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MULTI-LEVEL HEXAGONAL PATTERNS AS AN OPTIMAL MARKING TECHNIQUES FOR ADDITIVE MANUFACTURING

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Multi-level hexagonal patterns as an optimal marking techniques for Additive Manufacturing

1 Description of problem

Today, when we need to mark 3D printed pieces to measure their properties, we typically groove them with numbers that allow easy human part identification and tracking. While this strategy is very useful for manual processing, is much less susceptible to be automated as indo-arabic figures were not designed for automated detection.

There is also another difficulty in the process: the available space is short and we typically use just 2 or 3 figures that do not allow a full part identification.

We need to find a piece marking method:

1. allows machine detection
2. robust: tolerant to actual 3D manufacturing defects
3. use small surface of the piece
4. can be used in not flat surfaces
5. If possible, that exploits the unique characteristics of 3D printing

2 How the solution differs from other existing ones

For low cost marking in a surface, we have two well-known optical methods:

- the bar code (one dimensional marking)
- the QR code (two dimensional marking).

In the design of both methods we can see an evolution of the involved technology: the bar code was designed for simplicity of decoding but require a reasonable quality printing while the QR codes allows order of magnitude information capability. In its definition it is covered different levels of redundancy (based on Reed Solomon codes) that allow error-free decoding of the message even if parts of the image become unreadable.

Both methods were designed for dark ink printing over a white surface and for high contrast optical detection and are not optimal when used for 3D pieces.

In a 3D piece the optimum coding relies on the variation of the dept of the surface, strategy we could call «groove modulation».

A well-known example of this technique is the Braille code used by blind people, that codes every letter/number with small dots in relief that a person can detect and interpret with the finger. Braille code could be very favorable used for 3D marking but it is sub-optimal because relies on finger detection and thus contemplates only highly spaced dots with positive relief.

Marking a piece with an unique 32, 48 or 62 bit number will be more than enough for most applications: accessing to a database will provide all the relevant information of the piece: materials, process, printer ID, tuning of the default parameters, etc.

3 Invention description

The idea presented here is a technique for marking of pieces which is optimal for high quality 3D printing systems.

For a correct definition of the marking of pieces we need to closely consider how are we going to detect the marking (compliant to requirement 1). Because of that, we will start considering how the marking can be detected.

It should be noticed that detection technology does not take part of the idea. The proposal is to use available commercial technology to measure surface ruggedness in the surroundings of the marking.

3.1 Detection of the marking

The most simple methods for detecting ruggedness are:

1. Stereoscopic optical analysis: two synchronous cameras see the illuminated surface from different positions, which using well known algorithms, provide a map of the surface depth (ruggedness).
2. Using one or two cameras and a configurable projection system and by analyzing how a known pattern reflects in the surface, we can obtain a detailed knowledge of the surface ruggedness.

Both methods can be used with the proposed idea and could be used in flat surfaces or even in non-flat ones. For the later there is an intrinsic lack of precision and increase in the complexity of the algorithms that extract the reference surface over which the marking body is modified to add information.

3.2 Marking

The proposed method suggest the marking of pieces by using the simultaneous or single use of the following techniques:

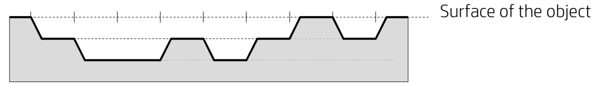

Figure 1: Section of a marked piece with 3 levels groove

3.2.1 Various level depth variation

The depth variation needs not to be two level one: the body surface and a prominence or depression: various possible levels can be used: 2, 3, 4... We do not need at all to use 2^n factors. See figure 1.

It should be noticed that the number of usable levels depends mostly on:

- the depth variation we can print with a reasonable quality. For example, if we print over a flat surface perpendicular to the Z axis, may be seems reasonable to use at least 4 printing layers for every marking level. When printing in other possible directions, the depth of the groove will need to be much higher.
- the impact in the part mechanical properties.

