Robotics and Computer-Integrated Manufacturing 29 (2013) 86–95

Contents lists available at SciVerse ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Remote robotic underwater grinding system and modeling for rectification of hydroelectric structures

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ARTICLE INFO

Article history:
Received 21 April 2011
Received in revised form
20 April 2012
Accepted 26 July 2012
Available online 4 September 2012

Keywords:
Underwater grinding process
Grinding modeling
Material removal rate (MRR)
Water drag effect
Air injector
Robotic grinding

ABSTRACT

A submersible grinding robot has been designed to automate the dam gate metallic structure repair process. In order to measure and control the amount of material removed during the process, an empirical approach for modeling the material removal rate (MRR) of the underwater grinding application is proposed and presented in this paper. The objective is to determine the MRR in terms of the process parameters such as cutting speed and grinding power over a range of variable wheel diameters. Experiments show that water causes drag and a significant loss of power occurs during grinding. An air injector encasing the grinding wheel has been prototyped, and it is shown that power loss can be reduced by up to 80%. A model, based on motor characterization and empirical relations among system and process parameters, is developed for predicting MRR which will be used for the robotic grinding control system. A validation is carried out through experiments, and confirms the good accuracy of the model for predicting the depth of cut for underwater grinding. A comparative study for dry and underwater grinding is also conducted through experiments and shows that the MRR is higher for underwater grinding than in dry conditions at low cutting speeds.

1. Introduction

Hydroelectric dam gates are made of metallic structures partially embedded in concrete, and are used to securely cut off water access to the turbine for maintenance and safety purposes. Water tightness is ensured by the coupled planarity at the interface of the metallic structure and the doorstep. Time, corrosion and water pressure damage the built-in structures, and so they must be periodically diagnosed and repaired in order to fulfill their lifetime expectancy. For major repairs to be accomplished, expensive cofferdams are built to isolate gates from water and allow a free and dry access to the surfaces that need to be reground. Hydro-Quebec's Research Institute (IREQ) has investigated different scenarios to perform underwater maintenance and inspection tasks. Lemieux et al. [1] in 2006 presented the preliminary results that were obtained and the main advantages of using linear direct drive motors for underwater vehicle-manipulator systems. In recent years, IREQ has pursued the design and assembled a submersible grinding robot prototype (patent pending) to study the feasibility of automating the repair process. Such automated repairing process with a high precision robot should reduce repair costs and turbine downtimes.

Grinding is selected over other material removal processes for multiple reasons. Classical machining, such as milling, requires a frame with a high level of rigidity to ensure the efficiency and precision of the process. Since the doorsteps to be repaired are at least 6 m long, building a rigid frame dedicated to the milling task is a costly option because of the size and the weight of the necessary structure. Grinding is thus a preferred option because of the lighter frame needed, which can also afford easier handling capabilities. Therefore, the robot's carrier axis is made of a modular aluminum truss structure. Compared to milling, grinding with a resinoid wheel is less prone to tool breakage or surface damage in case of perturbations, impacts and structure vibration. Although grinding is less efficient than machining, in our application, the removal volume per wheel will be significantly improved by using large diameter straight snagging wheels. Such wheels allow for less frequent tool changes and thus shorter down times in the field. The first step of this project consists in studying and understanding the grinding process in the underwater conditions. For an application such as the one we report in this paper, the entire resurfacing of the metallic surface requires high geometrical and dimensional precision. To the authors' knowledge, apart from the paper [2] by Thomessen who had studied remote underwater grinding of cracks near weld on steel truss structures, the literature provides few insights into underwater grinding. Therefore, a test bench was built to investigate how the process is influenced by the underwater environment and operating

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http://dx.doi.org/10.1016/j.rcim.2012.07.004

Nomenclature

a_e	depth of cut
D	grinding wheel diameter
d_{eq}	equivalent wheel diameter
F_n	normal force (N)
Fn'	normal force per unit of width of contact (N/mm)
F_t	tangential force (N)
Ft'	tangential force per unit of width of contact (N)
F_{TH}	normal threshold force (N)
G-ratio	grinding ratio: volume of work-material removed divided by wheel wear volume
I	grinder current (A)
$I_{empty\ load}$	grinder current to rotate the grinding wheel at empty load (A)
K_i	regression coefficient
K_p	metal removal rate constant
MRR	material removal rate (mm^3/s)
MRR'	material removal rate per unit of width of contact(mm^2/s)
P, P_{eff}	effective grinding power (W)
$P_{grinder}$	grinder mechanical power output (W)
$P_{empty\ load}$	required power to rotate the wheel at empty load (W)
q	ratio of wheel relative speed over feed rate
u	specific energy (J/mm^3)
u_{ch}	specific chipping energy (J/mm^3)
u_{pl}	specific plowing energy (J/mm^3)
u_{sl}	specific sliding energy (J/mm^3)
V_c	cutting speed (m/s)
V_f	feed rate (m/s)
WWR	grinding wheel wear rate (mm^3/s)

