Robotics and Autonomous Systems 74 (2015) 351–359

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

A thermographic visual inspection system for crack detection in metal parts exploiting a robotic workcell

Stefano Ghidoni *, Mauro Antonello, Loris Nanni, Emanuele Menegatti

Department of Information Engineering, University of Padova, via Ognissanti, 72 — I-35129 Padova, Italy

HIGHLIGHTS

- Thermography was explored as a means for the detection of micro defects.
- We developed a system capable of finding cracks in metal parts using thermography.
- The system is very robust thanks to the complete knowledge of the imaging process.
- The system is able to deal with parts of very complex geometry.
- The proposed inspection method is cleaner than other alternatives currently in use, and does not use polluting substances.

ARTICLE INFO

Article history:
Available online 9 September 2015

Keywords:
Computer vision
Automated visual inspection
Thermographic image analysis
Knowledge-based image analysis
Pattern recognition

ABSTRACT

Cracks are the main source of failure in the production of metal parts: systems for checking their presence are therefore crucial for defect-free production. In this paper, an autonomous system for performing this quality control is presented. The system is equipped with a heating tool, a thermocamera, and a robot to handle the part. The inspection process is based on the observation of the propagation of thermal waves through the inspected part, a method that can highlight very small cracks with high reliability. A knowledge-based approach to visual inspection is exploited for detecting the cracks: all the system parameters are known by means of an accurate calibration of the workcell. The system was tested on a large dataset and demonstrated its capability of detecting tiny production defects, that can lead to dangerous failures when the metal components are put under strong mechanical stress.

1. Introduction

Visual inspection is the key to defect-free manufacturing. A vision system that checks the parts along the production line offers multiple advantages, first of all the capability of analyzing each produced piece, that is a crucial requirement to satisfy the highest quality standards. Systems employed for visual inspection need to adapt to the parts to be checked: the complexity of such systems therefore ranges from light units, running on rather simple embedded hardware, to complex combinations of cameras, lighting, and robotics [1–3].

Focusing on the production of metal parts for high-performance components, like crankshafts for combustion engines, one of the main source of failure is represented by the presence of cracks: even very small fractures of the metal structure can break the part when it is subject to strong mechanical stress. Currently, the presence of cracks is performed using Magnetic Particle Inspection (MPI): the part to be analyzed is first washed, then put into a magnetic field and finally covered with magnetic particles, either in the form of a dry powder, or, more frequently, in a wet suspension. Cracks are detected because they cause leaks in the magnetic flux; such leaks are highlighted by the particles, which can be inspected by means of a UV light. The whole process is very complex and needs to be done manually; it is also extremely time-consuming, because parts need to be cleaned, magnetized, covered with magnetic particles, inspected, de-magnetized and cleaned again. Moreover, magnetic particles and their carrier are a source of pollution, and should be properly processed after use, with high costs.

Even though MPI is still used in industry, current technology offers a large set of tools that enables the introduction of alternative inspection methods, that offer the advantage of being green, fast, and automatic. Investigating how it is possible to replace MPI with more modern technology was the goal of the ThermoBot project

* Corresponding author.
E-mail addresses: ghidoni@dei.unipd.it (S. Ghidoni), mauro.antonello@dei.unipd.it (M. Antonello), nanni@dei.unipd.it (L. Nanni), emg@dei.unipd.it (E. Menegatti).

http://dx.doi.org/10.1016/j.robot.2015.07.020
0921-8890/

(www.thermobot.eu) funded by the European Commission in the Factory of the Future research program. A major advantage of visual inspection systems is that they are able to analyze parts exploiting not only cameras working in the visible domain, but also in different ones, like near infrared [4], far infrared [5,6] and X-rays [7]. This opportunity is exploited in the project, as its driving idea is to exploit thermography to replace MPI. The project goes beyond crack detection in metal parts: analysis of non-metallic materials, like carbon fiber, are also faced.

The two inspection systems developed in the project share the feature that inspection is performed by means a thermal excitation method (e.g. a laser or a high-power lamp) and a far infrared (FIR) camera, that observes how the heat diffuses inside the part: since defects cause alterations on the heat flux, such alterations can be exploited to inspect the part. This enables the system to detect not only cracks in metal parts, but also inspect inner defects in CFRP (Carbon Fiber Reinforced Plastic) parts.

This paper describes the system developed for detecting cracks in metal parts [8,9]. The paper is structured as follows: in Section 2 the state of the art is revised, while the system structure is explained in Section 3. The core of the visual inspection system, including the knowledge-based approach, that enables the inspection of very small defects, is detailed in Section 4, and the results obtained during the experiments are described in Section 5. Section 6 reports the final remarks.

