A model driven method for crack detection in robotic inspection

E. Pellegrino[1] and T. Stathaki[1]

[1]Department of Electrical and Electronic Engineering, Imperial College London, UK

e.pellegrino16@imperial.ac.uk

Abstract

Nowadays civil infrastructure is exposed to several challenges such as daily vehicular traffic and extreme weather conditions. It is well known that these may determine structural deterioration and damages, which can even cause catastrophic collapses related to significant socio-economic losses. For this reason automatic inspection and maintenance are expected to play a decisive role in the future. With the objective of quality assessment, cracks on large civil structures have to be identified and monitored continuously. Due to the availability of cheap devices, techniques based on image processing have been gaining in popularity, but they require an accurate analysis of a huge amount of data. Moreover, fracture detection in images remains a challenging task due to high sensitivity to noise and environmental light conditions. This paper proposes a mathematical method for detecting cracks in images along with a parallel implementation on heterogeneous High Performance Computing (HPC) architectures aiming both at automatizing the whole process and at reducing its execution time.

Keywords

Machine Vision; Smart Infrastructure; High Performance Computing

1 Introduction

Infrastructures can be exposed to different loading conditions, recurrent ones due to vehicular traffic and extraordinary ones caused by earthquakes, wind and strong rain. The consequently induced stresses may determine structural deterioration and damage, which can even cause catastrophic collapses related to significant socio-economic losses [1]. For this reason increasing the level of automation and maintenance is object of research interests. As matter of fact, several authors have pointed out that current visual inspections, which highly rely on a human subjective and error-prone empirical evaluation [2], can be enhanced by robotic/automatic assisted operations [3], [4]. Actually, actions performed by inspectors require often a long time to examine large areas and specialized equipment such as large under bridge units, heavy trucks etc. In most cases those expensive solutions may cause high logistical efforts and even interfere with normal operational conditions.

Recent works address the problem of the automation of inspection and maintenance tasks based on robotic systems [5]. Existing automatic or robotic systems based on ground or aerial solutions have been proposed for inspection of dangerous sites or those difficult to access, but at the present state-of-the-art, human-based procedures are not yet completely substituted. Examples of ground systems used for inspection are wheeled robots [6] and legged robots [7]. In case of inspection of vertical surfaces, wall-climbing robots were developed using magnetic devices [8] or using vacuum suction techniques [9]. Recently, unmanned aerial vehicles (UAVs), equipped with high definition photo and video cameras to get high-quality data, have shown a great potentialities in inspection applications [10, 11, 12]. Although they can significantly enhance infrastructure inspections and provide data to feed digital twin models [13], robotic systems are not yet fully embraced. The main reason is that algorithms are compute-intensive and require a significant computing capacity on hardware platforms that are subjected to strict limits on size, weight and power. For these reasons energy-efficient heterogeneous HPC architectures equipped with many-core processing units have being considered in order to speed up mathematical computations inherent to signal and image processing, motion planning etc [14].

Most of the infrastructure and civil structures are made by concrete, steel and masonry, which are prone to cracks due to deterioration of reinforcements. Crack information (e.g., the number of cracks and crack width and length) represents the current structural health indicators, which can be used for the proper maintenance to improve the structural safety [15]. Nowadays damages in buildings and bridges can be easily captured using a commercial digital camera and consequently analyzed and classified by image processing algorithms, but the detection of fractures is still challenging in image processing. The main reasons are that they have a complex topology, a thickness similar to the image resolution and are easily corrupted by noise [16].

Amongst the most widely used techniques there are those based on color detection and neural networks. In [17] a comparative analysis is proposed among different color spaces to evaluate the performance of color image segmentation using an automatic object image extraction technique. In [18] an Red Green Blue (RGB) based image processing technique was proposed for rapid and automated crack detection. Recently, an algorithm based on the Convolutional Neural Network (CNN) was considered in [19] to detect concrete cracks without calculating the defect features [20], [21]. Furthermore, a modified architecture of Fusion Convolutional Neural Network to handle the multilevel convolutional features of the sub-images is proposed and employed in [22] for crack identification in steel box girders containing complicated disturbing background and handwriting. Even though these techniques allow fast processing they are not suitable for real-world applications because they are affected by a significant false-positive rate due to a high sensitivity to environmental light conditions and noise [3].

In this paper we propose a mathematical method for detecting cracks in images that is more robust against all these factors. Aiming both at automatizing the whole process and at reducing its execution time a parallel implementation on heterogeneous HPC architectures is provided.