Greek symbols

β_{ij}	regression coefficient
μ	friction coefficient
ρ	density (kg/m3)
ω	angular velocity (rad/s)
Λ_w	removal rate parameter

parameters. The main objective was to determine the models that could be used to predict the material removal rate in terms of grinding parameters. Many approaches have been used for modeling the dry grinding process [3–5,15]. Brinksmeier et al. [6] presented an extensive review of the current state of the art in modeling and simulation techniques for grinding. In practice, empirical methods are widely used for modeling grinding processes because physical interrelationships in grinding cannot be accurately defined. Their limits lie in the fact that they apply only to the very specific situations in which the model was developed.

The targeted application, summarized in Fig. 1, can be divided into two main procedures which are completed in a consecutive order. First, a task planning procedure uses the results of a 3D scanning sequence [7] to feed a trajectory generation algorithm. The latter provides the desired robot trajectories input to the grinding robot system where closed-loop control ensures proper command of the grinding robot. The controlled grinding process is the final step to allow for proper rectification of water tight seals. From the application diagram, it can be seen that the grinding process model is invoked twice in the application. By providing precise MRR predictions, it allows the trajectory generation algorithm to determine appropriate trajectories for the robot to complete the grinding tasks. Afterwards, the process model will be used by the closed-loop control phase to evaluate, in real-time, the process parameters to be applied to respect the targeted MRR. The diagram shows the crucial role played by the grinding process model in enabling autonomous completion of grinding task planning and process. Such application configuration allows for fast rectification completion and therefore shorter down times and considerable cost reduction during maintenance of power dams embedded parts. One could see in this application some interesting fall-outs for underwater intervention on other civil infrastructures like bridges, harbors and wells.

This paper is structured as follows. In Section 2, several existing grinding models available in the literature are summarized. We then present a modified version of previous models which are adapted to our application for MRR prediction. Section 3 deals with our experimental set-up and measurement. The underwater grinding system configuration is presented first, and then we describe how the experimental tests and measurements are conducted. For process controlling purposes a grinder DC motor power model is described in function of the applied current and rotational speed output. A casing with a pressurized air inlet was designed to reduce the water drag effect during grinding. The benefits of this technique are also presented in Section 3. Experimental results are given in Section 4 for underwater and dry grinding conditions. In Section 5, the effects of two selected parameters on underwater and dry grinding processes are illustrated through data fitting. The model developed for underwater grinding is then validated by comparing the anticipated depth of cut with the one obtained using the predicted grinding parameters. It shows that the model can deliver a very good prediction for depth of cut and material removal rate (MRR) for the underwater grinding process.

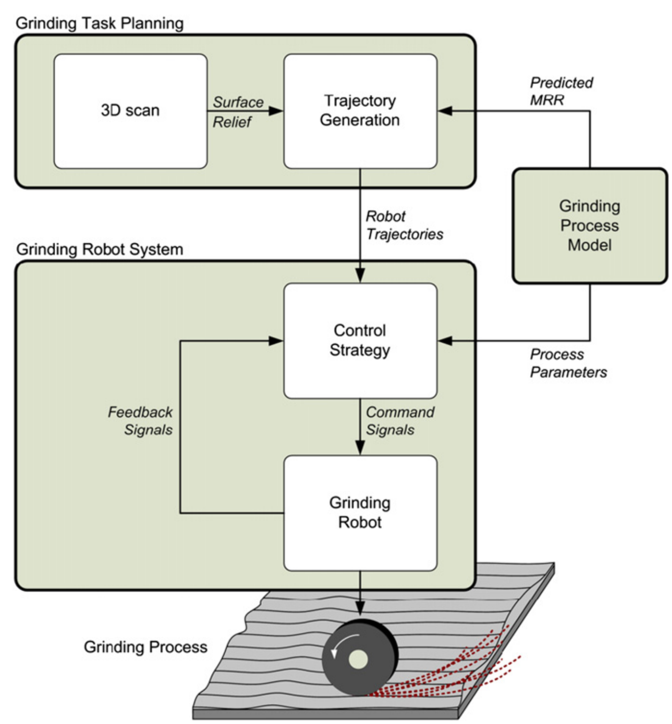

Fig. 1. Automatic underwater grinding application diagram.