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Closed-loop robotic deposition of material

Abstract

A robot system is configured to fabricate three-dimensional (3D) objects using closed-loop, computer vision-based control. The robot system initiates fabrication based on a set of fabrication paths along which material is to be deposited. During deposition of material, the robot system captures video data and processes that data to determine the specific locations where the material is deposited. Based on these locations, the robot system adjusts future deposition locations to compensate for deviations from the fabrication paths. Additionally, because the robot system includes a 6-axis robotic arm, the robot system can deposit material at any locations, along any pathway, or across any surface. Accordingly, the robot system is capable of fabricating a 3D object with multiple non-parallel, non-horizontal, and/or non-planar layers.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a continuation of the co-pending U.S. patent application titled, “CLOSED-LOOP ROBOTIC DEPOSITION OF MATERIAL,” filed on Apr. 24, 2017 and having Ser. No. 15/495,945. The subject matter of this related application is hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION
Field of the Invention
(1) Embodiments of the present invention relate generally to robotics and, more specifically, to closed-loop robotic deposition of material.
Description of the Related Art
(2) A three-dimensional (3D) printer is a device for fabricating real-world 3D objects based on simulated 3D models. A software application executing on a computer system typically interfaces with the 3D printer and coordinates all aspects of printing, including processing the 3D models and issuing printing commands to the 3D printer.
(3) To fabricate a 3D object, the software application first processes the 3D model to generate a set of slices. Each “slice” is a different two-dimensional (2D) cross-section of the 3D model. The software application generates each slice by computing the intersection between a 2D plane and the

3D model at a specific depth along a vertical axis associated with the 3D model. A given slice thus indicates a set of X, Y, Z coordinates where the 3D model occupies space. For a particular X, Y, Z coordinate, the Z coordinate indicates the height of the slice, while the X and Y coordinates indicate a planar location within the slice. As a general matter, each slice in the set of slices is substantially horizontal and also substantially parallel to an adjacent slice. Taken as a whole, the set of slices represents the overall topology of the 3D object to be fabricated and indicates the volume of material needed to print the 3D object.
(4) After generating the set of slices, the software application configures the 3D printer to iteratively deposit material based on the X, Y, Z coordinates included within each slice. Specifically, the 3D printer deposits material one slice at a time at the particular X, Y, Z coordinates where the 3D object occupies space. The material deposited across all X, Y, Z coordinates associated with a given slice forms a layer of material that resembles each slice. Material for each subsequent layer is deposited on top of a previous layer and substantially parallel to that previous layer. When the 3D printer has deposited material for all slices, the 3D object is complete. Although 3D printing has revolutionized fabrication of 3D objects, the fundamental approach described above suffers from two primary drawbacks.
(5) First, conventional 3D printers and corresponding software applications operate in a strictly open-loop capacity and therefore are not able to respond to feedback. Consequently, conventional 3D printers and the associated software applications typically cannot tolerate faults, deviations, or other unforeseen events that may arise or be experienced during the printing process. For example, suppose a thermoplastics 3D printer were to deposit a bead of material that had a density that exceeded the expected density for the material. Because of the higher density, the bead would take longer than expected to harden, which would then cause one or more subsequent layers of material to be deposited incorrectly when printed. Accordingly, when the 3D object completed printing, the object would sag near the location of the bead and appear shorter than expected.
(6) Second, conventional 3D printers are mechanically constrained and can deposit material only in substantially parallel, horizontal layers. Consequently, conventional 3D printers cannot fabricate 3D objects having certain types of geometry. For example, a conventional 3D printer would not be able to easily fabricate a 3D object with an extended overhanging portion, because the overhanging portion would lack physical support from any underlying layers of material.
(7) As the foregoing illustrates, what is needed in the art are more effective techniques for fabricating 3D objects.
SUMMARY OF THE INVENTION
(8) Various embodiments of the present invention set forth a computer-implemented method for fabricating a three-dimensional (3D) object, including causing a deposition tool to deposit a first portion of material proximate to a first target location, determining a first distance from the first portion of material to the first target location, updating a second target location based on the first distance to generate an updated second target location, and causing the deposition tool to deposit a second portion of material proximate to the updated second target location.
(9) At least one advantage of the techniques described herein is that the robot is capable of tolerating and compensating for a wide variety of potential faults, thereby increasing the likelihood of fabricating a 3D object that meets design specifications.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is

to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

(2) FIG. **1** illustrates a system configured to implement one or more aspects of the present invention;

(3) FIG. **2** illustrates various data and processing stages implemented by the control application of FIG. **1**, according to various embodiments of the present invention;

(4) FIG. **3** illustrates a guide curve along which the robot system of FIG. **1** deposits material, according to various embodiments of the present invention;

(5) FIG. **4** is a more detailed illustration of the guide curve of FIG. **3**, according to various embodiments of the present invention;

(6) FIG. **5** illustrates a deposition plan the robot system of FIG. **1** executes to fabricate branched structures, according to various embodiments of the present invention;

(7) FIGS. **6** and **7** illustrate how the robot system of FIG. **1** follows a deposition plan to fabricate a truss structure, according to various embodiments of the present invention;

(8) FIG. **8** is a flow diagram of method steps for fabricating a 3D object via a closed-loop control process, according to various embodiments of the present invention;

(9) FIG. **9** is a flow diagram of method steps for fabricating a branched structure based on a set of guide curves, according to various embodiments of the present invention;

(10) FIG. **10** illustrates how the robot system of FIG. **1** deposits a weld bead at a target location, according to various embodiments of the present invention;

(11) FIG. **11** illustrates how the robot system of FIG. **1** adjusts the deposition of weld beads to compensate for deviations from a guide curve, according to various embodiments of the present invention;

(12) FIGS. **12**A-**12**C illustrate various circuitry and data outputs for monitoring a welding process, according to various embodiments of the present invention;

(13) FIG. **13** illustrates a set of coordinate systems associated with different components of the robot system of FIG. **1**, according to various embodiments of the present invention;

(14) FIG. **14** illustrates relative positioning between an optical device and a 3D object under weld, according to various embodiments of the present invention;

(15) FIG. **15** illustrates how the robot system of FIG. **1** positions an optical device relative to a 3D object under weld to improve data capture, according to various embodiments of the present invention;

(16) FIG. **16** illustrates how the robot system of FIG. **1** locates a previously deposited weld bead, according to various embodiments of the present invention;

(17) FIG. **17** illustrates how the robot system of FIG. **1** determines a deposition location for a weld bead, according to various embodiments of the present invention;

(18) FIG. **18** illustrates how the robot system of FIG. **1** follows a guide curve based on previously deposited weld beads, according to various embodiments of the present invention;

(19) FIG. **19** is a screen capture that illustrates the real-time output of the robot system of FIG. **1** during welding, according to various embodiments of the present invention;

