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Process-Level Modeling and Simulation for HP's Multi Jet Fusion 3D Printing Technology

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***Abstract*—The 3D printing technology is expected to revolutionize part manufacturing by enabling rapid and inexpensive production at a small scale. HP's Multi Jet Fusion 3D printing technology is developed to provide new levels of part quality in a fast and inexpensive way compared to existing 3D printing technologies. The printed part quality is determined by the interplay of the printing device and materials used for printing. Thus, it is essential to have a proper cyber-physical system model for the printing system for process-level simulation of the HP's Multi Jet Fusion technology. In this paper, we propose an approach for the process-level modeling and simulation of HP's Multi Jet Fusion technology. Our approach can be used to carry out simulation of the 3D printing system, to provide guidance for optimization and development of the printing process and exploration of materials. Preliminary results potentially indicate that the simulation of our proposed model is significantly faster than the finite element method, which is a widely used technique for 3D printing simulation.**

I. Introduction

Additive manufacturing [1], namely, 3D printing technology is becoming more popular and expected to change the way of production and supply chain. The 3D printing technology enables highly customized and small scale manufacturing typically less than 1,000 units with complex parts. HP's Multi Jet Fusion 3D printing technology [2] is fast, inexpensive, and can offer new levels of functionality (e.g. colors, strengths, flexibility, conductivity, etc.).

The quality of printed 3D objects is determined during the 3D printing process. Specifically, the printed part quality depends on various physical characteristics of the process, such as the peak temperature of the fusion step, and the intrinsic properties of the powder materials used for printing. Therefore, precisely controlling the material behavior is the key to the success of a 3D printing technology.

The physical characteristics of the material during the printing process are determined not only by the operation of the printing device, but also by the physical and chemical properties of the material itself. Materials that can be used for 3D printing include polymers, metals, ceramics and composites. To provide guidance for development and optimization of future materials and processes of the 3D printing technology, it is beneficial to have a proper model for the 3D printing system including the printing devices and materials.

In this paper, we present an integrated solution for the process-level modeling and simulation of HP's Multi Jet Fusion 3D printing technology. Our 3D printing system model considers both the cyber part (printing controller and devices) and the physical part (materials used for printing). For the implementation of the proposed model, we use an open-source actor-based modeling tool for cyber-physical systems, *Ptolemy II* (http://ptolemy.org) [3]. The preliminary results are an initial indication that our model can achieve reasonable accuracy with over several orders of magnitude faster speed than previous component-level simulation techniques such as the finite element method (FEM).

II. Related Work

There have been various technologies for 3D printing, with different cost, printing speed, and part qualities. Fused deposition modeling (FDM) [4] uses the plastic filaments heated by a nozzle to be molten and extruded to form layers. Stereolithography (SLA) [5] is also widely used and produces 3D objects layer by layer, using a technique called photopolymerization. Techniques such as selective laser sintering (SLS) [6] deposit build materials in powder and selectively fuse the powder materials.

For simulation of physical/chemical reactions of the material, the finite element method (FEM) [7] is widely used. When used for 3D printing simulation, FEM can accurately represent complex geometry and capture local physical/chemical effects. However, FEM is too slow for simulating multiple layers of material in 3D printing because of its high computational complexity. To reduce the complexity of FEM in multi-layer 3D printing simulation, Patil *et al.* [8] use two separate scale models and Pal *et al.* [9] optimize and customize FEM for 3D printing simulation. However, even with fast FEM approaches, it is prohibitive to run process-level 3D printing simulation involving hundreds or thousands of layers.

Cyber-physical production systems (CPPS) [10] can benefit manufacturing systems through collaboration of computer science and manufacturing technologies. For the optimization and development of CPPS, Lee *et al.* [11] point out the importance of predictive techniques for manufacturing, such as modeling and simulation approaches.

