacing, and f is a constant conversion factor. In order for the system to remain completely stable, this additional energy must be lost from the part before the next layer is melted. If not, then there will be a temperature build up that will eventually lead to growth, caking and other undesirable features. For massive parts, it may be prudent to allow a long delay between layers to allow the part-bed heater to control the part-bed temperature. This would result in much longer build times and so it may be more desirable to control the amount of energy put into the part, based on what has been observed to already exist in the part.

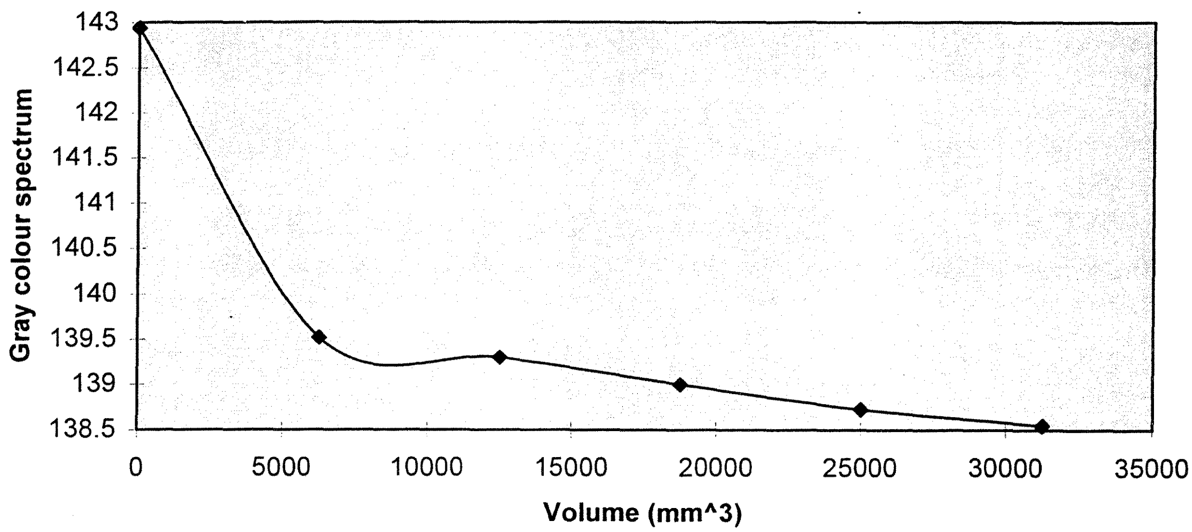

Figure 2 -grey colour against volume of a wedge-shape

Since the powder feed heaters are only very slightly affected by what goes on at the build platform, this implies that the only variable adjusted according to energy stored in the part is the part-bed heater. It has already been stated that the IR sensor focuses on the centre of the part-bed. If the part is not centred on the part-bed or the geometry of the part varies in some way then it is very difficult for this single measurement sensor to provide sufficient data for control of the energy within the part. This can be seen in figure 2. Under normal conditions, as a wedge shape is built (increasing volume), energy stored within the part changes the colour of the part.

Optical principle

The change in colour noted in figure 2 must correspond to a physical change in the powder. This physical change modified the optical properties of the powder in such a way as to look lighter or darker, dependent on the amount of energy supplied by the laser.

The camera used had automatic gain control (AGC) and focusing control disabled. The camera therefore did not attempt to compensate for any variation in the image. Similarly, the dominant lighting source was a stable, halogen lamp placed in close proximity to the camera, directed at the part-bed and not shining into the lens. The internal light source for the SLS machine was also disabled. However, although ambient variations must exist, it is the opinion of the authors that ambient conditions did not significantly affect results.