(20) FIG. **20** is a flow diagram of method steps for fabricating a 3D object based on real-time optical data, according to various embodiments of the present invention;

(21) FIG. **21** is a flow diagram of method steps for determining a weld location based on real-time optical data, according to various embodiments of the present invention;

(22) FIGS. **22**A-**22**B illustrate the robot system of FIG. **1** depositing material along non-horizontal layers of a 3D object, according to various embodiments of the present invention;

(23) FIGS. **23**A-**23**B illustrate the robot system of FIG. **1** depositing material along non-parallel layers of a 3D object, according to various embodiments of the present invention;

(24) FIGS. **24**A-**24**B illustrate the robot system of FIG. **1** depositing material along non-planar

layers of a 3D object, according to various embodiments of the present invention;
(25) FIG. **25** illustrates the robot system of FIG. **1** depositing material along non-horizontal, non-parallel, and non-planar layers of a 3D object, according to various embodiments of the present invention;
(26) FIGS. **26**A-**26**B illustrate the robot system of FIG. **1** adjusting a fabrication plan in real-time based on local deviations in a 3D object, according to various embodiments of the present invention;
(27) FIG. **27** is a flow diagram of method steps for fabricating a 3D object using different deposition techniques, according to various embodiments of the present invention; and
(28) FIG. **28** is a flow diagram of method steps for fabricating a 3D object to meet a set of design objectives, according to various embodiments of the present invention.

DETAILED DESCRIPTION

(29) In the following description, numerous specific details are set forth to provide a more thorough understanding of the present invention. However, it will be apparent to one of skill in the art that the present invention may be practiced without one or more of these specific details.

System Overview

(30) FIG. **1** illustrates a system configured to implement one or more aspects of the present invention. As shown, a robot system **100** includes a robot **110** configured to generate a three-dimensional (3D) object **120**. Robot **110** may be any technically feasible type of robot capable of operating in three dimensions. In the embodiment shown in FIG. **1**, robot **110** is a 6-axis robotic arm. Robot **110** includes a deposition tool **112** and an optical device **114**.
(31) Deposition tool **112** may be any technically feasible implement configured to output material, including a fused deposition nozzle, a fused filament device, a welder, and so forth. Deposition tool **112** is configured to deposit material onto 3D object **120** to fabricate 3D object **120**. In the embodiments discussed herein, deposition implement **112** is a metal inert gas (MIG) welder configured to deposit weld beads in order to fabricate 3D object **120**. Optical device **114** is a sensor configured to capture frames of video data related to the deposition process performed by deposition tool **112**. In practice, optical device **114** is a video camera, although other types of sensors fall within the scope of the present invention, including audio sensors, among others. In one embodiment, optical device **114** is a laser scanner configured to generate a 3D point cloud of geometry data.
(32) Robot **110** is coupled to a computing device **130**. In operation, computing device **130** receives various data signals from robot **110**, including feedback signals, sensor signals, and so forth, and then processes those signals to generate commands for controlling robot **110**. Computing device **130** transmits the commands to robot **110** to cause robot **110** to fabricate 3D object **120**. Computing device **130** includes a processor **132**, input/output (I/O) devices **134**, and a memory **136**, as shown.
(33) Processor **132** may be any technically feasible form of processing device configured process data and execute program code. Processor **132** could be, for example, a central processing unit (CPU), a graphics processing unit (GPU), an application-specific integrated circuit (ASIC), a field-programmable gate array (FPGA), any technically feasible combination of such units, and so forth.
(34) I/O devices **134** may include devices configured to receive input, including, for example, a keyboard, a mouse, and so forth. I/O utilities **134** may also include devices configured to provide output, including, for example, a display device, a speaker, and so forth. I/O utilities **134** may further include devices configured to both receive and provide input and output, respectively, including, for example, a touchscreen, a universal serial bus (USB) port, and so forth.
(35) Memory **136** may include any technically feasible storage medium configured to store data and software applications. Memory **136** could be, for example, a hard disk, a random access memory (RAM) module, a read-only memory (ROM), and so forth. Memory **126** includes a control application **138** and a database **140**. Control application **138** is a software application that, when executed by processor **132**, implements a closed-loop control process that is described in greater

detail below in conjunction with FIG. **2**.

(36) FIG. **2** illustrates various data and processing stages implemented by the control application of FIG. **1**, according to various embodiments of the present invention. As shown, a closed-loop control process **200** includes a code generator **210**, robot **110**, 3D object **120**, optical device **114**, and computer vision processor **220**.

(37) Before fabrication begins, code generator **210** receives fabrication data **202**. Fabrication data **202** defines 3D object **120** and/or defines a procedure for generating 3D object. For example, fabrication data **202** could include a 3D model of 3D object **120**. Alternatively, fabrication data **202** could include a set of guide curves that robot **110** would follow during the deposition process in order to fabricate 3D object **120**. Code generator **210** processes fabrication data **202** to generate control code **204**. Control code **204** generally specifies various actions for robot **110** to perform, and specifically indicates a set of target locations where robot **110** should deposit material. For example, control code **204** could include G-code for performing different operations as well as a set of X, Y, Z coordinates where robot **110** should deposit weld beads.

(38) During fabrication, robot **110** executes control code **204** to perform material deposition on 3D object **120**. Simultaneously, optical device **114** captures real-time video of that material deposition to generate frames **206** of video data. Computer vision processor **220** processes these frames to generate tracking data **208**. Computer vision processor **220** implements a technique known in the art as “template matching” to track specific locations on 3D object **120** where robot **110** deposits material. Computer vision processor **220** includes these locations in tracking data **208** and transmits this data to code generator **210**.

(39) Code generator **210** processes tracking data **208** and compares the specific locations where robot **110** deposited material to the set of target locations where robot **110** was instructed to deposit material. Code generator **210** analyzes the difference between each deposition location and the corresponding target location, and then updates control code **204** to compensate for those differences. In practice, numerous factors may prevent robot **110** from depositing material at the precise target locations set forth in control code **204**. For example, robot **110** and/or deposition tool **112** could be subject to process-voltage-temperature (PVT) variations, including those related to material impurities, voltage surges, heating or cooling inconsistencies, and so forth.

(40) FIGS. **3-9** describe in greater detail various techniques that robot system **100** implements in order to fabricate 3D objects.