III. Background

A. HP's Multi Jet Fusion 3D printing technology

HP Multi Jet Fusion™ [2] is a new technology built on decades of investment in HP's assets in inkjet printing, inks and jettable agents, precision low-cost mechanics, and material

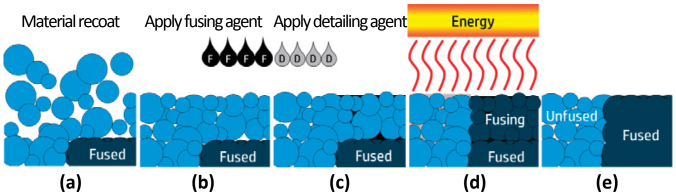

Fig. 1. HP's multi-agent printing process of Multi Jet Fusion technology [2]

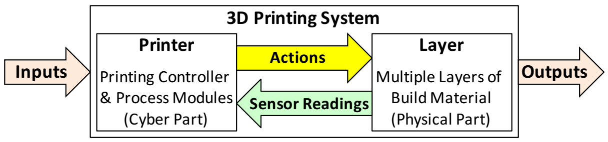

Fig. 2. 3D printing system model overview

science. The main process in HP's Multi Jet Fusion 3D printing technology is illustrated in Fig. 1. First, the build material is recoated on the surface layer as shown in Fig. 1 (a). The printing process applies a fusing agent selectively to the places where the 3D object to be (Fig. 1 (b)), and also applies a detailing agent where the fusing action needs to be controlled (Fig. 1 (c)). Radiation energy is applied on the entire surface as shown in Fig. 1 (d), so that the area for the 3D object is fused (Fig. 1 (e)). This process is repeated layer by layer until the full 3D object is printed.

B. Actor-oriented design/modeling of cyber-physical systems

Modeling cyber-physical systems [12] brings about challenges to cope with heterogeneity, concurrency and timing sensitivity. HP's Multi Jet Fusion system is considered as a cyber-physical system, because it involves both the cyber part (the printing controller and devices) and the physical part (build materials). For modeling of the HP's Multi Jet Fusion 3D printing system, we use Ptolemy II [13] to construct the model. Ptolemy II is an open-source modeling and simulation environment for cyber-physical systems, based on actor-oriented design and modeling [3].

The components in actor-oriented design/modeling are called *actors*, which can concurrently execute and communicate with others through input/output ports. The execution of actors is orchestrated by a set of rules, called model of computation (MoC). Ptolemy II supports heterogeneous MoCs and hierarchical actors, and can simulate models with heterogeneous MoCs together. Thus, it is a proper tool for modeling and simulation of cyber-physical systems.

IV. Modeling and Simulation Techniques

A block diagram in Fig. 2 shows an overview of our 3D printing system model, where the cyber part and physical part of the system are modeled separately. We name the cyber part *printer*, and the physical part *layer*. The *printer* model includes a printing controller and process modules. The *layer* model contains sub-models for multiple layers of build materials.

We also model the interaction between the printer and layer model as communication. Printer affects layer through printing devices and process modules. This behavior is modeled as messages sent from printer to layer, which we call *actions*. Printer senses the physical states of the build material layer through sensors, for example, a temperature sensor. This process including the behavior of sensors is modeled as messages received by printer, which we call *sensor readings*.

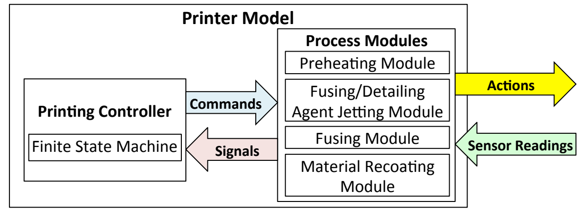

Fig. 3. Printer model block diagram

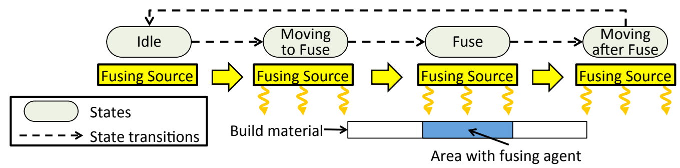

Fig. 4. A simplified model of fusing process module using a finite state machine (FSM)

The 3D printing system model takes *inputs* and generates *outputs*. The *inputs* include the configuration of the printer and 3D image file. For simulation, the model also takes the environment variables as its input for the physical part, specifying physical and chemical properties of build materials. After running the simulation, the 3D printing system model *outputs* simulation results. The simulation results include the physical characteristics of each printed layer such as the temperature and density evaluated during the simulation.

