

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

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.

SUMMARY

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.

According to a first aspect of the present invention, there is provided a system for scanning an object, wherein the object can be encased in potting material to form a potting assembly prior to scanning, the system comprising: a data gathering station including an image data acquisition device that gathers data from a focal plane, a material removal station, and a stage on which the potting assembly can be secured; wherein the stage can move toward the data gathering station on a fixed line transverse to the focal plane; wherein the system provides for selectively changing a distance between the object, when the object is encased in a potting assembly and secured to the stage, and the data gathering station along the fixed line; wherein the material removal station can repeatedly remove a series of pre-determined portions of the potting assembly to expose a new surface on the potting assembly that is positioned in the focal plane as the stage moves toward the data gathering station when the object is encased in the potting assembly and secured to the stage.

According to a second aspect of the present invention, there is provided a method of using the system of the first aspect of the present invention to produce electronic electronic data representations of the object, the object having a plurality of surfaces, wherein the method comprising: encasing the object within a preselected encasing material to form a potting assembly, such encasing being done so that all of the plurality of 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 encasement surface.

According to a third aspect of the present invention, there is provided a method of producing electronic data representations of an object, the object having a plurality of surfaces, wherein the method comprises: providing a system for scanning the object, wherein the object can be encased in potting material to form a potting assembly prior to scanning, the system comprising: a data gathering station including an image data acquisition device that gathers data from a focal plane, a material removal station, and a stage on which the potting assembly can be secured; wherein the stage can move toward the data gathering station on a fixed line transverse to the focal plane; wherein the system provides for selectively changing a distance between the object; when the object is encased in a potting assembly and secured to the stage, and the data gathering station along the fixed line; wherein the material removal station can repeatedly remove a series of pre-determined portions of the potting assembly to expose a new surface on the potting assembly that is positioned in the focal plane as the stage moves toward the data gathering station when the object is encased in the potting assembly and secured to the stage; encasing the object within a preselected encasing material to form a potting assembly, such encasing being done so that all of the plurality of 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 encasement surface.

According to a fourth aspect of the present invention, there is provided a method of scanning an object, the method comprising: (a) providing a system for scanning an object, wherein the object can be encased in potting material to form a potting assembly prior to scanning, the system comprising: a data gathering station including an image data acquisition device

that gathers data from a focal plane, a material removal station, and a stage on which the potting assembly can be secured; wherein the stage can move toward the data gathering station on a fixed line transverse to the focal plane; wherein the system provides for selectively changing a distance between the object, when the object is encased in a potting assembly and secured to the stage, and the data gathering station along the fixed line; wherein the material removal station can repeatedly remove a series of pre-determined portions of the potting assembly to expose a new surface on the potting assembly that is positioned in the focal plane as the stage moves toward the data gathering station when the object is encased in the potting assembly and secured to the stage; (b) encasing the object into a potting material to form a potting assembly; (c) while the potting assembly is not moving, progressively removing a portion of the potting assembly to expose a surface; (d) moving the potting assembly substantially only vertically to a position in a fixed position focal plane; and (e) scanning the surface.

BRIEF DESCRIPTION OF THE DRAWINGS

The figures illustrate a preferred embodiment and thus it should be understood that minor 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.

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 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-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 of stage **11** need be considered explicitly. However, although it is not preferred, it is possible for scanner **12** to 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 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 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 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 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).

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 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:
- 15 (1) a tool constructed and arranged to remove a predetermined contour of material from the part; 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.

Claims:

1. A system for scanning an object, wherein the object can be encased in potting material to form a potting assembly prior to scanning, the system comprising: a data gathering station including an image data acquisition device that gathers data from a focal plane, a material removal station, and a stage on which the potting assembly can be secured; wherein the stage can move toward the data gathering station on a fixed line transverse to the focal plane; wherein the system provides for selectively changing a distance between the object, when the object is encased in a potting assembly and secured to the stage, and the data gathering station along the fixed line; wherein the material removal station can repeatedly remove a series of pre-determined portions of the potting assembly to expose a new surface on the potting assembly that is positioned in the focal plane as the stage moves toward the data gathering station when the object is encased in the potting assembly and secured to the stage.
2. The system of claim 1, wherein the image data acquisition device can successively acquire images of the potting assembly after removal of the predetermined portions, in which the data gathering station further comprises an electronic device operatively associated with the image data acquisition device for receiving and storing the images.
3. The system of claim 1, in which the material removal station comprises at least one of: a tool constructed and arranged to remove the series of predetermined portions of the potting assembly; and a drive mechanism constructed and arranged to provide relative movement between the tool and the potting assembly.

4. The system of claim 1, wherein the fixed line is vertical and the stage further comprises a drive mechanism constructed and arranged to provide vertical movement between the stage and the data gathering station along the vertical fixed line.

