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Increasing the computational efficient of digital cross correlation by a vectorization method

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ABSTRACT

This study presents a vectorization method for use in MATLAB programming aimed at increasing the computational efficiency of digital cross correlation in sound and images, resulting in a speedup of 6.387 and 36.044 times compared with performance values obtained from looped expression. This work bridges the gap between matrix operations and loop iteration, preserving flexibility and efficiency in program testing. This paper uses numerical simulation to verify the speedup of the proposed vectorization method as well as experiments to measure the quantitative transient displacement response subjected to dynamic impact loading. The experiment involved the use of a high speed camera as well as a fiber optic system to measure the transient displacement in a cantilever beam under impact from a steel ball. Experimental measurement data obtained from the two methods are in excellent agreement in both the time and frequency domain, with discrepancies of only 0.68%. Numerical and experiment results demonstrate the efficacy of the proposed vectorization method with regard to computational speed in signal processing and high precision in the correlation algorithm. We also present the source code with which to build MATLAB-executable functions on Windows as well as Linux platforms, and provide a series of examples to demonstrate the application of the proposed vectorization method.

1. Introduction

Optical inspection methods provide the benefits of (a) non-contact measurement and (b) full-field evaluation at submicron scales [1]. Electronic speckle pattern interferometry (ESPI) and digital image correlation (DIC) are two methods of inspection based on signal processing and numerical computation. These techniques provide qualitative data related to the distribution of the deformation field as well as a quantitative assessment of displacement [2]. Interferometric techniques have been applied to the measurement of mode shape at high resonant frequencies in which bright and dark fringes represent the deformation of contours on the scale of hundreds of nanometers [3]. ESPI measures in-plane as well as out-of-plane displacement using an optical setup; however, interferometric metrology requires a coherent light source and isolated optical platform, thereby limiting the applicability of these methods as well as the size of specimens. Disturbances in the air and electronic fluctuations also detract from image quality and undermine the integrity of experiment results. This led to the application of standard deviation and automatic sweeping functions to enhance the quality of interferometric fringes [4].

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Compared with ESPI, DIC measurement can be conducted under a wide range of environmental conditions and the setup of experiments and specimen preparation is relatively simple [5]. Coherent lasers and additional speckle are generally unnecessary and the wide scale availability of imaging systems using digital cameras enhances the flexibility and practicality.

DIC systems can be used in conjunction with telescopes [6], focused ion beam (FIB) microscopy [7] and scanning electron microscopy (SEM) [8]. Systematic selection and combination of optical lenses and digital cameras enable rendering at resolutions ranging from millimeters to nanometers. In practical experiments, three major optical setups are generally used to measure the displacement of deformed objects in 2D or 3D: (1) DIC systems using a single camera have been applied to the measurement of in-plane displacement associated with simple extension or pure bending [9]; (2) DIC systems using dual cameras provide stereo vision for the inspection of deformation in curved surfaces in 3D [10]; and (3) DIC systems in conjunction with X-ray computed tomography (XRCT) have been used to image interior slices of a trabecular bone and other forms of nondestructive examination [11].

The noncontact nature of DIC metrology broadens the applicability of experimental measurement to include various fields of engineering, including mechanical, civil and biomedical branches. Research in solid mechanics uses true stress-strain curves to analyze the material properties associated with elastic and plastic deformation during tensile testing. DIC methods can be used to measure displacement and velocity without the need for additional sensors as well as provide quantitative values for local displacement and local strain. As such, these techniques have been growing in importance in experimental mechanics [12]. In civil engineering, the on-site application of conventional bending tests to structural columns involves the use of strain gauges, load cells, and accelerometers to monitor the deformation of reinforced concrete (RC) structures [13]. Preparing for these point-wise sensors can be time-consuming and requires analog-to-digital converters. In addition, extreme environments can introduce noise into the electronic signal, and the extended length of wire cables lowers the signal-to-noise ratio. With the aid of a telescope, DIC can be used to measure the whole field deformation of mega structures from a safe distance, as well as determine the displacement field and strain field of an RC column. Researchers in biomedicine commonly use computed tomography (CT) and magnetic resonance imaging to retrieve 3D images from within tissue. Digital volume correlation (DVC) has been used to measure the interior stress and strain of deformed organisms such as bones, teeth, and cellular foam [14]. The image correlation approach can be implemented on a compact system, providing high flexibility with regard to measurement and provide rapid results in real time.

Ideally, a DIC system comprises three major components: (a) a high-resolution imaging system; (b) a high-performance computer; and (c) a highly efficient algorithm. The specifications of these components largely determine the spatial resolution, temporal resolution, and computational speed of correlation metrology. Imaging systems comprise optical lenses and digital cameras, and numerous commercial products provide high magnification and low optical distortion as well as high resolution (over 500 million pixels in a single image) and high frame rate (over 10 thousand fps). The performance of the personal computer systems has improved to such an extent that current high-end computers provide multiple CPU cores running at high clock speeds. For example, the mid-level Intel i5 3230 M used in this study provides 2 CPU cores running 4 CPU threads at a clock speed of 2.6 GHz. We used 16 gigabytes of SDRAM with a working clock of 1.3 GHz. The graphic processing unit (GPU) is another crucial element in the DIC systems, many of which provide more than 1000 cores. In terms of the efficiency of correlation algorithms, researchers have made some impressive leaps [15]. Since Sutton et al. [16] proposed the core concept of image correlation in the 1980s, the criteria has been extensively investigated leading to its implementation in the spatial, time, and frequency domains. In the time domain, the iterative least-squares (ILS) algorithm has been combined with the pointwise least-squares (PLS) algorithm within a practical linear-intensity-change model to provide accurate measurements of 3D sub-voxel displacement/motion [17]. In the frequency domain, computer-aided speckle interferometry (CASI) uses the discrete architecture of fast Fourier transform (FFT) to convert correlation processes into arithmetic operations. These technologies reduce computational complexity and have been extended from the measurement of 2D surfaces to the investigation of 3D interior spaces [18–20]. Among the three aspects of overall performance, it is the algorithm that plays the most critical role in the efficiency and applicability of DIC systems.

Computational correlation can be achieved using either for-loop iteration or matrix operations. Interpreted high-level languages, such as MATLAB, Mathematica, and Octave, support loop-based as well as array-based statements and provide a complete software development kit (SDK) for the development of algorithms. This study employed MATLAB 2013a as the programming environment. This system has been widely used in education, engineering, and research, and has become a standard tool in many fields [21]. MATLAB is a matrix-processing language that facilitates the creation of highly efficient mathematical algorithms using array-based operations, far superior to those using loop-based iterations, except in the case where for-loops have been vectorized as matrix statements. Nonetheless, this means that the computational efficiency of MATLAB decreases exponentially with an increase in the number of loop layers. Most MATLAB programmers are fully aware of the differences in performance between the two methods; however, they maintain the habit of writing code in a nested-loop format due to the difficulties inherent in translating from nested for-loops to vector multiplication. The source code can largely be rewritten using the MATLAB process of “vectorization” or “vectorized statement”; however, the modified code often loses its original structure and becomes less flexible. The correlation criteria in 1D, 2D, and 3D cases requires two, four, and six layers of loops, respectively. The multilayering of loop iterations greatly decreases computational efficiency, and the vectorization of code requires additional time for the development of new algorithms. Semi-vectorization is a general solution in which N layer loops are separated into a series of $N-2$ loop iterations and several 2D matrix operations. Nonetheless, semi-vectorization is unable to provide optimal performance in MATLAB matrix computation. Thus, this paper presents source code that can be used for the direct conversion of loop-based formations into equivalent array-based statements.