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PROCESS DEVELOPMENT OF A LARGE-SCALE HYBRID MANUFACTURING PLATFORM FOR ADVANCED TOOLPATH AND PARAMETRIC CONTROL

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Abstract

A hybrid manufacturing testbed is developed and presented as a case study for considerations in designing convergent manufacturing processes. Hybrid manufacturing, in its most popular form, combines the unique design and repair capabilities of directed energy deposition (DED) with the dimensional accuracy and excellent surface finishes of CNC machining. As DED technologies advance, there is a significant need for integrated toolpath and parameter control schemes, deviating from commercial platforms that use prescriptive control via g-code based controllers. This work explores the design considerations in developing a custom hybrid manufacturing robotic testbed for advanced motion and peripheral control for real-time performance tuning. The system is generalizable to any localized manufacturing process; however, development is specifically presented toward a first-of-its-kind pellet extrusion additive, wire-laser DED additive, and milling configuration. The testbed fills a growing need in advanced control schemes and sensor integration within hybrid manufacturing, unlocking the combined benefits of additive and subtractive processes.

Keywords: hybrid manufacturing, automation, monitoring and control

Introduction

The hybrid manufacturing nomenclature typically denotes two or more additive, subtractive, or formative processes integrated within a single machine tool. Combining processes into a single machine enables a convergence of process capabilities and elimination of process limitations. One of the most common commercially available platforms for hybrid manufacturing combines directed energy deposition (DED) additive manufacturing (AM) with computer numerically controlled (CNC) milling or turning. In these systems, the AM benefits of lower material waste, compositionally gradient materials, and increased geometrical complexity are combined with excellent surface finishing and geometric tolerances of modern CNC machining centers. Figure 1 illustrates these benefits. Hybrid manufacturing offers a convergent manufacturing solution, allowing discrete feedstock materials to be consolidated and sculpted into finished geometries without leaving the machine tool. Because of this, interest in hybrid manufacturing has been offered to alleviate supply chain limitations and inefficiencies in centralized manufacturing and transportation.[1–3]

Of course, the consolidation of multiple manufacturing mechanisms also consolidates each processes' limitations. DED additive, for example, can easily suffer from unstable thermal conditions and process anomalies that contribute to defect formation, reduced geometric accuracy, or print failures. These conditions promulgate from the complex thermodynamic behavior of localized fusion and the evolving temperature distribution during deposition.[4,5] Overcoming these limitations has been a dominating hurdle in DED's application.[6,7] Several commercial solutions offer remediation of these issues via real-time peripheral tuning, however, critical remediation strategies such as toolpath trajectory modification are limited by current CNC control capabilities and simplistic toolpath software.

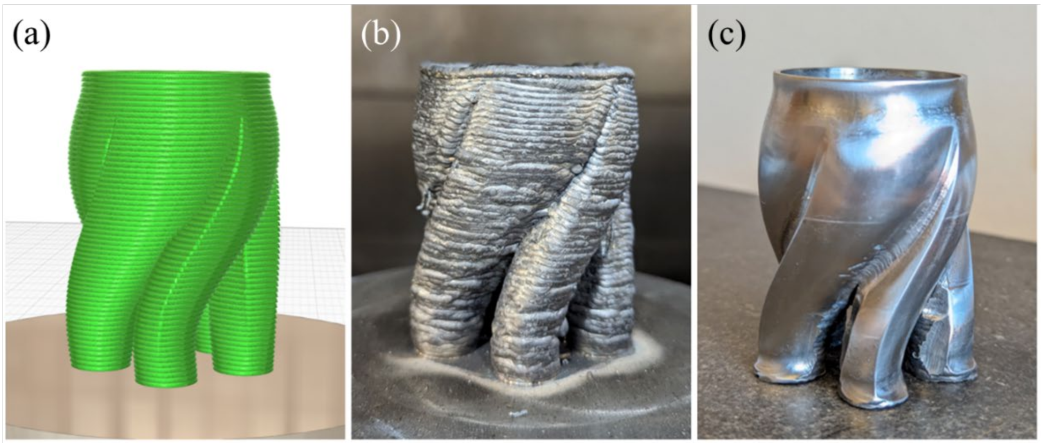

Figure 1. (a) Digital, (b) as-built, and (c) finish-machined models produced in a single machine tool via hybrid manufacturing.

