Title:

Using Collaborative Robots to Assist with Travel Path Development for Material Deposition Based Additive Manufacturing Processes

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Introduction:

Additive manufacturing (AM), or 3D printing, is a manufacturing solution where a CAD model is sliced into layers, and each layer manufactured using 2D travel path solutions. The final component is the resultant of a set of stacked layers. Typically the outer boundary contour are created first (either by depositing material or applying a heat source onto deposited material), and then a raster scan zig-zag pattern is used to fill the interior of the layer (Fig. 1(a)). For thin walled components, simple contours may be stacked to create a 3D component (Fig. 1 (b)). The AM fabrication strategy is advantageous compared to the thin wall problem set, as there is significantly less material usage. For the hexagonal shape in Fig. 1(b), the deposited material is approximately 12.5% of a solid hexagon with the same perimeter contour or 8% of a cubic stock block (a bounded cube). Consequently, the material deposition AM family of solutions introduces significant materials savings opportunities, especially for expensive, exotic metal alloys (i.e. superalloys, titanium, etc.).

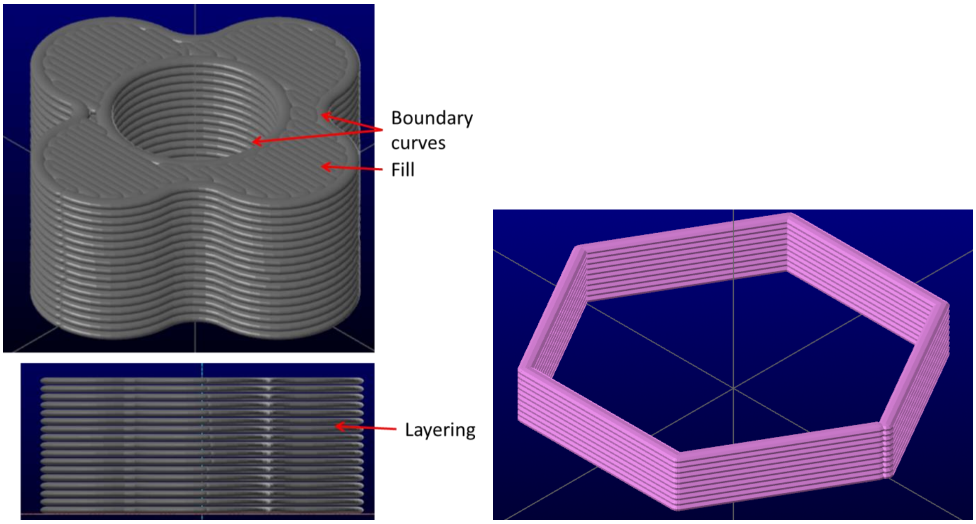

Fig. 1: Virtual simulation of an additive manufactured component, illustrating the contour and fill tool paths, and the layering.

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There are powder bed based AM metal fabrication solutions that are commercially available (direct metal laser sintering), but these systems are enclosed, which limits there work envelope, and only one material is used. Many metal bead based deposition systems are being developed by original equipment manufacturer (OEM) solution providers. Platforms for AM solutions are being established for laser cladding [6, 7], electron beam manufacturing [4], cold metal transfer as well as more conventional welding processes, such as metal inert gas (MIG) welding. Multi-axis system configurations, which could be serial 6 axis robot based or machine tool based, are being developed.

Unlike machining, there is limited software is available for process planning. As heat cycling is occurring during the process (Fig. 2), AM processes have distinctive tool path requirements, and the solutions are unique for each material-machine-part geometry combination. There are challenges linking the bead geometry to a machines process settings (travel speed, material feed rate, power input, etc.), and in understanding the resulting component properties.

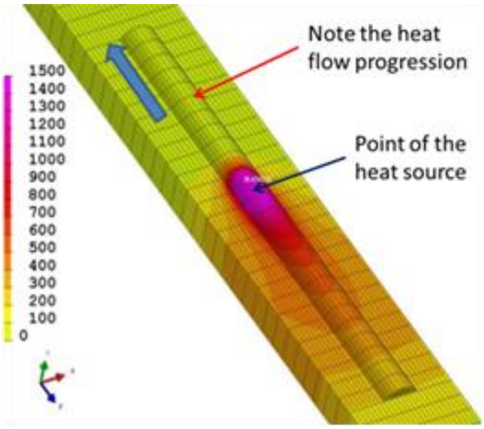

Fig. 2: Heat progression simulation for a laser cladding bead (420 stainless steel) being deposited onto AISI 1018 mild steel [4].