2. State of the art

The topic of crack detection has been tackled in a number of different ways in the literature, given the strong importance of this type of quality check. A variety of approaches have been used, like the propagation of ultrasounds that is used in [10] to detect cracks and lamination defects in metallic pipes, or Eddy currents [11–13]. Other methods exploit magnetic cameras to detect cracks in parts that are at high temperature [14], or magnetic flux leakage [15], while the method described in [16] studies the heat produced by the Joule effect.

Methods based on image analysis have also been exploited in the literature, ranging from detection of welding defects in pipelines [17] to concrete surface analysis [18] and the protection of cultural heritage [19]. Thermographic image analysis systems have recently been proposed for performing in-situ non-destructive inspections during thermomechanical fatigue tests [20]; the system showed a high sensitivity, being able to detect cracks smaller than 500 μm. The system proposed in [21] is slightly different from the others discussed above as it is meant to inspect different types of materials during fatigue tests, and detect the cracks as soon as they appear.

Thermography-based crack detection is often coupled with excitation methods like eddy currents [22] or laser beams; in particular, lasers provide the inspection process with high flexibility, as it is possible to concentrate the heat on a small spot, and enabling and disabling the heat source can be done instantly, generating pulses at high frequency. This last characteristic is exploited in pulse thermography and techniques that are derived from it [23]. Another technique based on laser technology is the "flying spot active thermography" [24], that refers to a laser spot that causes a local excitation on the part under inspection. This is similar to the analysis method employed in the ThermoBot project, and was chosen in [24] to inspect high pressure turbine blades.

3. A visual inspection system for crack detection

The inspection process described in this paper is based on the analysis of how thermal waves propagate through a metal part.

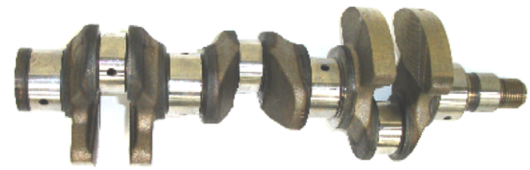

Fig. 1. The sample part used for the experiments: a metal crankshaft.

The inspection cell is composed by a laser, a thermocamera, and a robot. The laser is exploited to generate the thermal excitation and the robot is used to move the part, in order heat and inspect different regions of the part. The thermal waves are acquired by the thermocamera and automatically processed. To obtain highly detailed images and enhance the sensitivity of the system, the FOV (Field Of View) of the camera is narrow, therefore only a small region of the inspected part can be viewed. This does not limit the system, because only a small area around the laser spot is affected by the thermal waves.

The introduction of the robot in the inspection cell is needed because the thermal waves are generated by moving the heat source over the part. Moreover, the capability of moving the sample is crucial for inspecting parts of complex shape that causes a large number of self-occlusions, i.e. some sections of the inspected part hide other sections, depending on the perspective under which the item is framed. The robot is able to change such perspective, letting the system analyze the whole surface. Thanks to the robot, the visual inspection system offers a high level of flexibility, that enables it to inspect parts of very different size and shape.

3.1. Test samples

The system described above is meant for analyzing metal parts, that require a powerful heat source. The sample parts exploited in the experiments are heavy metal crankshafts, shown in Fig. 1.

To perform the analysis, the part is first fixed to the robot, whose movements determine which regions are thermally excited by the laser and framed by the camera. The robot path is automatically generated, based on the part geometry (provided as CAD data). The inspection process requires the laser to go over every area that should be checked: this leads to a long processing time for parts that are rather large, and have a complex geometry, as for the crankshaft of Fig. 1. To reduce the time needed, a set of regions where cracks are more critical was defined, and the analysis is restricted to those areas only.

3.2. Inspection system workcell

The scheme of the inspection system workcell is shown in Fig. 2(a). In (b) it is possible to see the components of the workcell: the yellow robot is clearly visible, the laser is the metal box on the top, while the thermocamera is the red box on the top right corner. During the inspection process, the robot places the part in a zone in which the camera FOV and the laser beam intersect: the crankshaft in Fig. 2(b) is in that area.

As said above, the workcell hosts a powerful laser source: when it comes to heavy metal parts, the amount of energy needed for generating a heat wave that is visible with a thermocamera is rather high: a source reaching a power level of 7 W was chosen in our case. The speed at which the laser spot runs over the inspected part (called "laser speed") is an important system parameter.

The robot path planning is performed in order to guarantee a laser speed which is almost constant, that should be related with the time needed for the heat to diffuse through the metal. For example, a low laser speed leads to a diffused heat that would make