2 Mathematical model and parallel implementation

Variational methods have addressed successfully problems such as image segmentation and edge detection. They proposed a minimizer of a global energy as a solution. A first example is described by Mumford and Shah (MS) in their paper [23] where they proposed a first order functional, whose minimization determines an approximation of the image by means of a piecewise smooth function and detects edges as singularities in the image intensity. However, this model is not suitable for cracks because they do not represent singularities in the intensity function, but in its gradient instead. For this reason, we propose a second order variational model based on the Blake-Zissermann (BZ) functional [24]. This was introduced with the aim of overcoming some limitations of the MS approach, such as the over segmentation and the lack in detecting gradient discontinuities. Being the original formulation not suitable for numerical treatment, we focused on a different approach that is based on the approximation proposed by Ambrosio and Tortorelli (AT) for the MS functional [25, 26]. In their model, they replaced the unknown discontinuity set by an auxiliary function which smoothly approximates its indicator function. In our case two auxiliary functions are introduced as indicators of both intensity discontinuity and gradient discontinuity sets. As numerical minimization algorithm we chose an "inexact" block-coordinate descent scheme (BCD) to address the heterogeneous computing environment. In order to process very large images a tiling scheme is adopted: the minimizer is assembled by merging together local solutions restricted to portion of images.

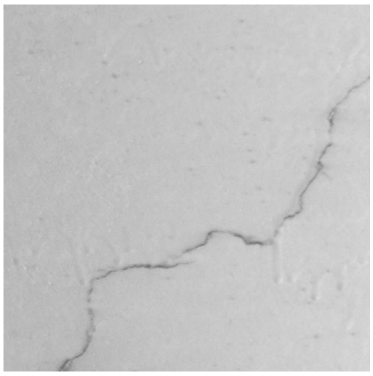

Figure 1. Crack on a concrete wall

3 Results

We tried our method on images of cracks taken in tunnels in Greece (Fig. 1) aiming at reconstructing the whole structure avoiding the effect of the noise and the environmental conditions (i.e. light conditions). We compared the results with the state-of-art technique based on mathematical morphology [16].

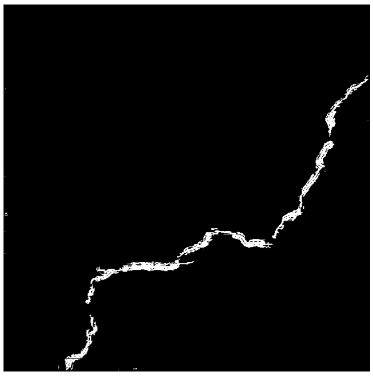

Figure 2. Our method

While in Fig. 3 the structure is broken in several points, our reconstruction is closer to the original one (Fig. 2). In order to reduce the execution time and to provide a automatic procedure we tested a sequential implementation with a parallel one based on the OpenMP framework that implements a strategy for collaboratively executing a program on an environment composed by devices of different types (aka heterogeneous architectures). Both the versions were executed on a High Performance Computing (HPC) cluster equipped with x86-64 processors, running a CentOS 7.6 operating system. The table 3 shows the execution times for Fig. 1. Overall, the parallel version is significantly more efficient with respect to the sequential one.

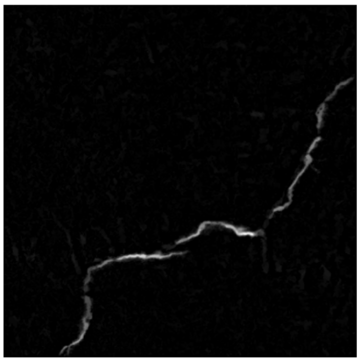

Figure 3. State-of-art based on mathematical morhphology

algorithm	time (s)
sequential	13.184868
parallel 24 cores	1.056701
parallel 48 cores	0.5915374

Table 1. Run time comparisons for a single image

4 Conclusions

In this paper we proposed an automatic procedure for detecting cracks in images. This is based on a variational method and its parallel implementation on heterogeneous HPC architectures. We got promising results for both the quality of the reconstruction and its execution time. As future plan, we would like to test our procedure on real world scenarios in order to understand if it could be used as useful tool for assessing civil structures. In order to reduce further the run time we plan to test the execution on several domain specific hardware accelerators. Moreover, we would like to address different structures for detecting new kind of damages.

References

[1] Gian Michele Calvi, Matteo Moratti, and Gerard J. O'Reilly. Once upon a time in italy the tale of the morandi bridge. *Structural Engineering International*, 29(2):198–217, 2019.

[2] H. Kim, Sung-Han Sim, and S. Cho. Unmanned aerial vehicle (uav)-powered concrete crack detection based on digital image processing. In *6th International Conference on Advances in Experimental Structural Engineering*. 11th International Workshop on Advanced Smart Materials and Smart Structures Technology, 2015.

