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Closed-Loop Manufacturing System Using Radar

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Abstract:

A closed-loop manufacturing system is designed to use small, low-cost radar to observe a manufacturing process and measure characteristics of a build product. The build data measured by the radar includes geometry, reflection characteristics, material density, and high resolution maps. A controller processes the build data to detect errors. Example errors include mistakes in geometry, delamination, curling, shrinkage, lack of material uniformity, air bubbles, inclusions, and contaminations in the build product. Based on the detected errors, the controller determines build corrections and reports the build corrections to the manufacturing process. Using radar, the closed-loop manufacturing system automatically detects and corrects errors, saving time and resources in additive and subtractive manufacturing.

Keywords: radar, closed-loop, additive manufacturing, subtractive manufacturing, build integrity

Background:

Conventional additive and subtractive manufacturing blindly manufacture layers without measuring and inspecting integrity of a product throughout the process. As a result, errors go undetected and uncorrected, wasting time and resources. External sensors, such as cameras and lasers are large, slow, expensive, low resolution, and unable to work with transparent materials. Furthermore, touch sensors are slow and invasive.

Description:

To address this problem, a closed-loop manufacturing system is designed to use small, low-cost radar to observe a manufacturing process and measure characteristics of a build product. The manufacturing process may involve additive and subtractive manufacturing and the radars are configured to observe the process of a head depositing and subtracting layers as well as a curing process. Positioning the radar near the head provides the radar with an unobstructed view of the build product. The radar is housed using an external layer of material, transparent to radar frequencies, to provide protection without degrading performance. Additionally, physically attaching or embedding the radar in the head allows the radar to move with the head. The build data measured by the radar includes geometry, reflection characteristics, material density, and high resolution maps. A controller processes the build data to detect errors in the build product. Example errors include mistakes in geometry, delamination, curling, shrinkage, lack of material uniformity, air bubbles, inclusions, and contaminations in the build product. Based on the detected errors, the controller determines build corrections and reports the build corrections to the manufacturing process. The manufacturing process implements the build correction. Using radar, the closed-loop manufacturing system automatically detects and corrects errors, saving time and resources during additive and subtractive manufacturing.

Figure 1 depicts an example closed-loop manufacturing system, which is described in further detail below.

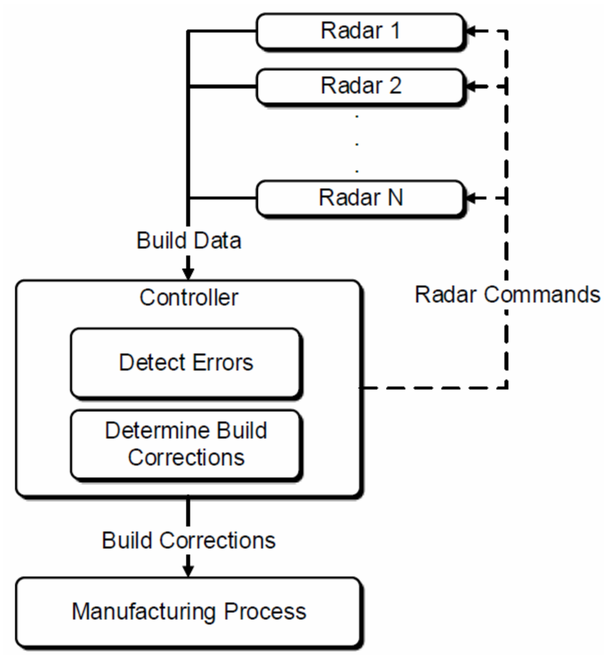

Figure 1

A variety of small, low-cost radar sensors may be used to implement the radar. The radar sensors may produce a variety of radiation fields, including wide fields, narrow fields, shaped fields (hemisphere, cube, fan, cone, cylinder), steered fields, un-steered fields, close range fields, and far range fields. Additionally, the radar sensors may use continuous wave or pulsed Doppler and a variety of frequencies, update rates, pulse widths, interpulse periods, transmit powers, and modulations. The radar sensors are designed to physically withstand vibrations generated during the manufacturing process and may optionally compensate for the vibrations. The radar sensors may be further configured in real-time by the controller. As an example, the controller may control the type of build data measured by the radar according to the manufacturing process.

Furthermore, the radar is configured to provide high-resolution build data. When the radar is attached to the moving head, the radar may use Synthetic Aperture Radar (SAR) to increase azimuth resolution. SAR allows the radar to synthetize a long antenna from the returns received over a period of time by the real, moving antenna. Additionally, multiple antennas may be used to make the beam width narrower. Furthermore, range resolution is increased by decreasing the pulse width and/or using pulse compression.