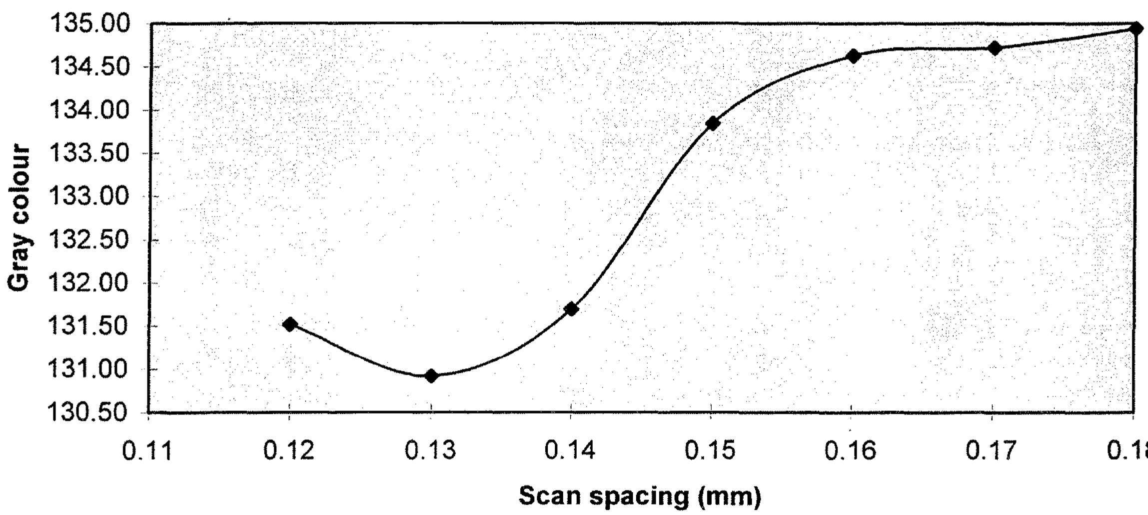

Figure 3 -grey colour against scan spacing

Figure 3 shows average grey colour measurements for a number of samples built using different scan spacings, varied around the optimum value. As the energy decreases, so the grey colour inside the boundary of the part shows a general increase making it appear lighter in colour. This can be explained in terms of the optical model used. As the energy increases, so the surface of the part becomes smoother and more reflective. The inside of the chamber is relatively dark compared with the powder and so less light is reflected back to the camera. The most marked change is between scan spacing of 0.14mm and 0.15mm corresponding to the most significant change in the melt conditions. 0.15mm is the default setting for critical melting. A similar relationship was observed for variations of laser power around the optimum value.

Control Principle

It has been established that there is a relationship between observed grey scale value from the camera (G) and the part volume (V) and laser power (L).

$$G = f(V,L)$$

$$dG = \frac{dG}{dV} . dV + \frac{dG}{dL} . dL$$

Since volume distribution is determined by the geometry of the part, the above equation should be rearranged to determine the required laser power setting based on an observed change of grey scale and the change in volume between observations. A test experiment for a simple part geometry establishes a control equation based on grey scale and incremental heights (h) in the form:-

$$dL = \frac{dG + 1.562dh - 0.156hdh}{-1.817}$$

the figures derived in this equation assume linear relationships for grey scale vs. volume and grey scale vs. laser power. For a wedge-shaped part geometry, modifications to laser power were calculated and adjusted according to a grey scale set point which was monitored throughout the height of the wedge (figure 4). Laser power was considered easier to calculate than scan spacing, although the latter would probably allow finer resolution and stabilize more quickly. As can be seen, the grey scale and laser power variation tends to a constant value, probably related to the reduction in surface area of the wedge indicating again that massive components are more sensitive to this problem. Although difficult to see from the images below, the wedge shape under vision control showed a marked improvement in consistency compared with the other part.