We believe that developing qualified hybrid manufacturing cells requires multi-modal monitoring and adaptive geometric and thermal control. The degree to which advanced control benefits process performance is not well quantified yet. This work discusses our advances toward this goal via integrated trajectory and peripheral control within a custom additive and subtractive manufacturing testbed. Owing to the ubiquity of joint DED/machining in the realm of hybrid processes, the following literature review will focus on such systems.

Relevant Literature

Compared to independent subtractive and additive processes, hybrid manufacturing platforms offer a unique ability to harness multi-modal sensor data and optimization criteria to transfer between processing modes. This benefit also serves as a significant challenge, as data handling, signal analysis, and decision-making are inherently complex tasks. Various manners of closed-loop control techniques have been studied independently in DED and CNC machining processes. Relevant control signals in closed-loop control studies have included melt pool temperature[4,8–11], part temperature,[5,12] melt pool geometry,[13–20] and solidified bead size.[21] Toolpath trajectory is a potential control variable that has improved geometric outcomes in formative[22,23] and subtractive[24,25] manufacturing processes. Real-time trajectory control in additive processes is less studied, which can likely be attributed to preferential implementation of analog signal control of peripherals, e.g., laser power and material feed rate. As an effect, development of robust hybrid manufacturing control techniques has suffered.

Adaptive control strategies aimed at AM post-process machining are gaining interest, specifically owing to non-uniform mechanical properties within as-built parts.[26] Machining cutting forces, typically assumed constant within uniform materials, will vary depending on the local material strength. These difficulties amplify when machining composite and functionally gradient components, where discrete hard phases can promote premature tool wear.[27–30] Adaptive control has been applied within the post-build machining process to promote constant cutting forces and reduce tool wear.[31]

Combining process-specific adaptive control strategies builds toward qualified hybrid manufacturing processes, creating digital twins of the manufacturing processes and fabricated components. Integrating process-specific sensors (acoustic,[32] vision,[33–35] infrared,[34] etc.), data handling, signal analysis, and decision making is complex, and extends beyond the current capability of CNC-based controllers. The following section examines an adaptive control scheme founded in Robot Operating System, or ROS.

Equipment

The hybrid manufacturing system is a custom testbed under development at Iowa State University. A Kawasaki Robotics CX110L 6-axis robot serves as the motion platform. A milling spindle, DED, and fused granule fabrication tools serve as interchangeable end effectors. The CX110L Robot Controller, an E02 model, is equipped with KRNX, Kawasaki Robotic's application programming interface (API). KRNX offers integration with ROS for advanced path planning, simulation, and trajectory execution via a digital twin. Similar robotic systems with real-time control via an API are commercially available. Although not used herein, a near-identical CX165L robot is positioned on the opposite side of the robotic manufacturing cell and is equipped with KRNX and a PushCorp grinding spindle. Both robots are shown in Figure 2.

Figure 2. The robotic manufacturing cell at Iowa State University with Kawasaki CX165L grinding robot (left) and CX110L hybrid manufacturing robot (right).

The peripheral control is handled via a ProductivityOpen P1AM-200 CPU. This low-cost controller is programmable in Arduino, CircuitPython, and C++, and is connected to 32 digital inputs, 30 digital outputs, 16 analog inputs, and 16 analog outputs. These signals are shared between interchangeable end effectors. Although many end effector tools are possible for this system, three end effectors are currently under development: milling, fused granule fabrication (FGF), and laser-wire DED (LW-DED). The milling spindle is an HSD ES915 spindle. The FGF tool is a Massive Dimension MDPH2 pellet extruder. The LW-DED tool is a LaserLine OTS-5

Optical Head attached to a 2kW LDM Blue Fiber Laser. These tools grant the ability to print and machine polymers and metals with the same hybrid system. To switch between end effector tooling, the robot is equipped with a Destaco RQC400 automatic tool change plate and each tool is equipped with a matching RTP400 plate. These plates are equipped with electrical and pneumatic passthroughs. Interchangeable tooling was chosen over a multi-robot system or a multi-tool end effector for its simplicity and ease of integration, although the former offers improved throughput via parallel processing.

