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Fast, large-scale, particle image velocimetry-based estimations of river surface velocity

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ABSTRACT

A modified high-speed implementation of cross-correlation (CC) based, large-scale particle image velocimetry (LSPIV) was used to estimate the surface velocity of a river with video collected from a gray-scale camera. To improve the quality of results in the high-noise low-signal environment, we introduce a temporal correlation averaging (TCA) scheme that merges a small number of correlation surfaces in the time domain. The TCA scheme is combined with a multi-size macroblock (MMB) sampling method that provides correlation scores from four different macroblock sizes. The TCA scheme is also used in conjunction with a signal-level indicator computed on the macroblock. The signal-level indicator is used to reject correlation scores prior to computation and helps to keep noisy results out of the TCA. These modifications were tested by comparing LSPIV calculations to Acoustic Doppler Current Profiler measurements. The percent difference of measured velocity between LSPIV with TCA and MMB and without TCA and MMB when compared to the ADCP was reduced by as much as 30%. The low processing cost of our modifications along with an efficient multithread implementation of LSPIV facilitates high speed processing of up to a few thousand vector points at rates that exceed the capture speed of common hardware.

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1. Introduction

Large-scale particle image velocimetry (LSPIV) is a commonly used image-processing method for determining water surface currents in large scale experiments and has been thoroughly described (Fujita et al., 1998; Holland et al., 2001; Bradley et al., 2002; Muste and Fujita, 2008). LSPIV is significant because it provides current vectors similar to in situ devices such as the ADCP, but from a remote sensing platform. LSPIV is also capable of producing a more dense field of current vectors over the surface of the body of water being measured than traditional in situ observations. LSPIV has a limited ability to produce accurate vectors when source imagery exhibits poor lighting, low spatial resolution, and when the density of particles on the water surface is limited (Jodeau et al., 2008; Le Coz et al., 2010). Time required to process LSPIV using the existing implementations is also a limiting factor. We show that both the accuracy of LSPIV (as compared with in situ measurements) and processing speed of LSPIV can be improved with modifications to the algorithm for cases where imagery is of low quality and surface signal is limited.

LSPIV has been applied to the problem of measuring river surface velocity from imagery with some favorable results (e.g., Bradley et al., 2002) and mixed results (e.g., Puleo et al., 2012; Tsubaki et al., 2011). Under controlled lab conditions, the method has been shown to work well (e.g., Muste and Fujita, 2008), but the conditions seen in field data collection are far from ideal and the imagery produced is often of low spatial resolution. Lighting conditions are often poor resulting in shadows and limited visible signal on the surface of the water. The water condition itself is also a factor that may limit the amount of visible correlation signal. LSPIV tends to produce a high number of noisy vectors under these conditions, reducing the quality of the results.

A number of modifications to LSPIV, in addition to alternative techniques, have been proposed to address some of its limitations. One alternative method, called space-time image velocimetry, STIV, is more robust to input noise and requires less computation than LSPIV but is a one-dimensional measurement oriented in the streamwise direction and cannot measure recirculating flows that have varying direction (Fujita et al., 2007). Most attempts to improve LSPIV quality focus on post-processing techniques that compare neighboring vectors to locate and eliminate outliers. Such

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methods are known to be effective and help to improve LSPIV results (e.g., Holland et al., 2001). Methods to improve correlation surface quality have also been used to produce higher quality results in laboratory PIV experiments. Examples of these methods include iterative window deformation and multipass interrogation methods (e.g., Stanislas et al., 2008). Window deformation and multipass interrogation have substantial processing overhead and for that reason are not suitable for LSPIV measurements that require high processing speed. We propose that similar methods may be applied to images in a video sequence over time to improve result quality, in the case of steady flows, without sacrificing per-image processing performance.

We have developed a high-speed, modified LSPIV method and applied that method to compute river surface velocity. Section 2 discusses the implementation and design of our LSPIV system with an emphasis on the performance considerations and the modifications made to the standard processing techniques. Section 3 presents the processing performance of our modified LSPIV method and the accuracy of the same method when compared to measurements captured by an ADCP device at the Wolf River experiment location in Mississippi. Finally, Section 4 contains a discussion of the results and some concluding remarks.