Process planners developing these technologies have distinct ideas how to generate travel path solutions as they have knowledge and/or experience with the heat transfer and cycling conditions, and the solutions will vary based on the part geometry. Introducing internal ribs to the hexagon (Fig. 3) presents precedence issues at the intersection points, and flow directional issues.

The fundamental question is: how can AM metal deposition tool paths be created that are appropriate with respect to the problem being solved? Along with the process-material combination, there are multiple cases related to geometry that need to be considered, which are: (i) the size of the deposited bead to the geometry, (ii) corner filleting conditions, and (iii) the control logic that occurs at multi-point junctions. With machining, establishing an overlapping criterion is standard; however, interference conditions occur for metal beads. A 100% overlap would stack one bead on top of another. When the bead size is smaller than the rib geometry, a contour and fill strategy will need to be employed. Multiple contours (Fig. 3 (b)) or a contour zig-zag fill (Fig. 3 (c)) would be a standard approach. However, for a bead thickness equal or greater than the model geometry, a median line needs to be established, and a tool path decision is required at each intersection point.

The decision would consider the input heat (a path direction constraint), and the feasibility of starting and stopping the material feeding system (a discontinuity constraint). The long term goal is to fabricate near net shapes for subsequent machining. Laser cladding and electron beam welding beads can vary between 2 – 10 mm. The power input from electron beam additive manufacturing (EBAM) may reach 42kW.

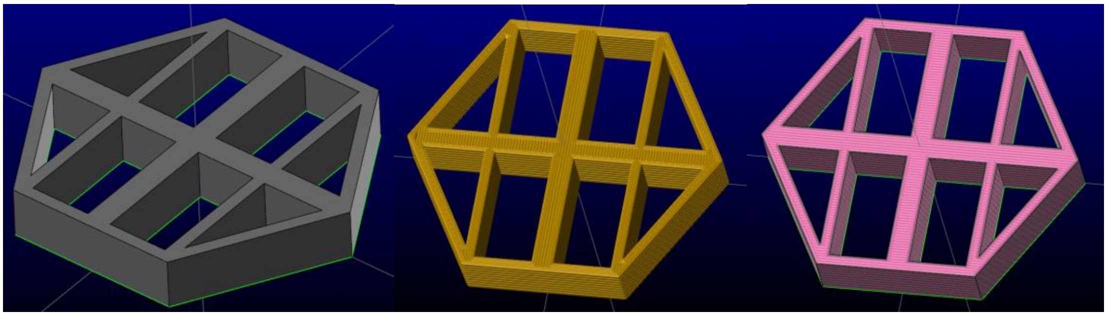

Fig. 3: (a) Boundary with variable thickness internal ribs, (b) 3 boundary curves with 50% overlap, and a 90° fill pattern, (c) 1 boundary curve, 50% overlap and a 0° fill pattern.

In the full paper, the logic challenges are presented. Experienced process planners know the preferred path strategy based on heat flows and the part geometry; however, presently they must create machining tool paths and modify them to suit. A method of ‘teaching’ a formalized tool path strategy needs to be developed, which is the objective of this research. It is proposed to ‘trace’ a tool path using a collaborative robot and a representative drawing. This representative data set will be imported into a CAD/CAM software package, and adjusted to suit based on the actual geometry. The proof of concept is presented in this work.

Collaborative Robots:

Collaborative robots (cobots) allow human operators to engage directly with this automation solution to realize enhanced performance. This advanced manufacturing technology solution is capable of transforming industrial automation [9]. Cobots are designed to safely and effectively interact with humans while performing tasks independently or collaboratively in a shared workspace. Human decision making is linked with the strength, robustness, durability, and dexterity of a robot. There are several cobot solutions that exist (e.g., ABB FRIDA - YuMi, BOSCH – APAS, F&P Personal Robotics -Prob 1U, Yaskawa Motoman, SDA10F dual-arm, Rethink Robotics –Baxter, and Universal Robots:UR3, UR5, and UR10). Researchers such as Ananda [1] predict 150,000 cobots are to be installed worldwide over the next three years. The Executive Summary World Robotics [5] predicts that double-digit growth of industrial robotics will happen between 2016 and 2019 and that linking the real-life factory with virtual reality will play an increasingly important role in global manufacturing.

