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Simulation based iterative post-optimization of paths of robot guided thermal spraying

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ABSTRACT

Robot-based thermal spraying is a production process in which an industrial robot guides a spray gun along a path in order to spray molten material onto a workpiece surface to form a coating of desired thickness. This paper is concerned with optimizing a given path of this sort by post-processing. Reasons for doing so are to reduce the thickness error caused by a not sufficiently precise design of the given path, to adapt the path to a changed spray gun or spray technology, to adapt the path to slight incremental changes of the workpiece geometry, or to smooth the path in order to improve its execution by the robot. An approach to post-optimization using the nonlinear conjugate gradient method is presented which employs a high-quality GPGPU-based simulation of the spray process for the evaluation of the coating thickness error and additionally taking care of the kinematic path quality. The number of computationally time-consuming calls of the simulation is kept low by analytically calculating estimates of gradients from a simplified material deposition model. A rigorous experimental evaluation on case studies of the mentioned applications shows that the method efficiently delivers improved paths which reduce the coating error on real free form surfaces considerably, i.e. the squared coating error is below 3.5% of the original value in every case study.

1. Introduction

Robot-based thermal spraying is employed in industrial production processes in order to coat workpieces with different materials [1]. A spray gun melts the coating material which may be supplied as a powder or wire. The molten particles are then accelerated by a carrier gas stream onto the workpiece surface, where they cool down and solidify. The spray gun is mounted onto an industrial robot which moves the spray gun over the surface. This way, the spray material builds up a coating on the workpiece. Different spray materials may be used depending on the purpose of the coating such as wear- or corrosion protection. A primary goal of the thermal spray process is to achieve a desired coating thickness. This may be difficult to achieve especially on complex free form surfaces.

1.1. Motivation

A challenging aim of computer-aided robot path planning is the automated generation of an appropriate robot program. In this paper it is assumed that an initial program, respectively a path defined by it, is already given. The source of this initial path can be a commercially available software, any process specific computation algorithm, a series of manually taught poses, or a path initially designed for a different, but similar purpose [2]. It is further assumed that this initial path definition does not completely satisfy the thickness requirements imposed by the process and thus needs to be optimized.

In practice such situations frequently occur for various reasons. For example, the spray gun parametrization might have changed slightly due to an intentional parameter modification or due to wear. Also, the workpiece shape might have been modified to some extent for a new variant of a related product. A path interactively generated by an experienced designer might almost, but not perfectly satisfy the requirements. For all these situations, the high efforts of creating a new path from scratch for free-form workpieces might be reduced by adapting an already existent path by a post-optimization step.

Another interesting issue is computationally efficient automatic path planning by dividing the process into a global and a local optimization phase. One reason for the 2-phases-approach is that precise deposition models usually cannot be described by a closed formula, but have to be evaluated by numerical simulation which could be computationally expensive. Because of their typically high number of simulation calls, this limits the application of global, meta-heuristic search strategies like, e.g. evolutionary

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approaches, to computationally efficient, more simple deposition models. Simplified path planning, however, might lead to weaknesses of the resulting path which may be overcome by slight changes based on more detailed information gained by simulation which can be used for post-optimization.

Within the context of thermal spraying, a post-optimization strategy has to satisfy several requirements. The central requirement is minimizing the coating thickness error based on a coating model which cannot be expected to be analytically available. A further important requirement is preserving or optimizing the kinematic quality of the path, e.g. with respect to curvature, velocity, and acceleration, in order to keep it executable by a robot. From a computational point of view, the number of evaluations of the simulation should be kept small.

The contribution of this paper is a post-optimization approach for spray gun paths which takes those requirements into account.

1.2. Overview

The above-mentioned requirements are specified as an objective function which is the sum of two sub-objectives whose contribution can be controlled by a weighting factor. The first sub-objective is minimization of the least squares coating error, evaluated by simulation. The coating simulation is based on mass-flow information experimentally acquired from real coating processes. This gives the model of a high realism. The second sub-objective is optimization of the kinematic quality of the spray gun path. The aim of optimization is to change the location, orientation and velocity of the spray gun so that the objective function is optimized.