[3] Eftychios Protopapadakis et al. Automatic crack detection for tunnel inspection using deep learning and heuristic image post-processing. *Applied Intelligence*, pages 1–14, 2019.

[4] Dongho Kang and Young-Jin Cha. Autonomous uavs for structural health monitoring using deep learning and an ultrasonic beacon system with geo-tagging. *Computer-Aided Civil and Infrastructure Engineering*, 33(10):885–902, 2018.

[5] Ronny Salim Lim, Hung Manh La, and Weihua Sheng. A robotic crack inspection and mapping system for bridge deck maintenance. *IEEE Transactions on Automation Science and Engineering*, 11(2):367–378, 2014.

[6] Shigeo Hirose and Hiroshi Tsutsumitake. Disk rover: A wall-climbing robot using permanent. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. Vol. 3. IEEE, 1992.

[7] Claudio Semini, Nikos G Tsagarakis, Emanuele Guglielmino, Michele Focchi, Ferdinando Cannella, and Darwin G Caldwell. Design of hyq–a hydraulically and electrically actuated quadruped robot. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 225(6):831–849, 2011.

[8] Lin Guo, Kevin Rogers, and Robin Kirkham. A climbing robot with continuous motion. In *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*. IEEE, 1994.

[9] J. Savall, A. Avello, and L. Briones. Two compact robots for remote inspection of hazardous areas in nuclear power plants. In Michigan Detroit, editor, *Proceedings of IEEE international conference on robotics and automation*, 1999.

[10] Norman Hallermann and Guido Morgenthal. Visual inspection strategies for large bridges using unmanned aerial vehicles (uav). In International Conference on Bridge Maintenance, editor, *Proc. of 7th IABMAS*. Safety and Management, 2014.

[11] Fabio Ruggiero, Vincenzo Lippiello, and Anibal Ollero. Aerial manipulation: A literature review. *IEEE Robotics and Automation Letters*, 3(3):1957–1964, 2018.

[12] Barrie Dams, Sina Sareh, Ketao Zhang, Paul Shepherd, Mirko Kovac, and Richard J Ball. Aerial

additive building manufacturing: three-dimensional printing of polymer structures using drones. *Proceedings of the Institution of Civil Engineer*, 173(1): 3–14, 2020.

[13] Rafael Sacks, Ioannis Brilakis, and Mark Girolami. Construction with digital twin information systems. *Data-Centric Engineering*, 1, 2020.

[14] Joseph Ortiz, Mark Pupilli, Stefan Leutenegger, and Andrew J. Davison. Bundle adjustment on a graph processor. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2020.

[15] Yufei Liu et al. Automated assessment of cracks on concrete surfaces using adaptive digital image processing. *Smart Structures and Systems*, 14(4): 719–741, 2014.

[16] Hugues Talbot. *Oriented patterns in image analysis*. PhD thesis, Université Paris Est, December 2013.

[17] Dina Khattab et al. Color image segmentation based on different color space models using automatic grabcut. *The Scientific World Journal*, 2014, 2014.

[18] HweeKwon Jung, ChangWon Lee, and Gyuhae Park. Fast and non-invasive surface crack detection of press panels using image processing. *Procedia Engineering*, 188:72–79, 2017.

[19] Young-Jin Cha and Wooram Choi. Deep learning-based crack damage detection using convolutional neural networks. *Computer-Aided Civil and Infrastructure Engineering*, 32(5):361–378, 2017.

[20] Young-Jin Cha et al. Autonomous structural visual inspection using region-based deep learning for detecting multiple damage types. *Computer-Aided Civil and Infrastructure Engineering*, 33(9): 731–747, 2018.

[21] Yi-zhou Lin, Zhen-hua Nie, and Hong-wei Ma. Structural damage detection with automatic feature-extraction through deep learning. *Computer-Aided Civil and Infrastructure Engineering*, 32(12):1025–1046, 2017.

[22] Yang Xu et al. Surface fatigue crack identification in steel box girder of bridges by a deep fusion convolutional neural network based on consumer-grade camera images. *Structural Health Monitoring*, 18 (3):653–674, 2019.

[23] David Mumford and Jayant Shah. Optimal approximations by piecewise smooth functions and associated variational problems. *Communications on pure and applied mathematics*, 42(5):577–685, 1989.

[24] Andrew Blake and Andrew Zisserman. *Visual reconstruction*. MIT press, 1987.

[25] L. Ambrosio-VM. Tortorelli. Approximation of functionals depending on jumps by elliptic functionals via gamma-convergence. *Comm. Pure Appl. Math*, 43: 999–1036, 1990.

[26] Luigi Ambrosio and Vincenzo Tortorelli. On the approximation of free discontinuity problems. :, pages 105–123, 1992.