2. LSPIV implementation

The standard LSPIV implementation may be divided into three parts that include image pre-processing, displacement computation, and displacement analysis. At the image pre-processing step, LSPIV requires two images as input. The two images, referred to as source and target, must be temporally separated by a known Δt value. The two images are warped, using a process called orthorectification, so that pixel coordinates map to ground coordinates. Parameters for orthorectification may be determined from a camera model or from point-to-point correspondence. Image filtering methods such as smoothing and mean removal are also applied at the pre-processing step.

Displacement computation is the second step in the LSPIV algorithm and involves determining the relative displacement of pixels as recorded in the two input images. Many different techniques have been proposed to determine pixel offsets but because the problem is ill-posed, no ideal method exists. One of the more commonly used methods is called cross correlation. Cross correlation or CC involves reading a block of pixels from the source image and searching for a similar block of pixels within a limited area in the target image. Source pixels are referred to as the macroblock and the target pixels as the searchblock. While the size of the searchblock could be as large as the target image, it is often limited by using a measurement or estimation of the maximum velocity expected on the water surface. A correlation score is generated for each coordinate within the limit of the searchblock by computing a multiplication between the macroblock and the target image. The resulting correlation score is placed in a correlation surface at the correct offset.

Determining cross correlation is a time-consuming process due to the number of computations required to compute a multiplication between the macroblock and the target image at all possible locations. The full-search method, as the name implies, computes one multiplication calculation for each pixel in the macroblock and repeats this at every possible offset as defined by the searchblock size. The full-search method has a complexity of $O(n^4)$, where n is influenced by the size of the macroblock and the searchblock and is computed as follows:

$$\Phi_{a,b} = \sum_{i=1}^{M_x} \sum_{j=1}^{M_y} M(i,j) \cdot B(a+i, b+j), \tag{1}$$

where M is the macroblock, M_x is the number of columns in the macroblock, M_y is the number of rows in the macroblock, $M(i,j)$ is the intensity level recorded by the (i,j) pixel in the macroblock, and B is an expanded block of pixels within the searchblock coordinates. The blocks M and B are extracted from the lag and lead images respectively. The size of B is determined by the size of M and the expected motion. A value for Φ is computed at every coordinate (a, b) limited by the size of the searchblock.

The third and final step of LSPIV is result processing. Result processing involves computing a velocity vector from a correlation surface by taking into account the peak of the correlation surface, a sub-pixel offset, and a conversion from pixel space to ground

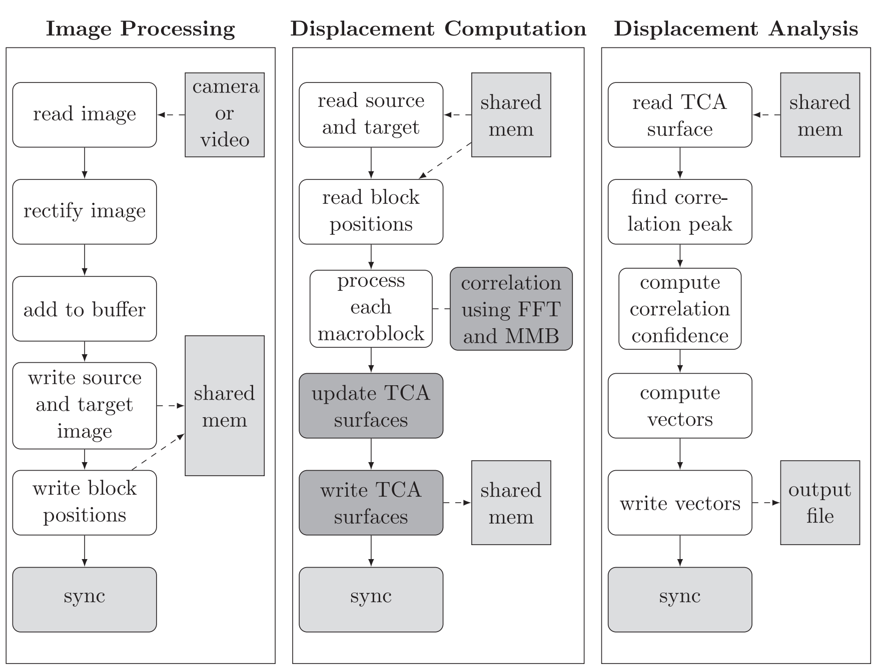

Fig. 1. Flowchart of concurrent LSPIV tasks. (Dark squares show modified components, lightly shaded shows thread communication and I/O, and unshaded show standard LSPIV).