The radar measures build data by transmitting radio waves and receiving reflected radio waves. As the radar illuminates a patch on a build product, the radar analyzes the reflected energy from the patch to determine dimensions and location of the patch, reflection characteristics of the patch, and patch density. Furthermore, the radar provides a high resolution map of the patch.

The radar reports the build data to the controller. The controller analyzes the build data and detects errors. The controller detects geometry errors caused by drift in the manufacturing process and errors caused by lack of material uniformity, air bubbles, inclusions, and contaminations in the build product. Based on the analysis, the controller determines the build corrections. The build corrections are reported to the manufacturing process which implements the build corrections. Example build corrections include adjusting the position of the head, adjusting tolerances in the manufacturing process, and alerting an operator. The build corrections are also used to compile a build quality report. The build quality report provides valuable feedback regarding performance of the manufacturing process, improving future builds. The controller is implemented in software and executed by a processor and may be separate from or included in the manufacturing process.

This manufacturing system is closed loop. The radar continues to report build data to the controller, the controller analyzes the received build data and determines build corrections, and the manufacturing process implements the build corrections. As such, the closed-loop manufacturing system automatically and intelligently responds to errors detected during the manufacturing process.

Example:

Figure 2 depicts an example additive manufacturing process.

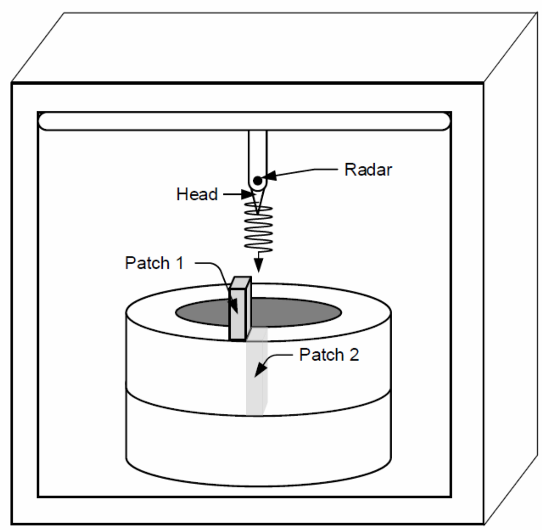

Figure 2

In Figure 2, the radar is attached to the moving head and measures build data with respect to deposited patch 1 and a previous deposited patch 2. The radar reports patch location and dimensions, patch reflection characteristics, patch density, and high resolution patch maps to the controller. The controller analyzes the build data to detect errors. As the head moves and deposits the next layer, unexpected drifts in the head's position or errors in depositing the material cause undesired deformations in the product. The build data provided by the radar allows the controller to detect these errors, determine the build corrections, and notify the manufacturing process.

As another example, the build data for patch 1 measured by the radar indicates a presence of a contaminant. The contaminant may be determined based on a difference in the reflection characteristics or the high resolution patch maps of patch 1. The controller analyzes the build data and detects the contaminant. The controller sends build corrections to the manufacturing process indicating the existence of the contaminant. In response, the manufacturing process stops the manufacturing process and alerts an operator.

Figure 3 depicts using the radar to provide profile measurements of the build product.

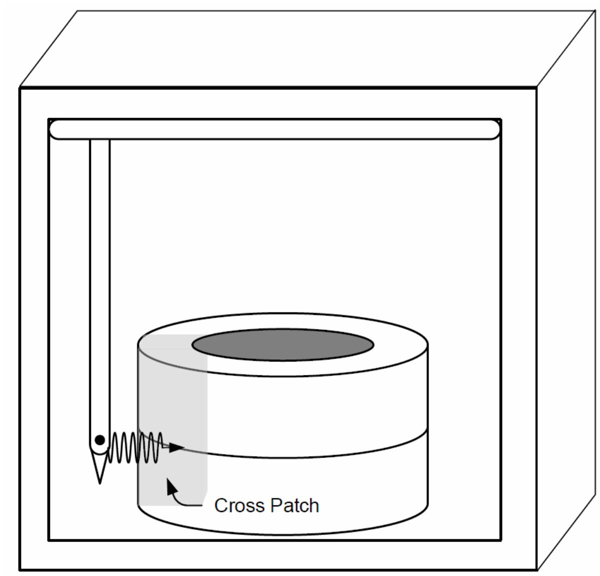

Figure 3

In Figure 3, the radar is swept along an outside of the build product. In this way, the radar measures build data with respect to cross patches, which provide a profile view of multiple deposited layers in the build product. The profile build data is used by the controller to detect delamination between the multiple deposited layers as well as height errors in the build product. The profile build data is collected during the manufacturing process and at the end of the manufacturing process. In addition, the profile build data is used in the build quality report. As an example, based on the profile build data, the controller determines the product height is too small. The controller reports build corrections to the manufacturing process, enabling the manufacturing process to correct the height error by adding additional deposited layers to the build product.