

METHOD AND APPARATUS FOR SINGLE-AXIS CROSS-SECTIONAL SCANNING OF PARTS

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BACKGROUND

Cross-sectional scanning of parts, and the processing of the data generated in the same, is described in US Patents 5,139,338; 5,261,648; 5,880,961; 6,091,099; and 6,407,735. Such techniques, broadly speaking, involve the repeated optical scanning of a part that has been encased in a potting material so that, as successive layers of the part/potting combination are removed, data regarding the dimensions of the part are generated by a computer processing the scanned data of the image of each successive surface remaining after the preceding layer is removed. The optical contrast between the portions of the surface due to the potting material and those due to the material of the part identifies the dimensions of the part itself. Post-acquisition data processing techniques improve the utility of the data for various purposes. One such technique is described in US Patent 6,407,735.

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SUMMARY

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Commercial embodiments of the techniques and systems disclosed in the patents listed above generally involve what may be called an "X-Axis" approach, meaning that a stage or shuttle carries the part/potting combination linearly back and forth along an axis between separate scanning and material removal stations. This application discloses various embodiments of improved methods and apparatus for cross-sectional scanning of parts, utilizing a so-called "Z-Axis" approach. These embodiments employ a scanning station in which the focal plane of the scanning apparatus never moves in the vertical or Z direction, *i.e.*, the direction in which the stage of the part/potting combination moves. The distinct steps of material removal and scanning alternate with an intermediate step of moving the part/potting combination in the Z direction after a surface layer has been removed, thus placing the newly-created surface back into the focal plane for the next scanning step. To accomplish this, a removal station (not the stage carrying the part/potting combination) repeatedly moves in the +/-X direction, *i.e.*, into and out of the field of view of the scanning station, between scanning steps. The material removal station is specially configured to remove the desired surface layer of the part/potting

combination and the created debris, without requiring the separate environment that previously mandated the use of the X-Axis approach in commercial applications.

BRIEF DESCRIPTION OF THE DRAWINGS

The figures illustrate a preferred embodiment and thus it should be understood that minor
5 changes in shape, proportion, size, and the like are not critical to the scope of the disclosure except as specifically noted elsewhere below.

Figure 1 is a schematic side view of a system according to the detailed description below.

Figure 2 is a close-up upper perspective view of a prototype embodiment of a portion of Figure
1.

10 Figure 3 is a close-up lower perspective view of a portion of Figure 2.

DETAILED DESCRIPTION

In general terms, this application pertains to substantially improved versions of the methods and apparatus for cross-sectional scanning disclosed in US Patents 5,139,338; 5,261,648; 5,880,961; and 6,091,099. Each of these documents is incorporated by reference and familiarity with the
15 basic operating principles taught in each of these documents is assumed in the following discussion. Thus, details known in the art will be understood, such as those associated with the removal of successive layers of the part/potting combination, generation of data regarding the dimensions of the part (including the computer processing of the scanned data of the image of each successive surface remaining after the preceding layer is removed), and the post-
20 acquisition data processing techniques that improve the utility of the data for various purposes.

Referring to Figures 1-3, a prototype cross-sectional scanner system **10** comprises vertically moving stage **11** and fixed-focal plane scanner **12**. In the preferred embodiment, scanner **12** is stationary with respect to system **10** and thus only the vertical motion motion of stage **11** need be considered explicitly. However, although it is not preferred, it is possible for scanner **12** to
25 move relative to stage **11**, but the remainder of this discussion assumes that only stage **11** moves in the vertical direction with the understanding that the non-preferred approach is also included.

Stage **11** supports part/potting combination **13** so that vertical motion of stage **11** advances combination **13** in the vertical direction toward scanner **12**. The initial motion places the upper surface of combination **13** at a position corresponding to the height of one thickness of material to be removed above the fixed location **F** of the focal plane of scanner **12**. Then such a thickness
5 is removed from the upper (scanner-facing) surface of combination **13** by cutting subsystem **14** described further below. This places the upper surface so created exactly at the position of the fixed focal plane of scanner **12**, and scanning proceeds according to conventional techniques. A repeated series of stepwise motions, each corresponding in distance to the thickness of material to be removed, alternates with removal of such material followed by scanning of the new upper
10 surface created. Thus, each scanning step occurs at the location of the fixed focal plane. The part/potting combination never shuttles in the X or Y directions.

In general, scanner **12** is any multi-pixel scanner, camera, or similar optical image capture device such as a CCD array, line scan camera, or area scan camera. High resolution (155,000 pixels per square centimeter or greater) (megapixel per square inch or greater) image capture
15 equipment is preferred for scanner **12**. In this case, a preferred, but not limiting, thickness of each slice is 25.4 micrometers [one thousandth (0.001) inch]. This combination results in data points measured at a scale that is 25.4 micrometers [one thousandth (0.001) inch] in each of the three orthogonal primary directions.