A. Modeling cyber part – Printer model

The details of the printer model are described in Fig. 3. The printer model contains two sub-models, the *printing controller* and *process modules*. The role of the *printing controller* is to control the printing processes and assign specific tasks to printing device modules by sending *commands*. *Process modules* consist of individual modules for individual stages of 3D printing, such as preheating, agent jetting, fusing, and material recoat. Each individual module receives commands from the controller and notifies the controller using *signals*.

As an example of process modules, Fig. 4 shows a simplified implementation of the fusing process model using a finite state machine. Different states in the finite state machine represent different stages of operations of the fusing source. The fusing source moves over the build material and generates radiation energy while it is moving. At the beginning, the fusing source is in its initial position (*Idle* state). It starts to move to the build material with the fusing source turned on (*Moving to Fuse* state), and begins fusing and generates fusing actions (*Fuse* state), and finally, moves back to its initial position (*Moving after Fuse* state). Other process modules are also modeled similarly.

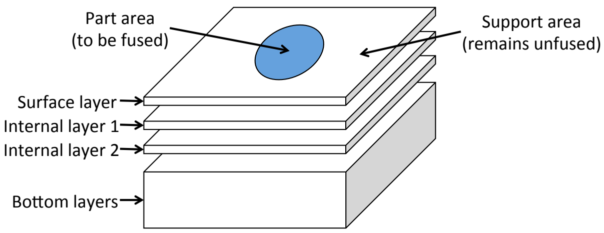

Fig. 5. Approximating and dividing build material part (physical part of the system) into well-defined areas for modeling and simulation

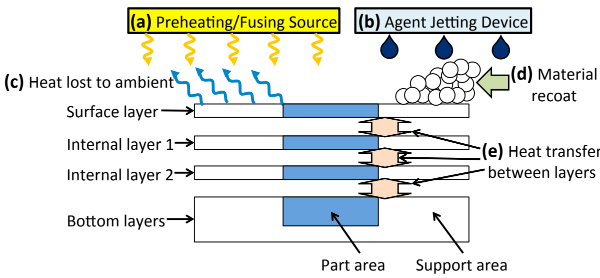

Fig. 6. Factors affecting physical characteristics of the layers of build material

B. Modeling physical part – Layer model

For fast process-level simulation, we use area approximation for the physical part, the layers of build material. Fig. 5 illustrates how the layers are approximated and divided into well-defined areas. We divide the build material into three categories, *surface layer*, *internal layers*, and *bottom layers*.

The *surface layer* is of particular interest because the actions from the printer affect the surface layer directly. *Internal layers* consist of more than one layer right below the surface layer. The internal layers are quite important because they can affect the surface layer by heat transfer, for example, by conduction. We can choose to have more internal layers for better accuracy, or less internal layers for faster speed of simulation. Within each layer, we define two different areas to be modeled and simulated separately. *Part area* is the portion of build material where the fusing agent is applied. The remaining area is *Support area* where the build material remains unfused.

Fig. 6 describes factors that affect physical characteristics of the build material. Radiation energy from preheating or fusing source (Fig. 6 (a)) and effect of fusing/detailing agent from agent jetting device (Fig. 6 (b)) directly affect the physical characteristics of the surface layer. Thermal energy of build material can be lost to the ambient as shown in Fig. 6 (c). The recoating process described in Fig. 6 (d) brings a new layer of build material on the surface. Each layer is affected by the thermal energy transfer between layers as shown in Fig. 6 (e).

The effect of material recoat process (Fig. 6 (d)) causes a new layer to be added to the model. However, adding simulation components for the new layer increases complexity, making it more difficult to scale for hundreds or thousands of layers. Instead of adding simulation components, we maintain the same number of components even when a new layer is added, by aggregating information, as illustrated in Fig. 7.