Fabricating 3D Objects

(41) FIG. **3** illustrates a guide curve along which the robot system of FIG. **1** deposits material, according to various embodiments of the present invention. As shown, a plot **300** includes a Y axis **302** and a Z axis **304**. Plot **300** includes exemplary fabrication data **310** that includes a guide curve **312**. Guide curve **312** indicates a fabrication pathway that robot **110** should follow during material deposition. Vertices V**0**, V**1**, V**2** and V**3** are disposed at intervals along guide curve **312**. Each vertex is a target location where robot **110** should deposit material. Tangent vectors T**0**, T**1**, T**2**, and T**3** are also disposed along guide curve **312** and associated with vertices V**0**, V**1**, V**2**, and V**3**, respectively. Each tangent vector is tangent to guide curve **312** at the corresponding vertex. Robot system **110** is configured to generate the set of vertices and tangent vectors based on fabrication data **310** and/or update those vertices and vectors based on real-time feedback. Robot system **110** may then generate or update control code **204** for robot **110** by processing these vertices and tangent vectors to compensate for deviations from guide curve **312**. This approach is illustrated in FIG. **3** in contrast to a conventional approach **320**, where layer upon layer of material is deposited without applying any compensation.

(42) In one embodiment, robot system **100** implements equation **318** to successively generate vertices and tangent vectors during fabrication. To generate a given vertex, robot system compares a previous deposition location to the target location associated with that deposition location. Robot system **100** may rely on computer vision processor **220** to determine the previous deposition

locations, as described above. Then, robot system **100** corrects a subsequent target location based on the difference between the previous deposition location and the corresponding target location.

(43) More specifically, to evaluate equation **314**, robot system **100** adds to point a, a Vector, T, that has been scaled by a parameter, t or ti. The result of the bottom portion of equation **318** is, therefore, local to a and in order to drive robot **110** must be re-located with respect to the origin, A**0**; the second term of equation **318** effects this relocation. Once a suitable pixel location is found for the next weld, robot system **100** finds the next closest pixel location, At, and parameter, ti+1, along the guide curve. This repeats until the guide curve has been printed or becomes irrelevant, at which time the next guide curve in a sequence is used. Although equation **318** is vector based, any parametric equation for a circle, curve, and so forth falls within the scope of the invention. This approach is described in greater detail below in conjunction with FIG. **4**.

(44) FIG. **4** is a more detailed illustration of the guide curve of FIG. **3**, according to various embodiments of the present invention. As shown, the deposition of material onto 3D object **120** generally follows guide curve **312**. In particular, robot **110** is configured to deposit material at discrete locations between vertices V**0** through V**3** in a manner that causes 3D object **120** grow along a smooth pathway between those vertices.

(45) In embodiments where deposition tool **112** is a MIG welder, robot system **100** may deposit a sequence of weld beads at target locations that reside between adjacent vertices, thereby interpolating between vertices. In doing so, robot system **100** tracks the deposition location of each weld bead using the computer vision techniques described above. For a given weld bead, robot system **100** computes the distance between the weld bead and a subsequent vertex, and then adjusts intermediate target locations to progress towards that subsequent vertex. As shown, robot system **100** determines weld bead location V**2***i* and distance between V**2***i* and the subsequent vertex, V**3**. Robot system **100** may then adjust one or more target locations that reside between V**2***i* and V**3** so that upon reaching V**3**, robot system **100** deposits a weld bead proximate to V**3**. In this manner robot system **100** follows guide curve **312**.

(46) The above techniques may be implemented with any technically feasible type of deposition tool and with any technically feasible technique for tracking deposition locations. For example, deposition tool **112** could be a fused-deposition modeling nozzle that ejects plastic filaments, while optical device **114** could be an infrared sensor configured to track heat signatures. With any such approach, robot system **100** is capable of fabricating highly complex structures due, at least in part, to having six degrees of freedom. Furthermore, robot system **100** is capable of fabricating such structures with a high degree of accuracy because of the closed-loop deposition technique described thus far. FIGS. **5-7** discuss how robot system **100** fabricates branched structures such as 3D trusses.

(47) FIG. **5** illustrates a deposition plan the robot system of FIG. **1** executes to fabricate branched structures, according to various embodiments of the present invention. As show, timeline **500** includes deposition plan **510** displayed against time axis **502** and Z axis **504**. Deposition plan **510** indicates a set of vertices V**0**, V**1**, V**2**, V**3**, V**4**, V**5**, V**6**, and V**7** at which robot system **100** should deposit material in order to generate 3D object **120**. In addition, deposition plan **510** also indicates structural relationships between those vertices. For example, deposition plan **510** indicates that V**0** is connected to V**1**, V**1** is connected to V**2** and V**3**, V**3** is connected to V**4** and V**5**, and V**4** and V**5** are connected to V**6** and V**7**, respectively. Each such connection may be associated with a different guide curve that mathematically describes a fabrication pathway for robot system **100** to follow during deposition. Code generator **210**, discussed above in conjunction with FIG. **2**, is configured to generate deposition plan **510** when translating fabrication data **202** into control code **204**.

(48) As also shown, deposition plan **510** is broken down into separate branches. Branch **512** defines a connection between V**0** and V**1**. Branch **514** includes branch **512** and other branches that connect V**1** to V**2** and V**3**. Branch **516** defines a connection between V**1** and V**2**, while branch **518** defines a connection between V**1** and V**3**. Branch **518** includes a portion of branch **514** and also includes