References to thickness measurements should be understood as referring to measurements taken
20 normal to the surface of the part/potting combination **13**. The part itself typically is oriented at some non-orthogonal angle within the potting material and thus distances measured in the principal X, Y, and Z planes may expose amounts of the part that are greater than or less than the thickness as measured normal to the surface of the part at the location of measurement.

As shown, part/potting combination **13** is generally rectangular in cross-section in each of the
25 three principal directions. It is preferred, but not required, that combination **13** have maximum dimensions on the order of 44.4 millimeters by 63.5 millimeters by 88.9 millimeters (1-3/4 inch by 2-1/2 inch by 3-1/2 inch). This is only a preference.

Cutting subsystem **14** is, in general, any means for removing an amount of the upper surface of the part/potting combination. In the embodiment illustrated, it specifically includes a rotating
30 single-end center-cutting end mill supplied by Niagara Cutter of Amherst, NY under their model

number A377 as designated by that manufacturer. This device has three flutes in a right-hand orientation at a helix angle of 37° and dimensions (flute diameter by shank diameter by cut length by overall length) of 9.5 millimeters by 9.5 millimeters by 38.1 millimeters by 82.6 millimeters (3/8 inch by 3/8 inch by 1-1/2 inches by 3-1/4 inches). The device may be uncoated
5 or coated as available from the manufacturer; a preferred coating is TiCN. The use of three flutes is preferred for creation of a smoother surface, but the number of flutes is not by itself a critical parameter. The preferred rotation speed is 1200 rpm. The right-handed orientation, coupled with counter-clockwise rotation (as observed looking at the tip of the device, as illustrated by the curved arrow in Figure 2) means that the cutting edges advance into the
10 workpiece in the same direction as the advancing hood, *i.e.*, the positive X-direction. It is possible, but not necessary, to continue rotation of the end mill as hood **15** is withdrawn (in the -X direction) so that the rapidly spinning cutting surfaces smooth out the surface of combination **13** to ensure greater accuracy.

The cutting length of cutting subsystem **14** should be greater than the width of part/potting
15 combination **13** to ensure that the entire width of part/potting combination **13** is cut in a single pass. The position of cutting subsystem **14** with respect to the location of part/potting combination **13** is coordinated accordingly.

Hood **15** enables conventional vacuum system **16** to quickly and efficiently remove debris **18** from chamber **17** as such debris is created by cutting subsystem **14** when it removes the layer of
20 part/potting combination **13**. The exact shape of hood **15** is not critical. The function of hood **15** is to concentrate the vacuum and keep the debris within a contained volume. In the embodiment illustrated, hood **15** substantially surrounds cutting subsystem **14** but for a relatively small open throat facing the upper surface of the part/potting combination, through which debris will be collected by the vacuum (see especially Figure 3).

25 As with the cutting length of cutting subsystem **14**, the width of hood **15** (measured in the Y-direction) is greater than the width of part/potting combination **13** to ensure that the entire width is cut in a single pass. Hood **15** is mechanically attached or otherwise coordinated with the position of cutting subsystem **14** so that both advance together (in the X-direction) across the face of part/potting combination **13** to remove the surface layer of material (thus generating the
30 debris).

Any debris **18** generated by such removal is withdrawn through vacuum hood **15**, which is attached to conventional vacuum system **16**. As illustrated in this embodiment, system **10** further comprises a working chamber **17**, which is optional in the sense that system **10** could be incorporated as a sub-system of a larger system if so desired.

- 5 Thus, the amount of motion required of the various components of system **10** is substantially reduced compared to prior commercial embodiments. To summarize, focal plane **F** remains fixed at all times; table **11** (and thus part/potting combination **13**) moves only in the Z direction and not at all in the X or Y directions; hood/vacuum system **15**, **16** moves only in the +/-X directions and not in the Y or Z directions; and cutting subsystem **14** (in the preferred
10 embodiment illustrated) comprises a rotating end mill, having an axis of symmetry located such that it is coordinated with the Z position of the part/potting combination **13** to thereby remove only the necessary and desired amount of material as that axis moves in only the +/-X direction and not the Y or Z directions. The substantial reduction in the amount of moving subassemblies enables a substantial reduction in the overall size of the system **10**, because it reduces overall
15 structural, mechanical, and electrical supporting equipment. This makes the system **10** highly suitable for use with small part/potting combinations **13** such as those having the non-limiting dimensions given above.