Hardware Integration

A key benefit of a convergent hybrid system is simultaneous integration of sensing and control platforms. In this instance, three legs are in communication with the ROS server: sensors, motion control, and peripheral control (Figure 3). The motion control platform relies on a singular Kawasaki 6-axis robot but is generalizable to one or more robots, gantry systems, etc. The primary requirement is having a ROS-compatible driver for real-time control. Kawasaki offers ROS drivers[36] for several robots and controllers, however, the CX110L robot used herein employs a custom driver and digital twin. The digital twin geometry and joint relationships are defined in unified robotics description format (URDF) with joint groups, default configurations, and collision constraints specified in a complementary semantic robot description format (SRDF) file.

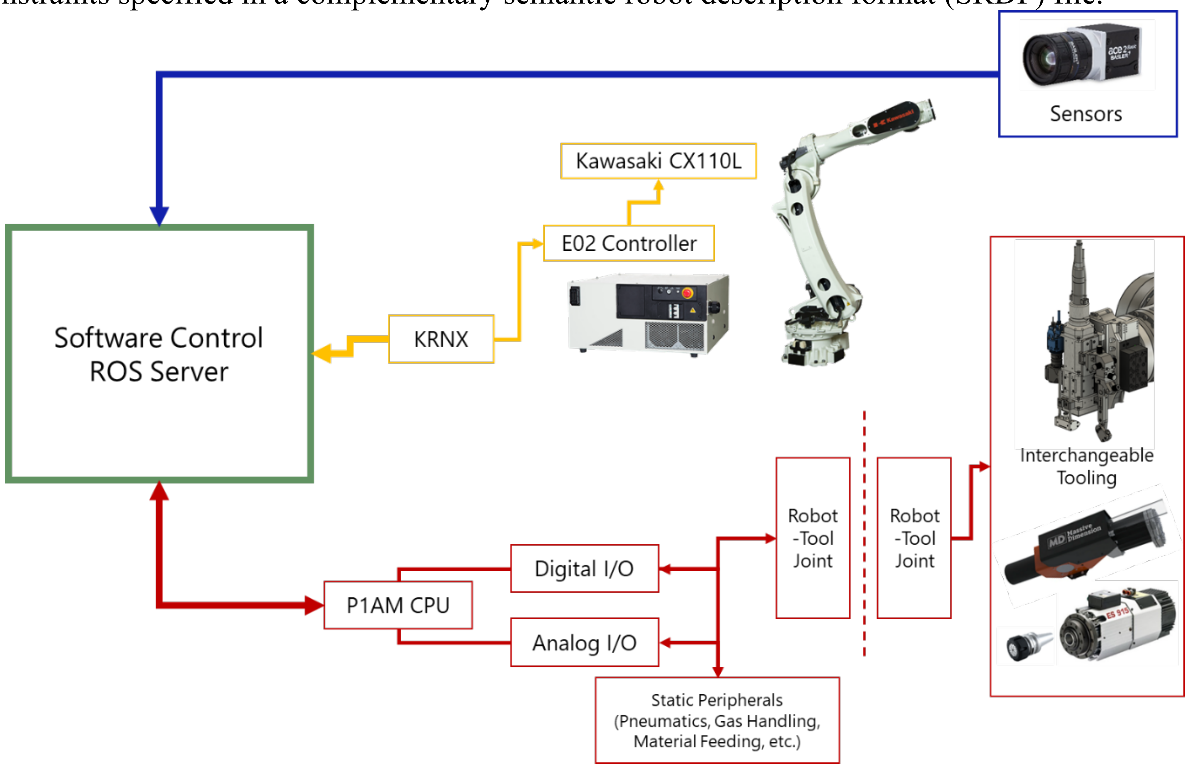

Figure 3. A block diagram illustrating the relationship between the three constituent legs of the hybrid system: sensor feedback (blue), motion control (yellow), and peripheral control (red).