other branches that connect V**3** to V**4** and V**5**. Branch **520** defines a connection between V**3** and V**4** and also includes another branch that connects V**4** and V**6**. Branch **522** defines a connection between V**3** and V**5** and also includes another branch that connects V**5** to V**7**. Branch **524** defines the connection between V**4** and V**6**, while branch **526** defines the connection between V**5** and V**7**.
(49) In order to execute deposition plan **510**, robot system **100** progresses sequentially from each vertex to a subsequent vertex and fabricates a connection between those vertices in the order shown. In doing so, robot system **100** follows the particular guide curve associated with each respective connection. One advantage of the deposition plan shown is that robot system **100** may avoid collisions between deposition tool **112** and portions of 3D object **120** during fabrication. When generating deposition plan **510**, code generator **210** may implement any technically feasible optimization algorithm to maximize the efficiency with which robot system **100** fabricates 3D object **120**, including path optimization techniques, among others.
(50) Robot system **100** executes deposition plans such as that shown here in order to generate complex structures such as trusses, as described by way of example below in conjunction with FIGS. **6-7**.
(51) FIG. **6** illustrates an example of how the robot system of FIG. **1** follows a deposition plan to manufacture a truss structure, according to various embodiments of the present invention. As shown, truss **600** includes vertices V**0** through V**7**. In order to fabricate truss **600**, robot system **100** executes a deposition plan that involves fabricating truss members sequentially for different truss portions. In particular, to generate truss portion **602**, robot system **100** fabricates truss members connecting V**0**, V**2**, and V**3** to V**4**. To generate truss portion **604**, robot system **100** fabricates truss members connecting V**1**, V**2**, and V**3** to V**5**. To generate truss portion **606**, robot system **100** fabricates truss members connecting V**2**, V**4**, and V**5** to V**6**. Finally, to generate truss portion **608**, robot system **100** fabricates truss members connecting V**3**, V**4**, and V**5** to V**7**.
(52) Robot system **100** may implement a particular technique for generating each such truss portion that is described in greater detail below in conjunction with FIG. **7**.
(53) FIG. **7** illustrates in greater detail the example of FIG. **6**, according to various embodiments of the present invention. As shown, to generate truss portion **604**, robot system performs a sequence of deposition circuits. For each deposition circuit, robot system **100** completes a set of passes. In particular, to perform deposition circuit **704**, robot system **100** completes passes **0**, **1**, and **2** to deposit material for the respective truss members connected to V**5**. To perform deposition circuit **706**, robot system **100** completes passes **3**, **4**, and **5** to deposit additional material to those truss members. To perform deposition circuit **708**, robot system **100** completes passes **6**, **7**, and **8** to deposit additional material. Finally, to perform deposition circuit **708**, robot system **100** completes passes **9**, **10**, and **11**.
(54) In this manner, robot system **100** builds up the various truss members associated with truss portion **604**. In some embodiments, robot system **100** may complete each truss member before proceeding to another truss member, thereby performing just one circuit where each truss member is fabricated completely before proceeding to a subsequent truss member. The approach set forth herein may be defined within deposition plan **510** discussed above in conjunction with FIG. **5**. In addition, robot system **100** generally performs the compensation techniques described above in conjunction with FIGS. **3** and **4** in order to generate truss members that follow guide curves defined in fabrication data **202**.
(55) The various approaches discussed thus far are also described below in stepwise fashion in conjunction with FIGS. **8-9**.
(56) FIG. **8** is a flow diagram of method steps for fabricating a 3D object via a closed-loop control process, according to various embodiments of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1-7**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.

(57) As shown, a method **800** begins at step **802**, where code generator **210** within closed-loop control process **200** of robot system **100** receives fabrication data **202**. Fabrication data **202** may define a 3D geometry associated with 3D object **120** and/or a set of fabrication paths according to which robot system **100** may deposit material to generate 3D object **120**. At step **804**, code generator **210** generates control code **204** that configures robot **110** to generate 3D object **120**. Control code **204** may include G-code or other commands for performing material deposition. At step **806**, robot **110** begins depositing material via deposition tool **112** based on control code **204**.
(58) At step **808**, robot system **100** causes optical device **114** to gather optical data representing real-time fabrication of 3D object **120**. That optical data may include frames **206** of video data and/or point cloud data gathered via laser scanner. In some embodiments, robot system **100** also gathers other types of data, including acoustic or vibrational data that represents the fabrication process. At step **810**, computer vision processor **220** within closed-loop control process **200** of robot system **100** processes the optical data gathered at step **808** to determine one or more locations where robot **110** deposited material onto 3D object **120**. Code generator **210** processes these locations to identify deviation of real-time fabrication from the fabrication procedure defined in fabrication data **202**. In embodiments where optical device **114** is a laser scanner, code generator **210** fits point cloud data generated via that laser scanner to a model of 3D object **120** using an iterative closest-point algorithm, and then evaluates deviations based on differences between the point cloud and the model. In evaluating these deviations, code generator **210** may train an artificial neural network to correlate system-level parameters, such as material feedrate and voltage load, to particular types of deviations. Then, code generator **210** may anticipate deviations and preemptively compensate accordingly.
(59) At step **812**, code generator **210** then generates updated control code **204** that compensates for these deviations. Deviations of this variety may occur due to PVT variations, among other sources of uncertainty. In performing the general approach discussed in conjunction with FIG. **8**, robot system **100** may generate complex branched structures, as described in greater detail below in conjunction with FIG. **9**.
(60) FIG. **9** is a flow diagram of method steps for fabricating a branched structure based on a set of guide curves, according to various embodiments of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1-7**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.
(61) As shown, a method **900** begins at step **902**, where code generator **210** within closed-loop control process **200** of robot system **100** processes fabrication data **202** to generate a tree of fabrication paths and a set of nodes joining branches of the tree. Each node in the set of nodes is a vertex where robot system **100** should deposit material when fabricating 3D object **120**. The fabrication paths between nodes are guide curves along which robot system **100** should deposit material. Deposition plan **510** of FIG. **5** is one example of a fabrication tree.
(62) At step **904**, code generator **210** determines an order with which the branches of the fabrication tree should be processed to perform fabrication of 3D object **120**. Code generator **210** generally determines the processing order of fabrication tree branches so that material is deposited in an upward direction and without causing collisions between robot **110** and portions of 3D object **120**.
(63) At step **906**, robot system **110** performs fabrication of a current branch of the fabrication tree. Upon completion of the current branch, robot system **110** advances to step **908** and proceeds to a subsequent branch in the fabrication tree.
(64) Referring generally to FIGS. **8-9**, robot system **100** is configured to implement the methods **800** and **900** in conjunction with one another in order to perform closed-loop fabrication of complex branched structures. In doing so, robot system **100** may implement a wide variety of computer vision processing techniques in order to track the deposition of material onto 3D object

120. FIGS. **10-21** describe some of these techniques in greater detail.

Tracking Weld Beads with Computer Vision

(65) As a general matter, FIGS. **10-21** are directed toward embodiments of robot system **110** where deposition tool **112** is a welder configured to deposit weld beads onto 3D object **120** during fabrication. However, those skilled in the art will understand that the techniques described herein can be adapted to other types of material deposition as well.

(66) FIG. **10** illustrates how the robot system of FIG. **1** deposits a weld bead at a target location, according to various embodiments of the present invention. As shown, at time t**0** robot system **100** causes deposition tool **112** to deposit weld bead **1010** onto 3D object **120**. In the embodiment shown, deposition tool **112** is a MIG welder feeding out wire to generate weld beads. At time t**1**, robot system **100** causes deposition tool **112** to retract, thereby allowing weld bead **1010** to cool. At time t**2**, robot system **100** determines the location of weld bead **1010** on 3D object **120** and then computes a target position **1020** for a subsequent weld bead. In doing so, robot system **100** compensates for any divergence between the target location for weld bead **1010** and the actual location where weld bead **1010** is deposited. At time t**3**, robot system **100** causes deposition tool **112** to begin welding proximate to target location **1020**. At time t**4**, robot system **100** completes welding, thereby generating weld bead **1022**. Weld bead **1022** may reside at or near target location **1020**.

(67) During the process described above, robot system **100** continuously captures frames **206** of video data that depict the deposition of weld beads onto 3D object **120**. Robot system **100** processes frames **206** to determine specifically where weld beads are deposited, and more generally, how closely the growth of 3D object **120** aligns with target geometry for 3D object **120** defined in fabrication data **202**. Robot system **100** may then compensate for deviations from that target geometry, as described in greater detail below in conjunction with FIG. **11**.