Leveraging human and cobot synergies can only be realized when the cobot and human tasks are well-defined [2]. However, this does not mean that the tasks details are precisely known, exactly repeatable, and consistent. The ability to adapt to circumstances is a strength of this technology. For this work, the ease of using a cobot (Fig. 4) is leveraged as a teaching tool to capture an idealized tool path strategy. The Rethink Robotics –Baxter cobot is employed to capture the digital data for start and stop points, and travel directions. Joint angle data is extracted, and translated into the end effector X, Y, Z coordinates. For this research at this time, manual methods are employed.

Fig. 4: (a) Baxter robot, (b) right arm with joint labels.

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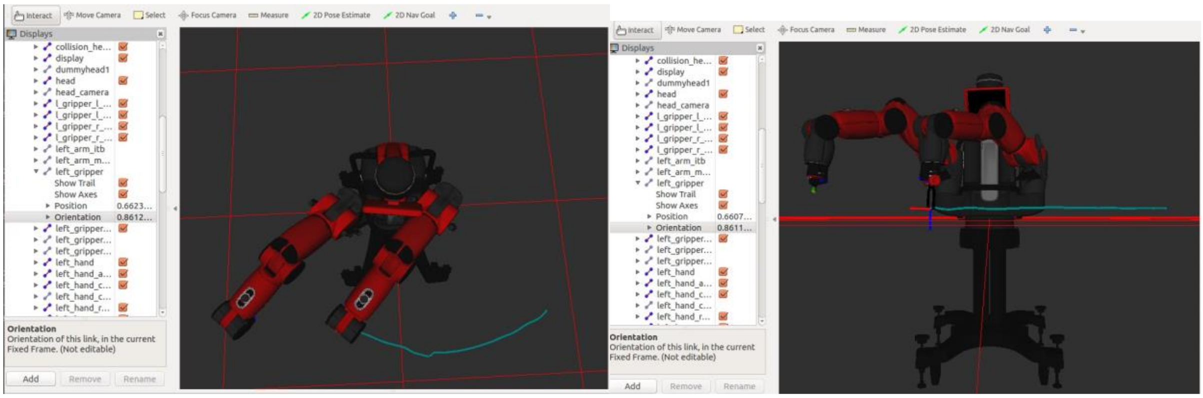
The Baxter robot has seven joints each, for a left and right arm. The kinematic model has been previously developed, and for a detailed analysis, refer to e Silva et al [3]. This unified model contains seven reconfiguration parameters: K1, K2, K3, K4, K5, K6, and K7. Using kinematic theory, the Baxter joint values are converted to the World Frame (points' position and orientation). Using the Matalb tools, the trajectory has been validated and visualized.

Results:

In Fig. 5, various views are provided which illustrate the trajectory path for a test case. The trajectory points are in Joint space and are expressed in radians.



Position 0.6623...
Orientation 0.8612...
Position 0.6607...
Orientation 0.8611...

Fig. 5: (a) Baxter robot and trajectory view 1, (b) view 2.

Using the Matalb tools, joint data is converted to Cartesian data points. The trajectory has been visualized (Fig. 6).