The peripheral control is handled by the P1AM CPU, effectively converting software commands into the requisite voltage and current signals for end effector control. The CPU also communicates via Modbus for simplified communication with PID thermal controllers and other distributed peripherals. Electrical signals can easily be passed through the robot-tool joint and used for tool-specific signals. For example, servo motor commands are used for turning the extrusion screw on the FGF tool and for feeding wire on the LW-DED tool. These tools share electrical passthroughs across the robot-tool joint, allowing for each tool's motor to be controlled only when the tool is connected. The P1AM CPU also functions as a driver for low-level sensors. Examples of these sensors include proximity sensors for workplane levelling, inclination sensors for LW-DED safety, temperature sensing for pellet extrusion, and inductive sensors for automated tool changing.

The sensing leg is responsible for sensors which require higher computational power or yield large amounts of data, e.g., CMOS cameras, depth cameras, infrared cameras, and spectrometers. These sensors require either a Python or C++ API for integration into ROS. Once integrated, however, the data yielded from the sensors can be used for informing and updating the digital twin's environment. An example implementation is the Scan-N-Plan tool developed by Southwest Research Institute (SwRI)[37]. A 3D range sensor attached to the robot scans a geometry and returns a 3-dimensional point cloud of the scan data. This data updates the digital twin's environment to appropriately plan tool trajectories while avoiding singularities and collisions.

Software

Figure 4 shows a depiction of the communication chain within ROS. The general chain of communication is as follows: (1) the user generates joint trajectory points for the robot to follow in a digital environment, (2) these positions are sent to a virtual robot *controller*, i.e., an action topic responsible for getting and setting robot positions, and (3) the KRNX driver converts joint trajectories to real robot commands in the OpenAS language. The "/move_group" node in Figure 4 is responsible for step (1), and the "/cx110l_arm_controller/follow_joint_trajectory" action topic communicates movements to the robot for step (2). The benefit of ROS is that this chain is bidirectional – robot position is updated synchronously and communicated with the digital environment via the "/joint_states" topic. This allows us to accurately predict collisions in a virtual environment, integrate sensor data within the physical-digital environment, and make recursive material processing operations to achieve a desired volumetric state. The robotic path planning and motion execution is built upon ROS2, while the low-level KRNX driver is executed in ROS1. ROS2 offers newer, more-developed trajectory planning applications. Movement commands and joint states are exchanged between ROS1 and ROS2 across a ROS bridge.

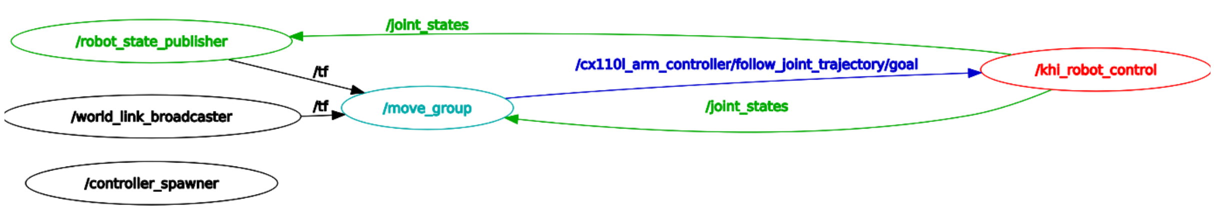

Figure 4. The *RQT Graph* of the robotic control chain. The nodes are represented by ellipses, and the arrows denote the topics and which notes are publishing or subscribing to each topic.

Hybrid manufacturing processes rely on multiple tools, and the digital environment must accommodate different path plans for material addition or removal and process-specific inputs. To enable FGF, DED, and milling, a magazine was installed to hold tooling when not in use. These tools are modeled as end effectors in the URDF and SRDF file formats within ROS. Exchanging tooling requires identifying the correct mounting space for a tool, placing the tool on the mount, disabling the pneumatic lock, moving to the desired tool mount, and re-enabling the pneumatic lock. Simultaneously, the digital model's end effector is updated to reflect the tooling exchange.

This exchange triggers tooling-specific constraints, as disabling/enabling tool-specific peripherals and safety criteria. Figure 5 shows the virtual and physical tooling mounted on the magazine.