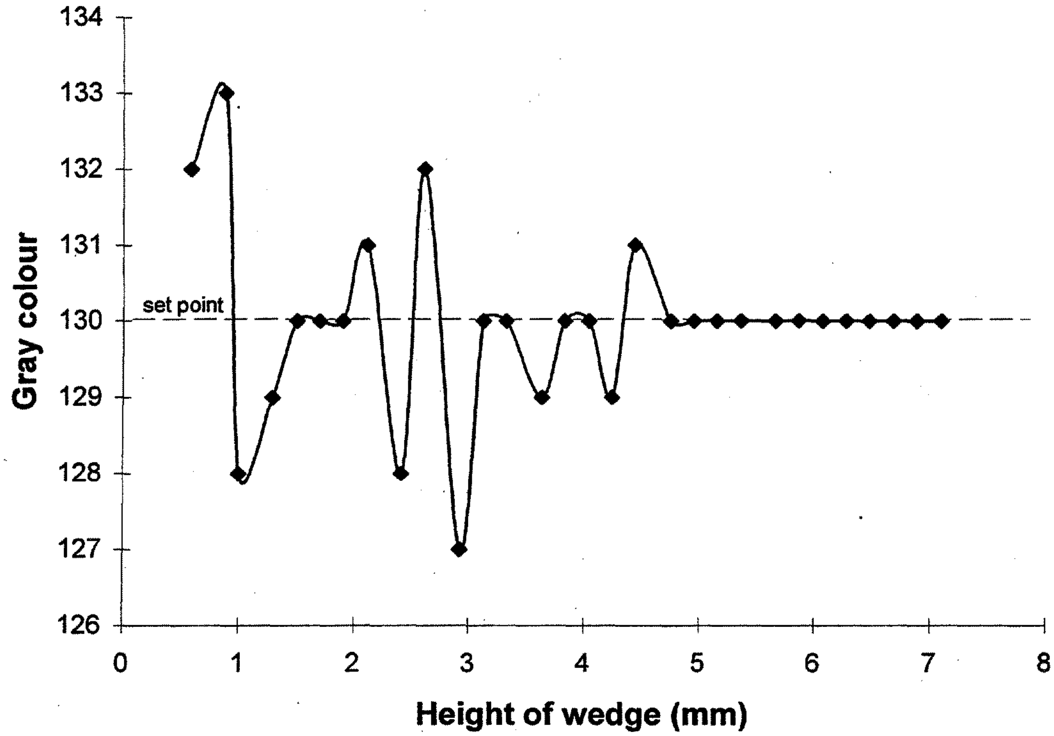

Figure 4 -grey colour against height of wedge

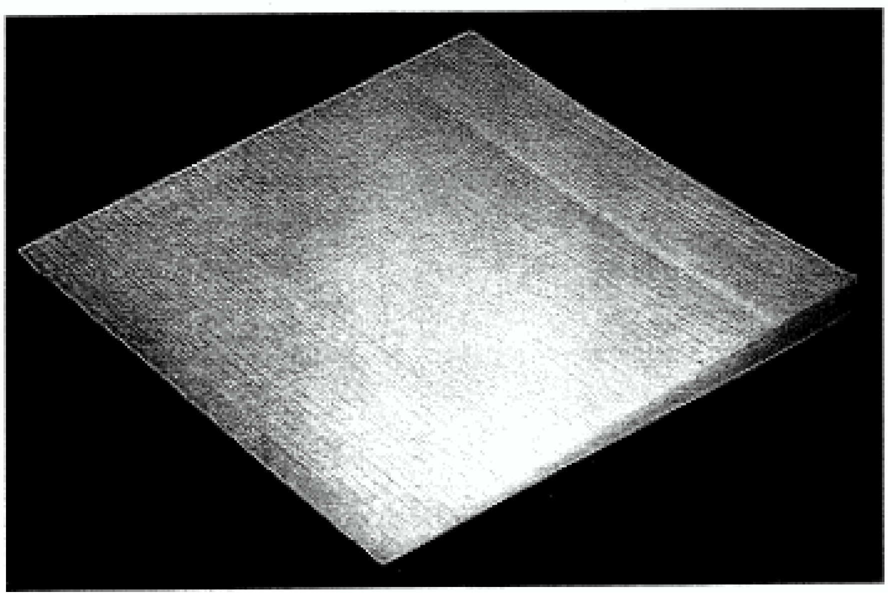

Photo 1 Wedge with vision control

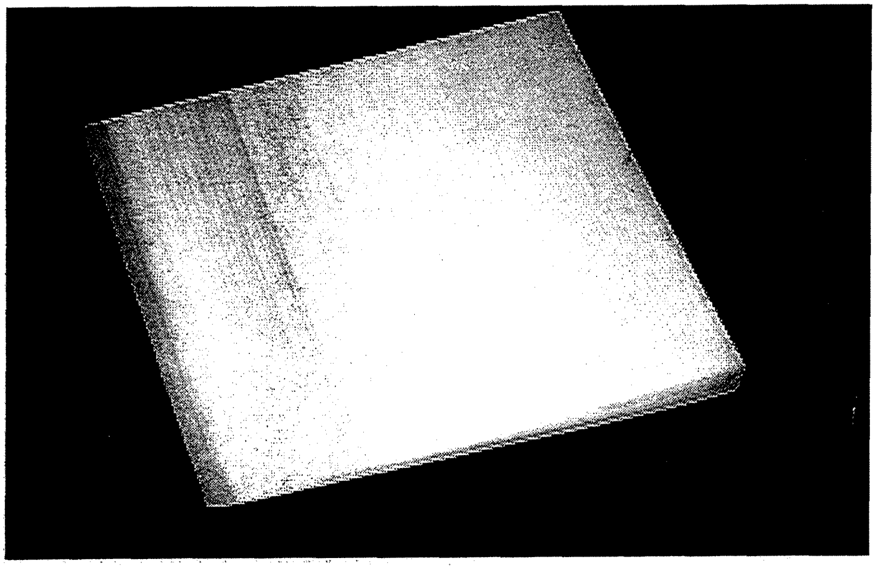

Photo 2 Wedge without vision control

Discussion and Further Work

These are only preliminary findings and require much additional work to verify and quantify. Work currently has been able to identify the following:-

- That there is a relationship between grey scale and part volume in terms of the energy build up within a massive part.
- That there is a relationship between grey scale and applied energy.
- That these relationships can be incorporated into a control function and applied to a simple geometry part.

There are also a number of problems that need to be overcome

- Vision processing on each layer: The data at the perimeter of each layer differs from inside the boundary and must be segmented out before calculation.
- A generalized control function needs to be extracted from the data, based on the height or volume of the part.
- Incorporation of process intelligence to compensate for variable feature geometry: Thin wall and thick wall structures may require different control strategies.
- Integration with the X-windows based SLS operating system to close the loop: Currently, the calculation is done off-line and entered manually.

These problems also need to be correlated with existing thermal models that describe the powder processing within the chamber of the SLS machine. Also, this process has been found to give a result that represents consistent quality within a part. Further work must identify methods to ensure optimum parameter settings. It may be possible to adjust these settings to give optimum performance according to different criteria (e.g. tensile strength, surface finish, density, etc.).