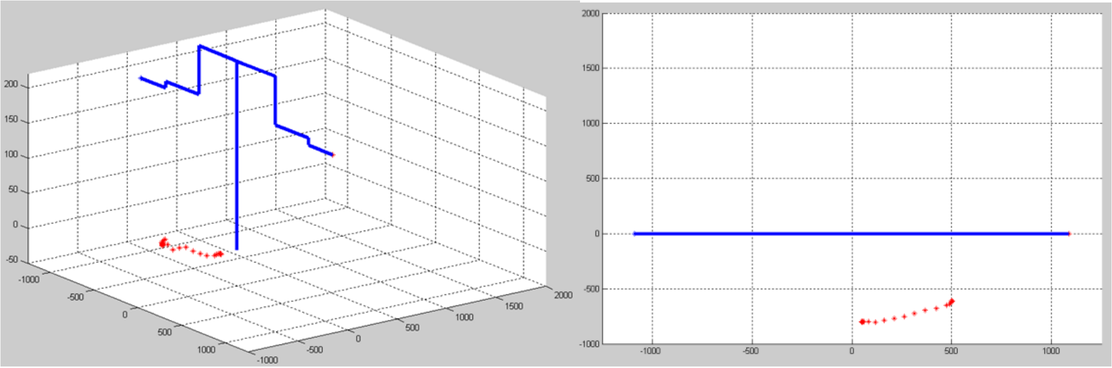


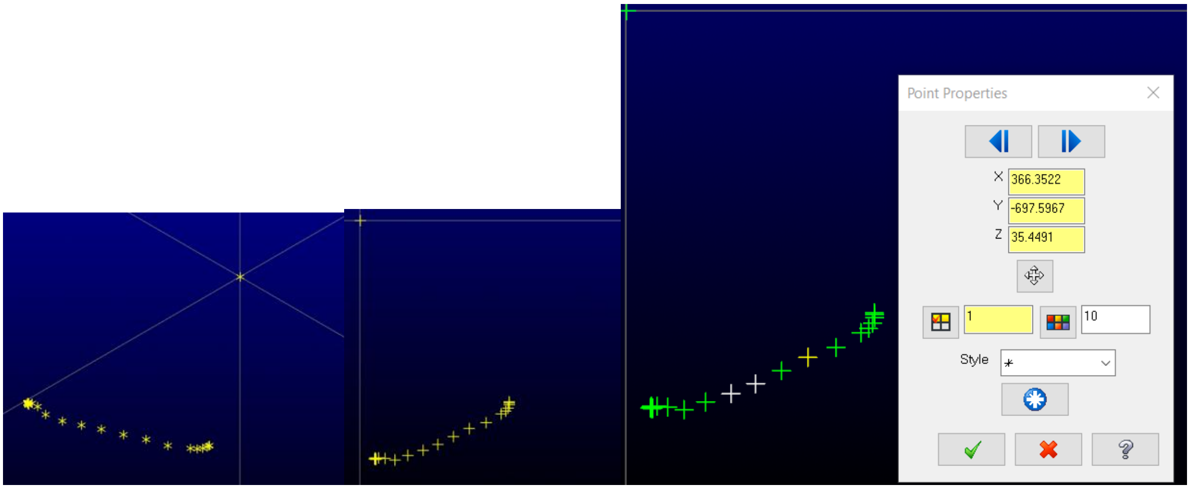
Fig. 6: (a) Isometric view (b) top view of the Matlab robot and trajectory.

In Fig. 7 (a), the points, including the origin, in the commercial CAD/CAM system are illustrated. In Fig. 7 (b), the point 10 is highlighted and the coordinate data displayed. This matches the value of point 10 in the World Frame. Consequently, the foundational links have been established.

Summary and Conclusions:

In lieu of machining, a block to result in a thin-walled component, thin walls can be built up using laser cladding or a similar process to generate a near net shape. Then this can be used as a stock model for machining. Establishing the appropriate relationships and the decision logic to automatically generate tool paths for multiple junction points, fillet regions, and variable wall thicknesses will depend on criteria such as minimizing discontinuities, or stop and starts, or 'pushing' the heat in a certain direction, and is beyond the scope of any AM process planning software available today. Hence, it proposed to teach a representative travel path, and parse the relevant point data and use this as input for actual travel path. If the essential information can be captured by a knowledgeable user and merged with tool path creation quickly, this would save considerable process planning time and effort. The Baxter collaborative robot is employed to generate a trajectory, and this information is successfully imported into commercial CAD/CAM software. Downstream processing can be subsequently initiated.

This research will be extended to investigate scalability, using a marker to represent a bead width to explore fill path solutions for a scaled drawing for a variety of part and junction regions, and to automate the procedures.



X 366.3522
Y -697.5967
Z 35.4491
1
10

Fig. 7. (a) Isometric view, (b) top view of the trajectory. Note the 'wiggle'

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