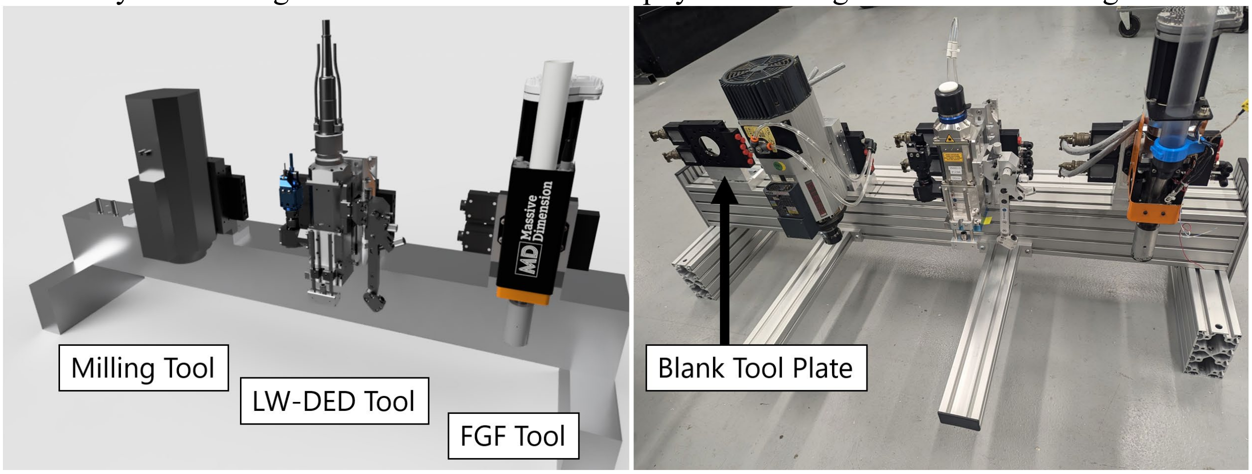

Figure 5. The magazine with the three primary tools shown in the virtual and physical environment. A blank tool plate is shown; this plate serves as the interface with the robot-side plate and provides electrical and pneumatic pass-throughs.

Discussion and Future Work

The specific implementation of ROS for toolpath planning and execution offers multiple benefits over typical numerical control (NC). NC-code is prescriptive, limiting movements to pre-planned paths. While macros, variables, and subroutines can be implemented for closed-loop numerical control, these are often manufacturer-specific and not transferrable across different machine platforms. As we shift machine control toward Industry 4.0 and 5.0 processes, machine control should accommodate for closed-loop feedback, +5 axis toolpath strategies, and part-level and process-level digital twins for qualification and certification.

An obvious limitation to current ROS integration is usability. The number of distributions between ROS1 and ROS2 and their operating system incompatibilities obfuscate the development process. For example, Kawasaki's KRNX ROS driver is built in ROS1, while current ROS packages are built upon ROS2. This requires a bridge between operating systems and limitations in backwards compatibilities. Requisite knowledge in Linux-based terminal, Python, and C++ languages far exceeds the training requirements for the generally easy-to-use user-interface of modern computer aided manufacturing software. A wealth of tutorials for installing and developing packages exists, but missing instructions, *a priori* knowledge, or broken packages further complicate the ROS development process.

Current development of this hybrid manufacturing robotic testbed at Iowa State University is largely centered around software and hardware integration with a focus on ROS control via trajectory commands. The use of ROS in this system is a differentiator from commercially available hybrid systems. The notable milestones for development include:

- ROS-integrated toolpath planning for different subtractive and additive processes,
- sensor integration within ROS including vision-based 2D and 3D cameras,
- software-driven tool changes,
- real-time toolpath modification based on in-situ sensing data,
- detailed and complete operational instructions.

Conclusions

A description of a robotic hybrid manufacturing system and the accompanying software control is offered as a mechanism to describe the considerations in building large-scale convergent manufacturing processes. This work outlines the features and limitations of control schemes based on Robot Operating System (ROS) software and highlights critical areas for development needed for robot-agnostic deployment. The work discussed herein builds toward deployable hybrid manufacturing systems with advanced control capabilities such as iterative path planning, in-process anomaly correction, and integrated surface scanning and toolpath planning.

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