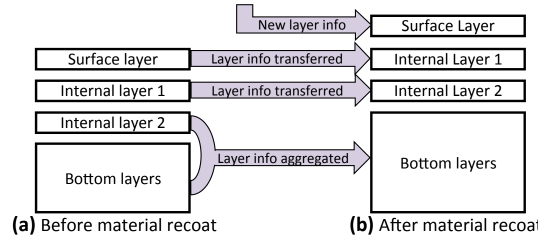

Fig. 7. Modeling build material recoat process

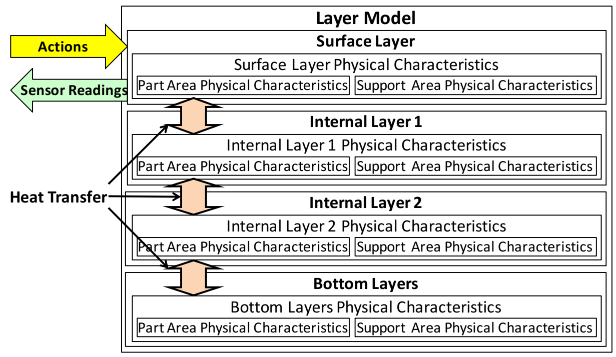

Fig. 8. Layer model block diagram

When the material recoat finishes, a new surface layer is added with new layer's information as shown at the top of Fig. 7 (b). The information for the surface layer model and internal layer 1 model before the material recoat (Fig. 7 (a)) is transferred to the internal layer 1 model and internal layer 2 after the material recoat (Fig. 7 (b)). The layer information of internal layer 2 and bottom layers in Fig. 7 (a) is integrated into bottom layers in Fig. 7 (b). One example of the layer information, the temperature of bottom layers after material recoat, T can be calculated using the following equation,

$$T = \frac{N \times T_{BL} + T_{IL2}}{N + 1}$$

where N is the number of layers in bottom layers, T_{BL} is the temperature of bottom layers, and T_{IL2} is the temperature of internal layer 2.

The resulting layer model is shown in Fig. 8 as a block diagram, with models for each area's physical characteristics information, such as the temperature and density.

C. Hybrid system modeling/simulation using Ptolemy II

We construct a Ptolemy II model with block diagrams in Fig. 3 and Fig. 8 as hierarchical actors. As introduced in Section III-B, Ptolemy II can simulate different MoCs (rules of execution) together. The printer model (cyber part) is constructed using *discrete event MoC*, and the layer model (physical part) is implemented using *continuous time MoC* in addition to *discrete event MoC*. The Ptolemy II implementations of MoCs are called *directors*. *Discrete event director* executes actors when there are time-stamped events, such as messages or time-triggered events, thus it is suitable for modeling computation and communication of the system. Since *continuous time director* executes actors continuously based on sampling, it is proper for modeling physical and chemical reactions, such as thermal variation in build materials.

When we construct the Ptolemy II model, we use configurable parameters for the operational details of the printing devices and material properties for flexible simulation of the 3D printing system. This allows us to use our model for process optimization and exploration of build materials, by changing the parameters for simulation.

V. Preliminary Results

For preliminary evaluation of our proposed approach, we compare the simulation results against actual experimental results using our prototype 3D printer and build material. To evaluate the efficiency of our process-level simulation, we measure the simulation speed using the Ptolemy II models illustrated in Fig. 3 and Fig. 8 above.

Our preliminary results are shown in Fig. 9, which compares physical characteristics of the surface layer simulated by our model (Fig. 9 (a)) and from actual experiments (Fig. 9 (b)). Different colored lines represent different areas. Although details are excluded for confidential information of HP, the results are in the same scale. These results suggest that our simulation has reasonable accuracy.

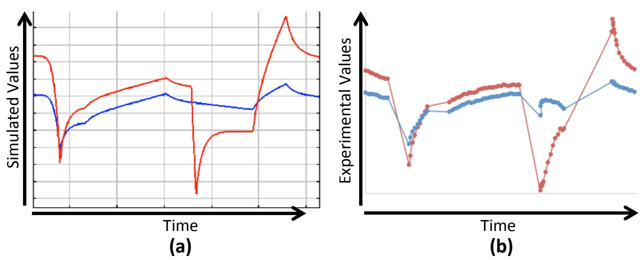

Fig. 9. Comparison between (a) simulation results and (b) experimental results (Details are excluded for confidential information)

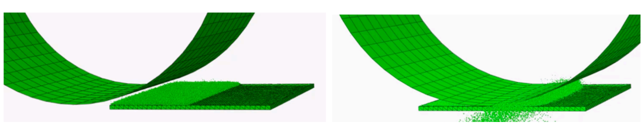

Fig. 10. Visualization of our material recoat process simulation in a small scale (1 cm × 1 cm) with finite element method (FEM)

To illustrate the efficiency of the proposed approach compared to FEM, we use our simulation result of the material recoat process using FEM in a reduced scale of 1 cm × 1 cm, which is visualized in Fig. 10. Measured on a computer with two Intel Xeon E5 @2.60 GHz (total of 12 CPU cores) and 64 GB RAM, the simulation time for one layer is 127 minutes. Considering that the size of printing area is generally at least 10 cm × 10 cm and the FEM simulation time is quadratic to the number of particles, we estimate the simulation time of the recoat process for one layer with FEM will be at least 10,000 × 127 minutes = 7.62 $\times 10^7$ seconds in a normal scale.