(68) FIG. **11** illustrates how the robot system of FIG. **1** adjusts the deposition of weld beads to compensate for deviations from a guide curve, according to various embodiments of the present invention. As shown, robot system **100** may cause deposition tool **112** to fabricate a 3D object **1100** using an open-loop process. In addition, robot system **100** also causes deposition tool **112** to fabricate 3D object **120** using closed-loop control process **200** described above.

(69) With the open-loop process, robot system **100** causes deposition tool **112** to follow guide curve **1102** during deposition. Robot system **100** generates guide curve **1102** prior to deposition based on geometrical constraints **1104** and **1106** and cannot change guide curve **1102** during deposition. Geometrical constraints **1104** and **1106** may represent a contour of a 3D model that represents the intended shape of 3D object **1100**. However, during deposition, 3D object **1100** may diverge from those geometrical constraints for various reasons. For example, gravity may cause 3D object **1100** to sag in the manner shown, therefore causing the contour of 3D object **100** to diverge from geometrical constraints **1104** and **1106**. Again, with the open-loop process shown, robot system **100** cannot adjust guide curve **1102** to respond to such divergences.

(70) By contrast, with the closed-loop process shown, robot system **100** is capable of applying guide curve adjustments in order to respect geometrical constraints. During fabrication, robot system **100** causes deposition tool **112** to follow guide curve **312**, similar to the open-loop process described above. Robot system **100** may generate guide curve **312** prior to deposition based on geometrical constraints **1110** and **1112**, similar to above. However, during deposition, if 3D object **120** diverges from those geometrical constraints, robot system **100** detects those diverges and computes various relevant parameters, including direction of divergence, magnitude of divergence, gravitational effects, and other parameters that are described in greater detail below. Based on these computed parameters, robot system **112** adjusts guide curve **112** to compensate for the corresponding divergences and to keep 3D object **120** aligned with geometrical constraints **1110** and **1112**.

(71) Robot system **100** implements a variety of logistical techniques in order to implement the

above closed-loop process, including welder monitoring and various coordinate transforms. These approaches are described in greater detail below in conjunction with FIGS. **12**A-**12**C.

(72) FIGS. **12**A-**12**C illustrate various circuitry and data outputs for monitoring a welding process, according to various embodiments of the present invention. As shown in FIG. **12**A, a controller **1200** is coupled to a circuit **1202**. Controller **1200** may be an Arduino® device or any other programmable hardware. Circuit **1202** is an application-specific integrated circuit (ASIC) that is configured to measure current consumed by deposition tool **112** during welding. Robot system **100** processes this data to estimate various physical characteristics of a weld bead being deposited in order to adjust target deposition locations and guide curves in the manner described above. As shown in FIG. **12**B, robot system **100** processes the current consumed by deposition tool **112**, as measured by circuit **1202**, to establish the linear response of an opto-coupler to the measured current. Based on this response, robot system **100** determines at any given moment whether deposition tool **112** is depositing material. FIG. **12**C illustrates the logged weld current over time.

(73) FIG. **13** illustrates a set of coordinate systems associated with different components of the robot system of FIG. **1**, according to various embodiments of the present invention. As shown, robot system **100** implements a variety of coordinate systems in order to deposit and track a weld bead **1300**, including coordinate systems **1302**, **1304**, **1306**, **1308**, **1310**, and **1312**. The coordinates of 3D object **120** are defined within coordinate system **1302**. The coordinates of a target deposition location for weld bead **1300** are defined within coordinate system **1304**. The coordinates of an actual deposition location (as determined via optical device **114**) are defined within coordinate system **1306**. The coordinates of optical device **114** are defined within coordinate system **1308**. Coordinates associated with robot **110** are defined within coordinate system **1310**. World space coordinates are defined within coordinate system **1312**. Robot system **100** may transform any of the coordinates discussed thus far into any of the other coordinate systems discussed.

(74) Robot system **100** implements the coordinate systems and transforms discussed above in order to process sensor data related to the deposition process. Robot system **100** also relies on these coordinate transforms to position optical device **114**, as described in greater detail below in conjunction with FIGS. **14-15**.

(75) FIG. **14** illustrates relative positioning between an optical device and a 3D object under weld, according to various embodiments of the present invention. As shown, fabrication tool **112** deposits weld beads along guide curve **312** to fabricate 3D object **120**. Robot system **100** is configured to transform coordinates between coordinate system **1304** and **1308** in order to maintain specific relative positioning between optical device **114** and a location on 3D object **120** where welding occurs. In particular, robot system **100** positions optical device **112** so that the axis along which optical device **114** captures optical data is perpendicular to the axis along which deposition tool **112** feeds welding material. Robot system **100** may also rotate optical device **114** to maintain a consistent alignment relative to deposition tool **112**. This positioning allows frames **206** of video data captured by optical device **114** to show the deposition process in a manner that does not require computer vision processor **220** to re-orient frames **206**. Robot system **100** may also position optical device **114** relative to a gravity vector, as described in greater detail below in conjunction with FIG. **15**.

(76) FIG. **15** illustrates how the robot system of FIG. **1** positions an optical device relative to a 3D object under weld to improve data capture, according to various embodiments of the present invention. As shown, robot system **100** may position optical device **114** anywhere along orbit **1500**. However, in order to record potential sagging due to gravity, robot system **100** may position optical device **114** perpendicular to a gravity vector. This alignment allows optical device **114** to capture frames **206** of video data that indicate when 3D object diverges from guide curve **312**. FIGS. **16-18** discuss how computer vision processor **220** processes frames **206** of video data to track deposited weld beads.

(77) FIG. **16** illustrates how the robot system of FIG. **1** locates a previously deposited weld bead,

according to various embodiments of the present invention. As shown, computer vision processor **220** processes a frame **206** of video data to identify a search frame **1600** within which material deposition occurs. Within search frame **1600**, computer vision processor searches for groups of pixels that match search template **1610**. Search template **1610** may be a conventional computer vision template that indicates a target image to locate within a search frame. In this instance, search template **1610** illustrates a characteristic weld bead during deposition.

(78) FIG. **17** illustrates how the robot system of FIG. **1** determines a deposition location for a weld bead, according to various embodiments of the present invention. As shown, robot system **100** causes deposition tool **112** to deposit a weld bead **1700** onto 3D object **120**. Subsequently, robot system **100** determines a target location **1710** for a subsequent weld bead. Robot system **100** may determine target location **1710** within a search frame **1600**(**0**). Robot system **100** then deposits a weld bead **1712** at or near target location **1710**. In practice, weld bead **1712** is typically offset from target location **1710** by an incremental amount in the X, Y, and/or Z directions due to fabrication variations. Robot system **100** processes search frames **1600**(**0**) and **1600**(**1**) to determine this incremental amount, and then adjusts the guide curve followed by robot system **100** accordingly to compensate for these offsets, as described in greater detail below in conjunction with FIG. **18**.