3.2.2 Add or grow

Although figure 1 shows marking in which the marking removes material over the surface, there is no reason to mark adding material in the opposite direction as shown in figure 2.

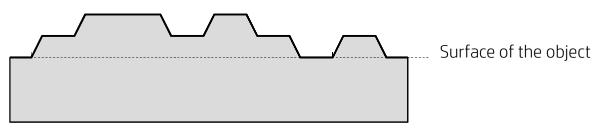

Figure 2: Section of marked piece with 3-level grow

3.2.3 Geometry of the marking

Some 3D printing technology imposes very few restrictions on how the marking could be done. For example, CNC machines privilege circular marking. However, circular marking does not make use an optimal use of the available surface to code information. We optimize the solution when we make use the maximum available surface to code information.

At a first approach, it would be reasonable to use very abrupt transitions to optimize the surface that carries information. However, it looks like that using very sharp transitions is not a good idea because it will be difficult to remove the remaining powder resulting from the process and later added dirtiness. See figure 3. It seems reasonable to use soft edges between transitions in order to improve the printing quality and minimize the powder adherence.

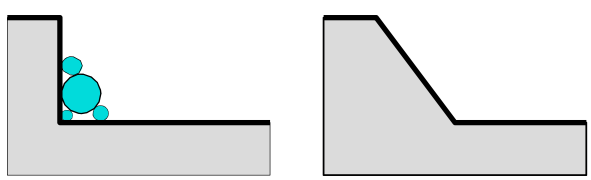

Figure 3: Groove sharpness

The deepness transitions could be seen as loss of efficiency in the coding, as takes part of the available surface for a purpose different than carrying information.

Which is the geometrical pattern that optimizes the contour length over the inside surface? The hexagon. Using hexagonal elements is an optimal solution as it cover the surface with the minimum transition surface. The gain of hexagonal surface over square one is about 15 %.

$$\frac{S}{L}_{sq} = \frac{1}{4}L \quad (1)$$

$$\frac{S}{L}_{hex} = \frac{\sqrt{3}}{8}L \quad (2)$$

$$\frac{\frac{S}{L}_{hex}}{\frac{S}{L}_{sq}} = \frac{\sqrt{3}}{2} = 0.866 \quad (3)$$

We should consider if this gain worth the complexity increase.

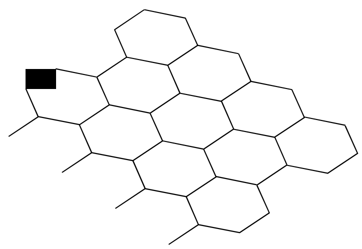

Figure 4: Hexagonal pattern

3.2.4 Selection of special surface codes with optimum properties

The information can be coded in the surface using two or more levels with or without redundancy.

The absence of redundancy does not provide error correction capability. See coding capabilities in table 1 and 2. There is no reason why the marking has to be square. A generic $m \cdot n$ pattern is possible.

Pattern	Combinations	Bit number
3x3	$2^9 = 512$	9
4x4	$2^{16} \sim 65.5 \cdot 10^3$	16
5x5	$2^{25} \sim 33 \cdot 10^6$	25
6x6	$2^{36} \sim 69 \cdot 10^9$	36

Table 1: Coding capability of two-level grooving (no redundancy)

Pattern	Combinations	Bit number
3x3	$3^9 \sim 20k$	14.2
4x4	$3^{16} \sim 43 \cdot 10^6$	25.3
5x5	$3^{25} \sim 850 \cdot 10^9$	39.6
6x6	$3^{36} \sim 150 \cdot 10^{15}$	57.1

Table 2: Coding capability with three-level grooving (no redundancy)

Adding redundancy provides much greater robustness against the presence of imperfections in the marking. It is not needed if manufacturing quality, combined with the chosen dimensions and depths is enough.

The adding of redundancy is well know in daat communications (which can be considered as one-dimensional –time– system). There are many methods of doing it like the following:

- Line codes

- Convolutional codes
- Cyclic redundancy check (CRC) or Reed Solomon checksum.

