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Ultra-fast laser-patterning computation for advanced manufacturing of powdered materials exploiting knowledge-based heat-kernels

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Abstract

The processing of powdered materials by laser processing has become quite widespread. One approach is to deposit a powder bed of material and to "flash" a pattern onto the bed in order to sufficiently heat up the material to sinter and/or fully melt the desired targeted pattern. This avoids rastering a single beam back and forth to produce the pattern. In order to adequately control the thermal fields that are induced by the laser pattern, simulation tools are needed to quickly ascertain the parameter setting needed, such as

- powder porosity,
- powder conductivity,
- beam spatial distribution and
- beam temporal duration.

The focus of this work is to develop a rapid computational tool that can be used in conjunction with manufacturing systems. The approach is to develop precomputed solutions for point-source "beamlets" and then to create patterns by arranging the point-sources in the proper configuration. The entire thermal field is then created by superposing the solutions. A series of three-dimensional problems are solved to illustrate the approach, which is geared to rapidly solving the response to complex patterns.
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1. Introduction

Over the last few years, a rapid digitalization of industry has been taking place, forcing manufacturers to rapidly meld simulation software with newer technologies such as the Internet of Things (IoT), sensor technology, robotics, virtual reality (VR) and artificial intelligence (AI) into their business strategies. Integrated advanced sensors, controls, simulation platforms and modeling have made next-generation advanced manufacturing, sometimes referred to as Industry 4.0, possible. One can refer to this entire evolving area as Advanced Manufacturing (AM). Advanced Manufacturing requires the development of models and simulation tools that can be run rapidly for design purposes,

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which then naturally lend themselves to optimization strategies such as Machine Learning Algorithms which require several hundred or thousand runs during a short period of time-real time models need to be developed. Many of these plans have highlighted the development of additive manufacturing techniques, such as 3D printing. Many emerging multistage additive manufacturing systems involve sintering and/or melting a powder-bed of material. Processes are being developed whereby complex patterns are projected onto a bed of powder. Because of the monochromatic and collimated nature of lasers, the targeted degree of precision and wide power range (100–100 000 W), they are an ideal heat delivery mechanism. The variety of laser-induced processes is wide ranging from bonding, softening, sintering, melting or ablation (Fig. 1). Industrial applications range from aerospace, shipping, transportation, rail, automobile and medical sectors involving the construction of engine parts, structural components, electrical devices, medical implants and prosthetics. However, in order for the process to function properly for a given application, and to adequately control the thermal fields that are induced by the laser pattern for a given powder porosity, powder conductivity and thickness, the beam distribution, intensity and duration must be properly selected. Improper laser calibration will lead to imprecisely controlled heat affected zones and subsequent damage, brought on by miscalibration of the laser power needed. It is for this reason that spatially distribution of power within the laser beam is a parameter to be controlled, in order to manage thermal stresses more effectively. Thus one of the goals of laser manufacturers is to adaptively control the intensity of the laser within the beam adaptively during the process. Because many of new multistage additive manufacturing processes require testing thousands of scenarios involving laser processing of powdered material, the focus of this work is to develop a rapid computational tool that can be used in conjunction with controls systems or as a batch processor for large numbers of successive patterns. The approach is to develop precomputed solutions for point-source "beamlets" (philosophically similar to classical Green's functions or fundamental solutions; Fig. 1) and then to create patterns by arranging the point-sources in the proper configuration. The entire thermal field is then created by superposing the solutions (Fig. 1). A series of three-dimensional problems are solved to illustrate the approach, which is geared to rapidly solving the response to complex patterns. This method enables process designers to rapidly and efficiently explore a variety system scenarios leaving more computationally-intensive "brute-force" PDE-discretization approaches such as Finite Element or Finite Difference methods towards the end of the design process.

Remark. In order to describe the motion of the robot kinematics, one can employ a simple open vector loop representation for the kinematics of a laser placed onto the end of a robot arm. Drawing on methods used in the robotics literature (for example, see Hunt [1], Hartenberg and Denavit [2], Howell [3], McCarthy [4,5], Reuleaux [6], Sandor and Erdman [7], Slocum [8], Suh and Radcliffe [9] and Uicker et al. [10]), one can then consider the idealization of robotic laser system illustrated in Fig. 2 as a linkage. The position vector ($\boldsymbol{r}^{laser}$) to the laser head is given by

$$\boldsymbol{r}^{laser} = \boldsymbol{r}_1^r + \boldsymbol{r}_2^r + \boldsymbol{r}_3^r. \tag{1}$$

Differentiating, a velocity vector loop is generated

$$\boldsymbol{v}^{laser} = \dot{\boldsymbol{r}}_1^r + \dot{\boldsymbol{r}}_2^r + \dot{\boldsymbol{r}}_3^r = \dot{\boldsymbol{r}}^{laser}. \tag{2}$$

Generally, both $\boldsymbol{r}^{laser}$ and $\boldsymbol{v}^{laser}$ are controlled in conjunction with the laser action.

2. Qualitative system response estimation

In order to understand the fundamental behavior of heated target, consider a disk-shaped targeted pattern domain in Fig. 3 of mass $m = \rho^* V_{pat}$, where ρ^* is the effective mass density of the powder, V_{pat} is the targeted pattern volume, $(\rho C)^*$ is the effective thermal mass density (C is the heat capacity) and S is the laser input (Watts). The simplest possible estimate for the system response is given by a "lumped mass" analysis of the first law of thermodynamics, assuming the energy is entirely contained within the targeted pattern domain and that the temperature in the targeted pattern is uniform (also ignoring conductive losses)[1] :

$$mC\dot{\theta} = (\rho C)^* V_{pat}\dot{\theta} = S, \tag{3}$$

[1] A lumped mass model, assuming a uniform temperature within a targeted pattern, is dictated by the Biot number. The Biot numbers have to be significantly less than unity for such an approximation to be reasonable. This is generally not the case, however, the solution still provides qualitatively useful information which will improve later in the paper.

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