(79) FIG. **18** illustrates how the robot system of FIG. **1** follows a guide curve based on previously deposited weld beads, according to various embodiments of the present invention. As shown, robot system **100** causes deposition tool **112** to follow guide curve **312** during deposition of weld beads, and optical device **114** captures frames **206** of video data, as discussed previously. Once deposition tool **112** has deposited weld bead **1712** proximate to target location **1710**, code generator **210** within robot system **100** determines the distance between target location **1710** and a computed centroid location of the deposited weld bead. Code generator **210** then evaluates equations **1800** and **1802** in conjunction with one another in order to update control code **204**, thereby modifying fabrication of 3D object **120** based on feedback generated during deposition.

(80) Equation **1800** includes three terms that generally govern (i) the rate at which deposited weld beads converge or diverge with corresponding target locations, (ii) the degree with which that convergence or divergence compares to a given region, and (iii) the effects of gravity relative to deposition angle. Equation **1800** evaluates to a tangent vector along guide curve **312**. Guide curve **312** may be dynamically defined by such vectors over many evaluations of equation **1800**. Thus, by evaluating equation **1800** continuously, robot system **100** modifies the direction along which deposition tool **312** deposits weld beads. In addition, equation **1802** may be evaluated to scale the vector generated via equation **1800** based on previously computed vectors and based on an influence parameter. With this approach, robot system **100** may smooth guide curve **312** so that large divergences between weld beads and target locations do not cause correspondingly large changes to guide curve **312**. In one embodiment, robot system **100** maintains separate a print curve that is separate from guide curve, and applies modifications based on equations **1800** and **1802** to print curve in order to better align print curve with guide curve.

(81) During the deposition process, robot system **100** outputs a collection of real-time data discussed, by way of example, below in conjunction with FIG. **19**.

(82) FIG. **19** is a screen capture that illustrates the real-time output of the robot system of FIG. **1** during welding, according to various embodiments of the present invention. As shown, screen capture **1900** shows the deposition of weld beads onto 3D object **120** and also outputs other data and metadata related to material deposition. In one embodiment, robot system **100** processes any and all of the data shown in screen capture **1900** to establish one or more trends that represent the welding process over time. Robot system **100** may then combine this trend data with newly acquired real-time data to compensate for unexpected process variations.

(83) Referring generally to FIGS. **10-19**, the techniques described in these figures are also described in stepwise fashion below in conjunction with FIGS. **20-21**.

(84) FIG. **20** is a flow diagram of method steps for fabricating a 3D object based on real-time

optical data, according to various embodiments of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1-7** and **10-19**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.
(85) As shown, a method **2000** begins at step **2002**, where robot system **100** generates a guide curve that includes a sequence of vertices and a corresponding sequence of tangent vectors. Guide curve **312** shown in FIG. **3** is one example of a guide curve. Robot system **100** may generate the guide curve based on fabrication data **202**. At step **2004**, robot system **100** identifies a current vertex on the guide curve. At step **2006**, robot system **100** causes deposition tool **112** to deposit a portion of material proximate to the current vertex.
(86) At step **2008**, optical device **114** captures frames **206** of video data associated with the deposition performed at step **2006**. At step **2010**, computer vision processor **220** processed frames **206** to identify 3D coordinates where the portion of material was deposited at step **2006**. In doing so, computer vision processor **220** implements the techniques described above in conjunction with FIGS. **16-18**. Computer vision processor **220** also determines a heading vector associated with those 3D coordinates. At step **2012**, code generator **210** within robot system **100** compares the 3D location with the current vertex to determine a distance between that location and the vertex. At step **2014**, code generator **210** compares the heading vector with a tangent vector corresponding to the current vertex. At step **2016**, code generator **210** computes a vector based on the location comparison performed at step **2012**, the vector comparison performed at step **2014**, a gravity vector, and one or more previous vertices. In doing so, robot system **100** may evaluate equations **1800** and **1802**.
(87) Step **2010** of the method **2000** may be implemented via a method described in greater detail below in conjunction with FIG. **21**.
(88) FIG. **21** is a flow diagram of method steps for determining a weld location based on real-time optical data, according to various embodiments of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1-7** and **10-20**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.
(89) As shown, a method **2100** begins at step **2102**, where computer vision processor **220** receives a frame **206** of video data from optical device **114**. At step **2102**, computer vision processor **220** identifies a search frame within the frame of video data. At step **2104**, computer vision processor **220** searches within the search frame identified at step **2102** for a search template, and identifies a set of pixels within the search frame that match the search template. At step **2108**, computer vision processor determines a deposition location within the search frame based on the template match. In doing so, computer vision processor **220** may determine a centroid location for a weld bead depicted in the search frame. Persons skilled in the art will understand that the method **2100** represents only one approach to determining a weld location, and that other approaches may also be possible.
(90) Referring generally to FIGS. **1-21**, the techniques described herein allow robot system **100** to perform highly complicated fabrication operations to generate complex 3D objects. Because such operations cannot be performed with conventional 3D printers, such 3D objects cannot be created with conventional 3D printing techniques either. FIGS. **22**A-**27** describe various unconventional printing techniques made possible by robot system **100**.
Unconventional Deposition Techniques
(91) FIGS. **22**A-**22**B illustrate the robot system of FIG. **1** depositing material along non-horizontal layers of a 3D object, according to various embodiments of the present invention. As shown in FIG. **22**A, robot system **100** causes deposition tool **112** to deposit a layer **2202** of material when fabricating a 3D object **2200**. A conventional 3D printer would only be able to deposit another horizontal layer having equal thickness and continuous cross-section compared to layer **2202**.