5. The system of claim 1, wherein the stage moves only along the Z-axis, the image data acquisition device is stationary and the material removal station moves only along the X-axis.

6. The system of claim 5, wherein the material removal station includes a tool that rotates about the Y-axis.

7. A method of using the system of claim 1 to produce electronic data representations of the object, the object having a plurality of surfaces, wherein the method comprises:

encasing the object within a preselected encasing material to form a potting assembly, such encasing being done so that all of the plurality of 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 encasement surface.

8. The method of claim 7, wherein the selected electronic representation is a three-dimensional point cloud representative of the object.

9. The method of claim 7, further comprising lofting a surface onto each layered point cloud.

10. The method of claim 7, in which the selected electronic representation selected from the group consisting of a solid model of the object and a surface model of the object.

11. The method of claim 7, wherein the acquiring step includes scanning each encasement surface using a scanner to create a scanned image of each encasement surface.

12. The method of claim 7, wherein the removing step includes removing a contour of material such that successively exposed encasement surfaces of the object are substantially parallel to each other, the method further including the steps of:

identifying a feature of interest in the object; and

orienting the object such that the exposed encasement surfaces of the object are non-parallel to the feature of interest so that at least one exposed encasement surface extends through the feature of interest.

13. The method of claim 7, wherein the layers have upper and lower encasement surfaces and a substantially uniform thickness, the upper and lower surfaces being substantially parallel to each other.

14. A method of using the system of claim 1 used to scan an object, the method comprising:

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

15. The method of claim 14, further comprising repeating (b) and (c) after (d).

16. A method of producing electronic data representations of an object, the object having a plurality of surfaces, wherein the method comprises:

providing a system for scanning the object, wherein the object can be encased in potting material to form a potting assembly prior to scanning, the system comprising: a data gathering station including an image data acquisition device that gathers data from a focal plane, a material removal station, and a stage on which the potting assembly can be secured; wherein the stage can move toward the data gathering station on a fixed line transverse to the focal plane; wherein the system provides for selectively changing a distance between the object, when the object is encased in a potting assembly and secured to the stage, and the data gathering station along the fixed line; wherein the material removal station can repeatedly remove a series of pre-determined portions of the potting assembly to expose a new surface on the potting assembly that is positioned in the focal plane as the stage moves toward the data gathering

station when the object is encased in the potting assembly and secured to the stage;

encasing the object within a preselected encasing material to form a potting assembly, such encasing being done so that all of the plurality of 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 encasement surface.

17. The method of claim 16, wherein the selected electronic representation is a three dimensional point cloud representative of the object.

18. The method of claim 16, further comprising lofting a surface onto each layered point cloud.

19. The method of claim 16, in which the selected electronic representation selected from the group consisting of a solid model of the object and a surface model of the object.

20. The method of claim 16, wherein the acquiring step includes scanning each encasement surface using a scanner to create a scanned image of each encasement surface.

21. The method of claim 16; wherein the removing step includes removing a contour of material such that successively exposed encasement surfaces of the object are substantially parallel to each other, the method further including the steps of:

identifying a feature of interest in the object; and

orienting the object such that the exposed encasement surfaces of the object are non-parallel to the feature of interest so that at least one exposed encasement surface extends through the feature of interest.

22. The method of claim 16, wherein the layers have upper and lower encasement surfaces and a substantially uniform thickness, the upper and lower surfaces being substantially parallel to each other.

23. A method of scanning an object, the method comprising:

(a) providing a system for scanning an object, wherein the object can be encased in potting material to form a potting assembly prior to scanning, the system comprising: a data gathering station including an image data acquisition device that gathers data from a focal plane, a material removal station, and a stage on which the potting assembly can be secured; wherein the stage can move toward the data gathering station on a fixed line transverse to the focal plane; wherein the system provides for selectively changing a distance between the object, when the object is encased in a potting assembly and secured to the stage, and the data gathering station along the fixed line; wherein the material

removal station can repeatedly remove a series of pre-determined portions of the potting assembly to expose a new surface on the potting assembly that is positioned in the focal plane as the stage moves toward the data gathering station when the object is encased in the potting assembly and secured to the stage;

(b) encasing the object into a potting material to form a potting assembly;

(c) while the potting assembly is not moving, progressively removing a portion of the potting assembly to expose a surface;

(d) moving the potting assembly substantially only vertically to a position in a fixed position focal plane; and

(e) scanning the surface.

24. The method of claim 23, further comprising repeating (b) and (c) after (d).

25. The method of claim 23, wherein the stage moves only along the Z-axis, the image data acquisition device is stationary and the material removal station moves only along the X-axis.

26. The method of claim 25, wherein the material removal station includes a tool that rotates about the Y-axis.