- The techniques described above may be contrasted to the disclosure of the patents listed above, which specifically disclose the use of separate, dedicated locations for the material removal
20 station and the scanning station, such stations being separated from each other along the so-called X axis. The time required to shuttle the stage bearing the part/potting combination back and forth between these physically separate stations reduces the cycle time of the entire process compared to the approach disclosed above. By contrast, very low cycle times of approximately 8-10 seconds are believed possible in commercial production of the approach described above.

- 25 It is well known to use computers to control the operation and location of the system as well as to process the data generated by the scanning subsystem. The preferred, but not required, technique to convert the scanning data is disclosed in the patents incorporated by reference above, as well as US Patent 6,407,735, which is also incorporated by reference.

Application to Cross-Sectional Scanning Systems

The techniques described above may be employed in a cross-sectional scanning system of the following general design. Details of particular embodiments of such systems are in the patents incorporated by reference above.

- 5 The system produces electronic data representations of an object or part. The major components of the system are: (1) a data gathering station having a focal plane, the position of the focal plane being fixed relative to the surface of the part; (2) a material removal station that moves into and out of position over the surface of the part; and (3) a table providing only vertical relative movement of the part to put the surface at the position of the focal plane. The data
- 10 gathering station typically, but not necessarily, comprises: (1) an image data acquisition device for successively acquiring images of the part after removal of a predetermined contour; and (2) an electronic device operatively associated with the image data acquisition device for receiving and storing the images. The material removal station typically, but not necessarily, comprises: (1) a tool constructed and arranged to remove a predetermined contour of material from the part;
- 15 and (2) a drive mechanism constructed and arranged to provide relative movement between the tool and the part. The table holds the part and is moved by a drive mechanism constructed and arranged to provide only vertical relative movement of the table; and a means to determine the relative locations of the part and the focal plane along the vertical direction.

The operation of a typical configuration of such a system is as follows. The image data

20 acquisition device successively acquires images of the part after removal of a predetermined contour. The tool is moved into and out of relative material removing engagement with the part. The relative movement between the table and the tool along the path is such that the part and the tool are moved in material removal alignment for removing a predetermined contour of material from the part and in imaging alignment to the image data acquisition device after removal of a

25 predetermined contour. The position determining apparatus actuates the image data acquisition device at predetermined positions of the part relative to the tool. For example, a linear encoder with a scale, a sensor, and a computer may be arranged to send signals to the computer in response to the relative movement between the sensor and the scale. The computer is programmed to determine the position of the scale relative to the sensor in response to the

30 signals received from the sensor. Thus, because the scale and sensor are operatively associated

with each other, the position of the part relative to the tool along the path is incrementally determined by the computer.

Commercial embodiments of such systems employ visible light (400-700 nm wavelength) for illumination and scanners sensitive to light typically having a wavelength centered on 550 nm.

- 5 However, such values are not critical provided that sufficient contrast is provided at the detection wavelength chosen. Similarly, while directly impinging illumination and scanning normal to the surface have been illustrated, as is commercially common, more complicated geometries are possible but not preferred.

- 10 While the above description refers to many specific details for the sake of explanation, these details should not be construed as limitations unless explicitly included in the following claims.

We claim:

1. A system for scanning a substantially transparent part having an outer surface, comprising: a data gathering station, a material removal station, and a table providing only vertical movement of the part relative to the data gathering station along a vertical path; in which the part is encased in a potting material to form an assembly; the material removal station removing a portion of the assembly to expose a surface.
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2. The system of claim 1, in which the data gathering station comprises at least one of: an image data acquisition device for successively acquiring images of the part after removal of a predetermined contour; and an electronic device operatively associated with the image data acquisition device for receiving and storing the images.
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3. The system of claim 1, in which the material removal station comprises at least one of: a tool constructed and arranged to remove a predetermined contour of material from the part; and a drive mechanism constructed and arranged to provide relative horizontal movement between the tool and the part.
- 15 4. The system of claim 1, in which the table holds the part and further comprises a drive mechanism constructed and arranged to provide vertical movement between the table and the data gathering station along the vertical path.

5. A method for producing electronic data representations of an object having a plurality of surfaces, the method comprising:

encasing the object within a preselected encasing material to form an encasement, such encasing being done so that all surfaces of the object are coated with the encasing material and so that the encasing material substantially fills all interior volumes of the object;

removing successively from the encasement a plurality of layers of material, each layer of material removed having predetermined dimensions of length, width and depth and a predetermined geometric shape, so as to expose an encasement surface, and assigning a value to each layer representative of its elevation within the object;

acquiring an electronic representation of selected exposed encasement surfaces after a predetermined layer has been removed; and

processing each electronic representation to create a predetermined electronic representation of each the encasement surface.