(92) However, as shown in FIG. **22**B, robot system **100** is capable of depositing a layer **2204** that is not horizontal to layer **2202** and has a cross-section with varying thickness. Robot system **100** may perform such deposition by varying the flow rate of material used for deposition and/or following guide curves that define layer **2204**, while also varying the angle of deposition tool **112** relative to horizontal.
(93) FIGS. **23**A-**23**B illustrate the robot system of FIG. **1** depositing material along non-parallel layers of a 3D object, according to various embodiments of the present invention. As shown in FIG. **23**A, robot system **100** causes deposition tool **112** to deposit layers **2302**, **2304**, **2306**, and **2308** when fabricating a 3D object **2300**. A conventional 3D printer can only deposit additional layers on top of layer **2308**.
(94) However, as shown in FIG. **23**B, robot system **100** is capable of depositing additional layers **2310**, **2312**, **2314**, **2316**, and **2318** at off-horizontal angles. Robot system **100** may perform such deposition based on a branching deposition plan, such as deposition plan **510** shown in FIG. **5**.
(95) FIGS. **24**A-**24**B illustrate the robot system of FIG. **1** depositing material along non-planar layers of a 3D object, according to various embodiments of the present invention. As shown in FIG. **24**A, robot system **100** causes deposition tool **112** to deposit layers **2402**, **2404**, **2406**, and **2408** to fabricate 3D object **2400**. Unlike conventional 3D printers, robot system **100** is capable of depositing layers that are non-planar, as is shown.
(96) As shown in FIG. **24**B, robot system **100** fabricates non-planar layers by sweeping deposition tool **112** from position **2410** to position **2414** across an arc **2414**. To implement this technique, robot system **100** may follow a guide curve that traverses from vertex **2408**(**0**) to vertex **2408**(**1**) along arc **2414**.
(97) FIG. **25** illustrates the robot system of FIG. **1** depositing material along non-horizontal, non-parallel, and non-planar layers of a 3D object, according to various embodiments of the present invention. As shown, robot system **100** causes deposition tool **312** to fabricate a 3D object **2500** that includes multiple non-planar, non-horizontal, and non-parallel layers **2502**, **2504**, and **2506**. 3D object **2500** has a central axis **2510**. Because this central axis is curved, layers **2502**, **2504**, and **2506** vary in thickness between side **2512** and **2514** of 3D object **2500**. As fabrication progresses and 3D object **2500** grows, that object will begin to overhang towards side **2514**. Unlike conventional 3D printers, though, robot system **100** does not need to provide support for this overhang. In one embodiment, robot system **100** fabricates 3D object **2500** by generating one continuous spiraling layer aligned with central axis **2510**.
(98) FIGS. **26**A-**26**B illustrate the robot system of FIG. **1** adjusting a fabrication plan in real-time based on local deviations in a 3D object, according to various embodiments of the present invention. As shown, robot system **100** causes deposition tool **112** to deposit layers of material to fabricate 3D object **2600**. Optical device **114** detects a dimple **2602** in a previous layer of 3D object **2600**. However, 3D object **2600** is subject to the constraint that top surface **2604** of 3D object **2600** must have an angle **2610** relative to horizontal. In order to adhere to this constraint, robot system **100** dynamically accounts for dimple **2602** in the manner shown in FIG. **26**B.
(99) As shown in FIG. **26**B, robot system **100** adjusts deposition rate **2610** to increase proximate to dimple **2602** and decrease in other places. For example, deposition rate **2610**(**2**) is greater than deposition rates **2610**(**1**) and **2610**(**3**) and much greater than deposition rates **2610**(**0**) and **2610**(**4**), as indicated by arrow thickness. Thus, progressing from left to right, deposition rate **2610** increases when approaching dimple **2602** and then decreases afterward. Robot system **100** determines deposition rates **2610** based on frames of video data gathered by optical device **114** and processed by computer vision processor **220**.
(100) FIG. **27** is a flow diagram of method steps for fabricating a 3D object using different deposition techniques, according to various embodiments of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1-7**, **10-20**, and **22**A-**26**B, persons skilled in the art will understand that any system configured to perform the method steps,

in any order, is within the scope of the present invention.

(101) As shown, a method **2700** begins at step **2702**, where code generator **210** within closed-loop control cycle **200** of robot system **100** receives fabrication data **202** that defines a fabrication procedure. At step **2704**, code generator **210** processes fabrication data **202** to generate a set of guide curves along which robot system **100** deposits material. At step **2706**, robot system **100** causes deposition tool **112** to deposit material along a first path having a first orientation relative to horizontal and aligned with a first axis. At step **2708**, robot system **100** causes deposition tool **112** to deposit material along a second path having a second orientation and with a deposition rate that changes along the second path. In this manner, robot system may fabricate 3D object **2200** shown in FIG. **22**.

(102) At step **2710**, robot system **100** causes deposition tool **112** to deposit material along a third path having a third orientation relative to horizontal and aligned with a second axis having a first angle relative to the first axis. In this manner, robot system **100** may fabricate 3D object **2300** shown in FIG. **23**. At step **2712**, robot system **100** causes deposition tool **112** to deposit material along a fourth path that is non-planar by sweeping deposition tool **112** from a start angle to a finish angle along a first arc that is aligned with the fourth path. Robot system **100** implements step **2710** to generate 3D object **2400** of FIG. **24**.

(103) By performing individual steps of the method **2700**, robot system **100** can fabricate any of the shapes shown in FIGS. **22**A-**24**B. In addition, by performing all steps in conjunction with one another, robot system **100** may fabricate complex objects such as 3D object **2500** shown in FIG. **25**.

(104) FIG. **28** is a flow diagram of method steps for fabricating a 3D object to meet a set of design objectives, according to various embodiments of the present invention. Although the method steps are described in conjunction with the systems of FIGS. **1-7**, **10-20**, and **22**A-**26**B, persons skilled in the art will understand that any system configured to perform the method steps, in any order, is within the scope of the present invention.

(105) As shown, a method **2800** begins at step **2802**, where code generator **210** within closed-loop control cycle **200** of robot system **100** receives fabrication data **202** that defines a fabrication procedure, similar to step **2702** of the method **2700**.

(106) At step **2804**, code generator **210** within closed-loop control process **200** of robot system **100** processes fabrication data **202** to identify a set of design objectives associated with a 3D object to be fabricated based on the fabrication procedure. The design objectives indicate that certain portions of the 3D object have a specific shape, as described by way of example in conjunction with FIG. **26**.

(107) At step **2804**, code generator **210** processes fabrication data **202** to generate a set of paths for fabricating the 3D object. At step **2806**, robot system **100** causes deposition tool **112** to deposit material onto a first substrate of the 3D object along a first path in the set of paths. At step **2808**, robot system **100** detects variations in the first substrate and, in response to those variations, adjusts deposition of the material along the first path to compensate. In one embodiment, robot system **100** implements a laser scanner to detect variations in the first substrate. Dimple **2602** shown in FIGS. **26**A-**26**B is one example of a variation. According to this technique, robot system **100** may meet the design objectives set forth in fabrication data **202** despite local variations in the 3D object.