Future work is likely to involve a higher resolution camera. Whilst resisting the temptation to use thermal or other expensive camera systems, digital cameras with much higher resolutions are commonly available, allowing greater precision in calculation. Much more attention will also be devoted to improving the lighting arrangement to achieve consistent and stable lighting.

The indication is that this process can be applied as a form of adaptive control. Normally, a significant dwell time is used between each layer to allow the build temperature to stabilize. Using this method to control energy delivery through the laser power, it may be possible to significantly reduce this dwell time (perhaps down to zero). With the part-bed heater, the energy delivery can be a significant distance from the build surface.

Conclusions

For certain geometries of parts, the current SLS control model does not work satisfactorily. A method of using a camera with a digitally sampled image has been proposed. This image can be used to extract process information by observation through the process chamber window. This information relates to the amount of energy observed at each layer during the build process. From this the amount of energy required in order to build the next layer can be calculated in terms of an adjustment of the laser power. Initial studies using a simple experimental set-up indicate that this process can be used to control the quality of build throughout a simple geometry part.

References

1. The Sinterstation 2000 System Selective Laser Sintering Guide to Materials Optimizing and Understanding the Process - DTM Corporation
2. Selective Laser Sintering : A Definition Of the Process and an Empirical Sintering Model - Nelson, James Christian, UT-Austin, Ph.D. dissertation, UMI Dissertation Services, 1993