6. The method of claim 5, in which the selected electronic representation is a solid model of the object and in which the processing step includes converting each electronic representation into a layered point cloud representative of the object.

7. The method of claim 5, in which the method further comprises lofting a surface onto each layered point cloud.

8. The method of claim 5, in which the method further comprises importing each the layer into CAD space and stacking the layers according to their assigned elevation value.

9. The method of claim 5, and further including creating a solid between adjacent layers.

10. The method of claim 5, in which the selected electronic representation is a solid model of the object.

11. The method of claim 5, in which the selected electronic representation is a surface model of the object.

12. The method of claim 5, in which the contour removing step removes contour of material such that successively exposed surfaces of the object are substantially parallel to each other, the method further including:
- identifying a feature of interest in the object; and
- 5 orienting the object such that the exposed surfaces of the object are non-parallel to the feature of interest so that at least one exposed surface extends through the feature of interest.
13. The method of claim 5, in which the acquiring step includes scanning each encasement surface using a scanner to create a scanned image of each encasement surface.
- 10 14. The method of claim 5, in which the selected electronic representation is a surface model of the object and in which the processing step includes convening each electronic representation into a line an drawing defining the perimeter edges of the internal and external edges of the object.
- 15 15. The method of claim 14, in which the processing step further includes stacking the line art drawings and lofting a surface thereon.
16. The method of claim 14, in which the processing step further includes converting the line art drawings into a vector data file.
17. The method of claim 16, in which the processing step further includes importing the vector data file into 3D CAD space and lofting a surface thereon.
- 20 18. The method of claim 5, in which the layers have upper and lower surfaces and a substantially uniform thickness, the upper and lower surfaces being substantially parallel to each other.
19. The method of claim 5, in which the electronic representation is a raster planar image and in which the processing step further includes importing the raster planar image into
- 25 3D CAD space and converting the imported images into a solid model of the object.
20. The method of claim 5, in which the layers have upper and lower surfaces being substantially parallel to each other and in which the layers increase in thickness as

successive layers of the encasement are removed to form each the predetermined contour.

21. The method of claim 5, in which the layers have upper and lower surfaces being substantially parallel to each other and in which the layers decrease in thickness as successive layers of the encasement are removed to form each the predetermined contour.

22. The method of claim 5, in which the predetermined contour has a substantially uniform thickness.

23. Apparatus for producing electronic data representations of an object, the object being formed from at least one material, the apparatus comprising:

a material removal station;

a data gathering station having a fixed position focal plane; and

a stage movable in only a vertical direction perpendicular to the fixed position focal plane;

in which the material removal station comprises:

means for removing a predetermined layer of material from the object;

in which the data gathering station comprises:

means for successively imaging the object after removal of a predetermined layer; and

means for storing data gathered by the means for imaging; and

in which the stage comprises:

a table for holding the object;

means for moving the table only in a single direction to maintain the object in imaging alignment with the means for successively imaging the object before

and after the means for removing a predetermined layer of material from the object moves into and out of position for removing a layer of material; and

means for moving the material removal station in a second direction substantially perpendicular to the Z axis into and out of relative material removing position in which it removes a pre-determined layer of material.

24. The apparatus of claim 23, in which the data gathering station further comprises means for manipulating data gathered by the imaging means and stored in the data storage means to produce a three-dimensional drawing of the object.

25. The apparatus of claim 23, in which the object is encased within an encasing material to form an encasement and in which the layer removing means removes a predetermined layer of the encasement.

26. The apparatus of claim 23, in which the means for removing a predetermined layer of material comprises an end mill including at least one flute, the end mill being rotated about an axis substantially perpendicular to the axis of motion of the stage and substantially parallel to the common plane, such that a planar surface of the object is exposed by the removal of material by at least one flute as the end mill is rotated.

27. The apparatus of claim 23, in which the removal of the predetermined layer exposes an object surface and an encasing material surface and in which the object surface contrasts with the encasing material surface so that a line of demarcation may be determined between the surfaces.

28. The apparatus of claim 23, in which the predetermined layer is of substantially uniform thickness.

29. The apparatus of claim 23, in which the data gathering station further comprises means manipulating data gathered by the imaging and stored in the data storage means to produce a three-dimensional drawing of the object.

30. A method of scanning a part, comprising:

(a) encasing the part into a potting material to form an assembly;

- (b) while the assembly is not moving, progressively horizontally removing a portion of the assembly to expose a surface;
- (c) moving the surface substantially only vertically to a position in a fixed position focal plane; and
- 5 (d) scanning the surface.

31. The method of claim 30, further comprising repeating (b) and (c) after (d).