(108) In sum, a robot system is configured to fabricate three-dimensional (3D) objects using closed-loop, computer vision-based and/or reality capture-based control. The robot system initiates fabrication based on a set of fabrication paths along which material is to be deposited. During deposition of material, the robot system captures video data or 3D point cloud data and processes that data to determine the specific locations where the material is deposited. Based on these locations, the robot system adjusts future deposition locations to compensate for deviations from the fabrication paths. Additionally, because the robot system includes a 6-axis robotic arm, the robot system can deposit material at any location, along any pathway, or across any surface. Accordingly, the robot system is capable of fabricating a 3D object with multiple non-parallel, non-

horizontal, and/or non-planar layers.
(109) At least one advantage of the techniques described above is that the robot system is capable of tolerating and compensating for a wide variety of potential faults, thereby increasing the likelihood of fabricating a 3D object that meets design specifications. Those potential faults may relate to process-voltage-temperature (PVT) variations, material composition inconsistencies, and unexpected heat transfer and/or cooling effects, among others. In addition, the robot system is capable of fabricating 3D objects with a much wider variety of geometries compared to conventional 3D printers, including geometries that include overhangs and geometries with complex branching structures.
(110) The descriptions of the various embodiments have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments.
(111) Aspects of the present embodiments may be embodied as a system, method or computer program product. Accordingly, aspects of the present disclosure may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a “module” or “system.” Furthermore, aspects of the present disclosure may take the form of a computer program product embodied in one or more computer readable medium(s) having computer readable program code embodied thereon.
(112) Any combination of one or more computer readable medium(s) may be utilized. The computer readable medium may be a computer readable signal medium or a computer readable storage medium. A computer readable storage medium may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. More specific examples (a non-exhaustive list) of the computer readable storage medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.
(113) Aspects of the present disclosure are described above with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems) and computer program products according to embodiments of the disclosure. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, enable the implementation of the functions/acts specified in the flowchart and/or block diagram block or blocks. Such processors may be, without limitation, general purpose processors, special-purpose processors, application-specific processors, or field-programmable processors or gate arrays.
(114) The flowchart and block diagrams in the figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods and computer program products according to various embodiments of the present disclosure. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should

also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.
(115) While the preceding is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

Claims

1. A computer-implemented method for fabricating a three-dimensional (3D) object, the method comprising: causing a deposition tool to deposit a first weld bead at a first deposition location on the 3D object; capturing first optical data from the first deposition location while depositing the first weld bead; identifying a first image of the first weld bead within the first optical data; determining the first deposition location based on the first image; determining a second deposition location on the 3D object based, at least in part, on the first deposition location comprising comparing a distance between the first deposition location and a target location to a radius of influence to generate a first ratio, wherein the second deposition location is determined based, at least in part, on the first ratio; and causing the deposition tool to deposit a second weld bead at the second deposition location on the 3D object.
2. The computer-implemented method of claim 1, wherein the first optical data comprises a search frame, and identifying the first image comprises searching the search frame based on a search template that includes a characteristic image of a weld bead during deposition.
3. The computer-implemented method of claim 1, wherein determining the first deposition location comprises identifying a centroid location within the first image of the first weld bead.
4. The computer-implemented method of claim 1, wherein capturing the first optical data comprises positioning an optical device based on the deposition tool that, in operation, deposits the first weld bead.
5. The computer-implemented method of claim 1, wherein determining the second deposition location further comprises: generating a heading vector that indicates a direction in which the first weld bead is deposited; generating a pull vector between the first deposition location and a target location associated with the first deposition location; combining the heading vector with the pull vector to generate a combined vector; and evaluating a rate of change of the combined vector to determine the second deposition location.
6. The computer-implemented method of claim 5, wherein determining the second deposition location further comprises generating a guide vector based on the rate of change of the combined vector and the first ratio, wherein the second deposition location resides along the guide vector.
7. One or more non-transitory computer-readable media including instructions that, when executed by one or more processors, cause the one or more processors to fabricate a three-dimensional (3D) object by performing the steps of: causing a deposition tool to deposit a first weld bead at a first deposition location on the 3D object; capturing first optical data from the first deposition location while depositing the first weld bead; identifying a first image of the first weld bead within the first optical data; determining the first deposition location based on the first image; determining a second deposition location on the 3D object based, at least in part, on the first deposition location comprising comparing a distance between the first deposition location and a target location to a radius of influence to generate a first ratio, wherein the second deposition location is determined

based, at least in part, on the first ratio; and causing the deposition tool to deposit a second weld bead at the second deposition location on the 3D object.
8. The computer-implemented method of claim 1, wherein the first optical data is captured from the first deposition location while depositing the first weld bead via an optical device pointed in a direction that is perpendicular to a direction associated with a gravity vector.
9. The one or more non-transitory computer-readable media of claim 7, wherein the step of capturing the first optical data comprises positioning an optical device based on the deposition tool.
10. The one or more non-transitory computer-readable media of claim 9, wherein the first optical data comprises a search frame, and the step of identifying the first image comprises searching the search frame based on a search template that includes a characteristic image of a weld bead during deposition.
11. The one or more non-transitory computer-readable media of claim 9, wherein the step of determining the first deposition location comprises identifying a centroid location within the first image of the first weld bead.
12. The one or more non-transitory computer-readable media of claim 9, wherein the step of determining the second deposition location further comprises: generating a heading vector that indicates a direction in which the first weld bead is deposited; generating a pull vector between the first deposition location and a target location associated with the first deposition location; combining the heading vector with the pull vector to generate a combined vector; and evaluating a rate of change of the combined vector to determine the second deposition location.
13. The one or more non-transitory computer-readable media of claim 9, wherein the first weld bead and the second weld bead reside on a first branch of the 3D object, and further comprising the step of depositing a third weld bead on a second branch of the 3D object.
14. A system, comprising: one or more memories that include instructions; and one or more processors that are coupled to the one or more memories and, when executing the instructions, are configured to: cause a deposition tool to deposit a first weld bead at a first deposition location on the 3D object; capture first optical data from the first deposition location while depositing the first weld bead; identify a first image of the first weld bead within the first optical data; determine the first deposition location based on the first image; determine a second deposition location on the 3D object based, at least in part, on the first deposition location comprising comparing a distance between the first deposition location and a target location to a radius of influence to generate a first ratio, wherein the second deposition location is determined based, at least in part, on the first ratio; and cause the deposition tool to deposit a second weld bead at the second deposition location on the 3D object.
15. The system of claim 14, wherein the one or more processors are further configured to generate a tangent vector based on the first deposition location and a guide curve, and wherein the second deposition location is further based, at least in part, on the tangent vector.
16. A computer-implemented method for fabricating a three-dimensional (3D) object, the method comprising: causing a deposition tool to deposit a first weld bead at a first deposition location on the 3D object; capturing first optical data from the first deposition location while depositing the first weld bead; identifying a first image of the first weld bead within the first optical data; determining the first deposition location based on the first image; determining a second deposition location on the 3D object based on the first deposition location; causing the deposition tool to deposit a second weld bead at the second deposition location on the 3D object, wherein the first weld bead and the second weld bead reside on a first branch of the 3D object; and depositing a third weld bead on a second branch of the 3D object.