These methodology can be extended to be used into two dimensional coding and I am sure that are actually used for extended coding mechanisms like QR codes.

The message here is that the redundancy level in the coding is another factor that can be configured when creating the codes for coping with different levels of printing imperfections. For sure, adding redundancy is more optimum than increasing the size or the depth of the marking.

3.2.5 Setting reference levels for flat and not flat surfaces

The limitations of the 3D printing technology privilege coding in the horizontal planes and dis-recommend using coding in the vertical planes that may suffer for defects like *elephant skin*. However, considering he small needed pattern, the piece marking is very likely to be perfectly reproduced over non flat surfaces or planes different that perpendicular to Z axis.

In order to calibrate the reader, I suggest to draw a rectangular contour with the depth of the maximum groove, as shown in figure 5. This has the double purpose to set the reference surface and the grooving depth in order to set decision thresholds.

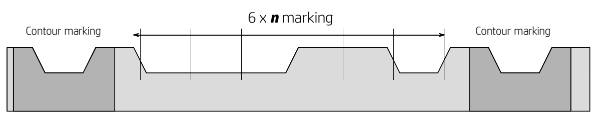

Figure 5: Contour marking

While this is convenient when the marking is placed in a horizontal plane, it is of vital importance for non-flat ones, as set two axis reference for setting the geometric model of the reference surface.

3.2.6 Setting coordinate axis

The previously described contour can provide rotation reference with a very small area penalty by using the solution described in figure 6. The contour extends in one of the edges, establishing a rotational reference.

3.2.7 Marking over non-flat surfaces

When the surface of the piece is not flat, this invention suggest keeping a constant groove depth, parallel to the surface with the chosen number of levels. Maintaining a constant depth is optimal from a detection perspective.

3.3 Extracting information

3.3.1 Working with non-flat surfaces

Working with non-flat surfaces poses special difficulties because the *reference surface* has to be extracted from the contour (see section 3.2.5).

The most simple scenario for non-flat surfaces is when in one axis, the surface is flat and in the other, it can be modeled as an arc with a given curvature radius. That is, the code is over the surface of a cylinder. If the arc surface model is not sufficiently valid other polynomial models could be used.

In these circumstances it is better to use a non-square coding and privilege the axis in which the surface is flat.

When neither of the axis are flat, the problem grows in complexity because the reference level in the Z axis is dependent on the X and Y dimensions, unless the 3D model of the printed piece is previously known.

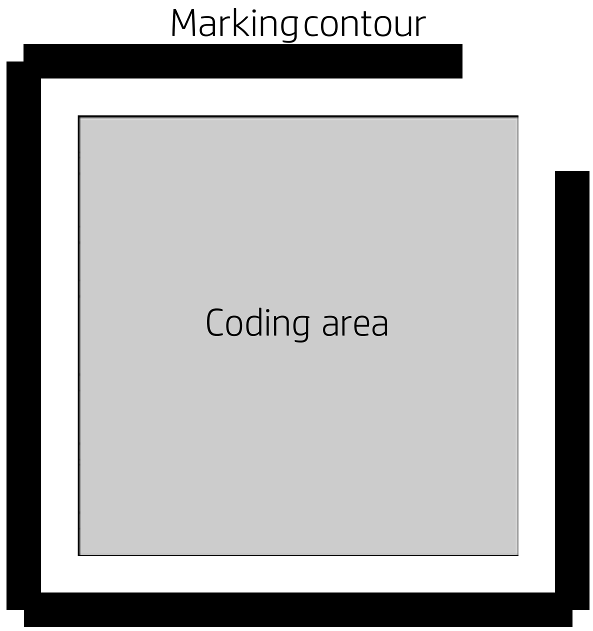

Figure 6: Setting a rotational reference - a coordinate axis reference

Version history

Version	Author/Date	Changes
1.0	LMB/March'2019	Initial version of the document
1.1	LMB/March'2019	Deeper development
1.2	LMB&JL/May'2019	Includes some JL ideas

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