AUTOMATIC AND SCALABLE SURFACE CRACK MEASUREMENT IN BRIDGE INSPECTION VIA THE INTEGRATION OF UAV, LOW-COST METROLOGY, AND DEEP LEARNING

L. A. Bedriñana [(1)], Y. Zaldivar [(2)], D. Medina [(3)], R. Cespedes [(4)], H. Zuo [(5)], N. Shirzad-Ghaleroudkhani [(6)], Q. Mei [(7)], and J. Fiestas [(8)].

[(1)] *Associate Professor, Universidad de Ingenieria y Tecnologia – UTEC, lbedrinana@utec.edu.pe*
[(2)] *Graduate Research Assistant, Universidad de Ingenieria y Tecnologia – UTEC, yeimi.zaldivar@utec.edu.pe*
[(3)] *Graduate Research Assistant, Universidad de Ingenieria y Tecnologia – UTEC, dmedina@utec.edu.pe*
[(4)] *Graduate Research Assistant, Universidad de Ingenieria y Tecnologia – UTEC, rodrigo.cespedes@utec.edu.pe*
[(5)] *Graduate Research Assistant, University of Alberta, hzuo4@ualberta.ca*
[(6)] *Assistant Industrial Professor, University of Alberta, shirzadg@ualberta.ca*
[(7)] *Assistant Professor, University of Alberta, qipei@ualberta.ca*
[(8)] *Professor, Universidad de Ingenieria y Tecnologia – UTEC, jfiestas@utec.edu.pe*
…

Extended abstract

Reinforced Concrete (RC) bridges are among the most important elements of road infrastructure; however, RC bridges are prone to deterioration throughout their service life, which can compromise their structural integrity. Therefore, it is essential to ensure their safety and functionality throughout their service life. The presence of cracks in RC bridges is generally considered an indication of potential structural issues. Moreover, surface cracks in RC bridges can compromise the durability and strength of the structure by allowing the ingress of harmful agents such as water, carbon dioxide, and chlorides, which accelerate steel reinforcement corrosion and concrete degradation. For this reason, surface cracking is a critical aspect for the damage assessment of RC bridges.

Even when accurate measurement of crack dimensions is essential for reliable bridge condition assessment according to current bridge inspection guidelines, manual crack inspection presents significant challenges. For instance, traditional inspections, relying mostly on in-site visual inspection, require access to certain bridge areas, complex logistics, and high operational costs and time. Moreover, manual measurements of cracks often require inspectors to work at considerable heights or in potentially hazardous environments, increasing safety risks. In other cases, the use of specialized equipment such as cranes or scaffolding, combined with the temporary closure of traffic lanes, results in high operational costs and extended

inspection times. To address these challenges, the engineering community is working toward adopting unmanned aerial vehicles (UAVs) for bridge inspection, in combination with computer vision-based models for damage assessment. Different Deep Learning (DL)-based methods have emerged, enabling the automatic extraction of features directly from raw images by leveraging large datasets as references. These approaches are generally categorized into three types: crack identification through binary image classification, damage detection based on bounding boxes, and pixel-level segmentation. For damage quantification in bridge inspections, semantic segmentation is critical for practical implementation. Moreover, most of the previous proposed predictive models exhibit long inference times and are restricted to datasets collected under laboratory conditions. On the other hand, most UAV-based inspection systems provide only pixel-level information, lacking a true, accurate metric measurement for engineering decisions.

To provide an efficient, cost-effective, and robust solution for RC bridge inspection, this study proposes an end-to-end system for the segmentation and measurement of surface cracks using 2D images captured by UAVs, in addition to information provided by a lightweight, drone-agnostic hardware module that enables real-world measurements. The proposed system includes crack width quantification and automatic conversion from pixels to metric units, so current inspection guidelines can be applied in this automatic inspection.

The proposed system takes high-resolution images along with sensor information as input. The uploaded images undergo a preprocessing stage, where they are divided into subimages of 512 × 512 pixels and filtered. At the software level, the system combines patch-based and pixel-level segmentation using binary image classification and crack segmentation models. All preprocessed subimages are sent to a classification stage, where the model identifies which ones contain cracks. Subimages classified as positive are passed to the segmentation model, which delineates cracks at the pixel level. Subsequently, the segmented masks are processed in the reconstruction and measurement stage, where they are placed back in their original positions to generate the mask of the full image. The crack width is then calculated in pixels and later converted to millimeters. For this conversion, each image must include information about the distance to the surface and a scale reference, both obtained through the low-cost metrology hardware mounted on the UAV. This hardware consists of a distance sensor and a Diffractive Optical Element (DOE) laser that projects a pattern serving as a scale reference. The resulting crack width values are compared against the thresholds established by the Manual for Bridge Element Inspection – AASHTO to determine the condition state.

Experimental results showed that the binary classification model achieved an *F1-Score* of 0.93 on the validation set, while the segmentation model achieved an *F1-Score* of 0.83. After field experiments, the overall system performance yielded a coefficient of determination of 0.82 and an average inference time of 4.11 seconds per high-resolution image. Through integrating UAVs, low-cost metrology hardware, and deep learning, the proposed system offers an alternative for rapid and accurate bridge inspections.

Keywords*: UAV; bridge inspection; deep learning; convolutional neural network; concrete cracks.*