The total simulation time using our process-level modeling approach measured on HP's Z Book with Intel Core i7 2.8 GHz and 16 GB RAM is 592 seconds for 100 layers. This is equivalent to a speed of 5.92 seconds per layer, for all printing processes including the recoat process. This fact potentially indicates the simulation using our Ptolemy II-based approach is faster than FEM by more than several orders of magnitude.

VI. Conclusion

In this paper, we propose an integrated solution for the cyber-physical modeling and simulation of HP's Multi Jet Fusion 3D printing technology. By using the approximation of layers of build material and information aggregation for additive layers of the 3D-printed object, our approach achieves significantly faster speed than existing simulation techniques such as FEM, while having reasonable accuracy. Our model has a flexible design in configuration of the 3D printing system, and we expect the proposed approach can be easily extended and improved.

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References

[1] I. Gibson, D. W. Rosen, B. Stucker *et al.*, *Additive manufacturing technologies*. Springer, 2010.

[2] "HP Multi Jet Fusion(TM) technology," HP Development Company, L.P., Technical white paper, Nov. 2015. [Online]. Available: http://www8.hp.com/h20195/v2/GetDocument.aspx?docname=4AA5-5472ENW

[3] E. A. Lee, S. Neuendorffer, and M. J. Wirthlin, "Actor-Oriented Design of Embedded Hardware and Software Systems," *Journal of Circuits, Systems and Computers*, vol. 12, no. 03, pp. 231–260, Jun. 2003.

[4] S. S. Crump, "Apparatus and method for creating three-dimensional objects," Jun. 1992, US Patent 5121329.

[5] P. F. Jacobs, *Rapid prototyping & manufacturing: fundamentals of stereolithography*. Society of Manufacturing Engineers, 1992.

[6] J.P. Kruth, X. Wang, T. Laoui, and L. Froyen, "Lasers and materials in selective laser sintering," *Assembly Automation*, vol. 23, no. 4, pp. 357–371, Dec. 2003.

[7] I. A. Roberts, C. J. Wang, R. Esterlein, M. Stanford, and D. J. Mynors, "A three-dimensional finite element analysis of the temperature field during laser melting of metal powders in additive layer manufacturing," *International Journal of Machine Tools and Manufacture*, vol. 49, no. 1213, pp. 916–923, Oct. 2009.

[8] N. Patil, D. Pal, and B. Stucker, "A new finite element solver using numerical eigen modes for fast simulation of additive manufacturing processes," in *Proceedings of the Solid Freeform Fabrication Symposium*, Austin, TX, Aug. 2013, pp. 12–14.

[9] D. Pal, N. Patil, K. Zeng, and B. Stucker, "An Integrated Approach to Additive Manufacturing Simulations Using Physics Based, Coupled Multiscale Process Modeling," *Journal of Manufacturing Science and Engineering*, vol. 136, no. 6, Oct. 2014.

[10] L. Monostori, "Cyber-physical Production Systems: Roots, Expectations and R&D Challenges," *Procedia CIRP*, vol. 17, pp. 9–13, 2014.

[11] J. Lee, E. Lapira, B. Bagheri, and H.-a. Kao, "Recent advances and trends in predictive manufacturing systems in big data environment," *Manufacturing Letters*, vol. 1, no. 1, pp. 38–41, Oct. 2013.

[12] P. Derler, E. Lee, and A. Sangiovanni-Vincentelli, "Modeling Cyber–Physical Systems," *Proceedings of the IEEE*, vol. 100, no. 1, pp. 13–28, Jan. 2012.

[13] J. Eker, J. Janneck, E. Lee, J. Liu, X. Liu, J. Ludvig, S. Neuendorffer, S. Sachs, and Y. Xiong, "Taming heterogeneity - the Ptolemy approach," *Proceedings of the IEEE*, vol. 91, no. 1, pp. 127–144, Jan. 2003.