This results in a rather high-dimensional optimization problem which excludes derivative-free local optimization methods like the Nelder–Mead approach [3]. However, derivative-based methods also cause troubles since derivatives cannot be expected to be analytically available because of employing a simulation. To cope with this problem a novel approach is presented in this paper, which calculates derivatives of the objective function analytically from a simplified material deposition model, while the objective function itself is still evaluated simulation-based. This opens the possibility of optimization by the nonlinear conjugate gradient method within reasonable computing times. The idea is that the simplified model might also provide a reasonable search direction.

The proposed method is experimentally evaluated. One aspect of the evaluation is to get insight in the sensitivity of the optimization approach with respect to different parameters controlling the optimization model. The main result is that the approach is quite robust with respect to the quality of approximation by the simplified material deposition model. Furthermore, the usefulness of the algorithm is quantitatively demonstrated for several use cases, including general path optimization, changing of the spray characteristics, and changing of the workpiece geometry.

Section 2 gives an overview of existing work. The simulation of the spray coating process is described in Section 3. In Section 4, the problem is specified and Section 5 gives an overview of the solution. The details of the solution are presented in Section 6. Section 7 reports on the evaluation and results. Section 8 presents the effect of the proposed method for several use cases of path post-optimization. Section 9 concludes the paper.

2. Related work

The following survey includes approaches related to the topic of the paper, reaching from the specific problem of spray coating to similar problems for other production techniques. It describes drawbacks of existing methods, and shows relations and differences of the solution presented by the paper to existing solutions.

In contrast to e.g. NC-machining, spray processes have found considerable less attention in basic research. Most research for spraying applications has been done in the field of paint spray processes that is closely related to thermal spraying [4–7]. Frequently, simple fixed path patterns are used to generate paths for spraying processes. A prominent example is the meander pattern.

The parameters of such a basic pattern and of the related motion of the spray gun have to be adapted to the specific process. Candel and Gadow et al. [8,9] use a numerical heat simulation to evaluate the quality of a surface coating generated by moving a thermal spray gun along a meander path of a given inter-curve distance, spray distance, velocity, and spray angle. The low number of degrees of freedom of the motion type chosen may allow the search for an optimum with practical effort even if the numerical simulation is time consuming. A drawback is the significantly restricted space of possible paths which may exclude interesting solutions on surfaces of complex shape.

Fasching et al. [10] also use meander paths and similar parameters of motion and focus on achieving a desired coating thickness. Instead of a numerical simulation for every path, they use pre-determined coating patterns for different parameter settings which are composed depending on the width of the meander pattern. The saving of time by the avoided numerical simulation allows a practical optimization of the coating thickness. A drawback may be a lower precision of the result and limitations with respect to applicability depending on the investigated effects.

The solution presented in this paper optimizes a given path based on a simulation of the coating process. The spray gun paths can be arbitrary and are adapted locally, in contrast to the global adaption of the mentioned approaches, thus offering a high flexibility of adaptation. The approach of this paper is also based on pre-determined footprints, but in contrast to [10], those are used to control a deposition model for the simulation of the execution of a path. This way the required adaptation to the varying path and surface shapes is achieved with lower calculation times for this partially empirical deposition model than those of a truly physical deposition model, but with a still practical precision.

Path planning has been investigated intensively in the field of milling as well, see [11,12]. Many of these approaches are not suited for thermal spraying due to the significant differences in the processes. While the milling tool has to work directly on the workpiece surface, the spray gun in thermal spraying is farer away from the impact points of the particles, and may have significantly varying distances from the surface for free-formed workpieces. Thus, the spray gun paths may fill a larger region of space, cf. e.g. Fig. 3, whereas cutter paths are located in a well-defined, restricted spatial region close to the impact location.

Deng et al. [2] analyze necessary steps for path planning in thermal spraying. They conclude that offline programming approaches are superior to online programming but no concrete path planning algorithm is proposed.

Jones et al. [13,14] present a path generation method concentrating on minimizing the thermal variation on the workpiece surface during the spray process. They constrain the workpiece to a flat and rectangular surface and the path structure to mirror-box paths, and derive an analytical solution for the optimal path. Hegels et al. [15] generalize the path pattern and the surface shape, and perform the optimization by an evolutionary algorithm. Both approaches are restricted to flat surfaces.

In [16], an ant colony optimization approach for an optimal task assignment to two cooperative robots is proposed. While optimizing the amount of spray time needed due to optimal robot movement between path points, the actual path generation of these path points is not subject to their research.