Postprint: Transverse Velocity Field Measurement in NVST High-Resolution Solar Images Using Demons Registration

Authors: Liu Hui, Yang Yunfei, Shang Zhenhong, Li Runxin

Date: 2018-05-28T00:00:00+00:00

Abstract

The measurement of transverse velocity fields in high-resolution solar images has been widely applied to the dynamic analysis of photospheric and chromospheric surface features, yet issues regarding insufficient measurement precision remain. The Demons method is introduced in detail and applied to the processing of high-resolution observational data from the 1-meter New Vacuum Solar Telescope (NVST). First, three datasets representing different observational time intervals and various wavelengths of the photosphere and chromosphere are selected as test samples. After measuring the velocity field, its measurement precision is evaluated by performing non-rigid registration with the previous moment' s image and comparing the Structural Similarity Index (SSIM). The results demonstrate that the Demons method significantly outperforms traditional FLCT and DAVE methods in the fine determination of small-scale motions. Furthermore, sub-pixel and super-pixel simulated displacement experiments using photospheric and chromospheric images indicate that the pointwise measurement precision of this method can reach the order of 0.1 pixels.

Full Text

Measurement of Transverse Velocity Field in NVST High-Resolution Solar Images Based on Demons Registration

Liu Hui[1], Yang Yunfei[2], Shang Zhenhong[1], Li Runxin[1]
[1]Faculty of Information Engineering and Automation, Kunming University of Science and Technology, Kunming, Yunnan 650500, China
[2]Key Laboratory of Computer Technology Application of Yunnan Province, Kunming University of Science and Technology, Kunming, Yunnan 650500, China

Abstract

The measurement of transverse velocity fields in high-resolution solar images has been widely applied to the dynamic analysis of photospheric and chromospheric features, yet challenges remain regarding measurement accuracy. This paper introduces the Demons method in detail and applies it to the processing of high-resolution observational data from the 1-meter New Vacuum Solar Telescope (NVST). Three representative datasets with different temporal intervals and wavelengths characteristic of the photosphere and chromosphere were selected as test samples. After measuring the velocity field, the accuracy was evaluated by performing non-rigid registration with the previous frame and comparing the Structural Similarity Index (SSIM). The results demonstrate that the Demons method significantly outperforms traditional FLCT and DAVE methods in the fine measurement of small-scale motions. Furthermore, sub-pixel and super-pixel simulated displacement experiments using photospheric and chromospheric images indicate that the point-wise measurement accuracy of this method can reach 0.1 pixel magnitude.

Keywords: solar high-resolution image; velocity field; optical flow field; Demons registration

Solar observations have entered an era of high spatial and temporal resolution. High-resolution telescopes such as Japan' s HINODE satellite [?], China' s 1-meter New Vacuum Solar Telescope (NVST) [?], the US Goode Solar Telescope [?], and the Swedish Solar Telescope [?] have produced massive amounts of multi-band observational sequence data, presenting both important opportunities and challenges for solar physics research [?]. These data intuitively reveal the details and variations of activity phenomena occurring at all scales in the solar atmosphere (from solar storms and large- and small-scale activities to magnetohydrodynamic waves and oscillations existing at various scales) through intensity measurements. High spatiotemporal resolution images not only display morphological intensity changes in the solar atmosphere but also enable quantitative analysis and description. Among these capabilities, calculating the transverse velocity fields of these activities through temporal intensity variations has been extensively applied to the dynamic analysis of photospheric and chromospheric surface features.

Typical transverse velocities in the solar photosphere and chromosphere range from several to tens of kilometers per second. Given the spatial and temporal resolution of current high-resolution solar image sequences, this means precisely measuring sub-pixel or few-pixel displacements between consecutive frames. Numerous developments have emerged in solar image data processing for this purpose. The most classical methods include Local Correlation Tracking (LCT) [?] and its Fourier-based variant, Fourier Local Correlation Tracking (FLCT) [?]. The Differential Affine Velocity Estimator (DAVE) [?, ?], after incorporating the magnetic induction equation, was initially used for non-potential studies of magnetograms and later applied to intensity image measurements [?, ?]. Additionally, Potts et al. [?, ?] proposed a Balltracking method for studying photospheric supergranulation. Although these methods have yielded good results, their measurement accuracy does not yet meet the requirements for processing high-resolution images from instruments like NVST, which achieves a pixel resolution of 0.05 arcseconds and temporal resolutions as high as ten seconds. Therefore, further in-depth research on relevant methods is necessary.

The measurement of transverse velocity fields essentially involves measuring feature displacements between two image frames over a certain time interval. Since solar sequence images represent temporal variations in light intensity, the velocity field constitutes a typical optical flow field. From another perspective, displacement measurement between two frames can also be viewed as a non-rigid image registration problem. With advances in computer image processing technology, both optical flow measurement and non-rigid image registration techniques have seen significant development.

Non-rigid image registration methods can be described by three components: (1) spatial transformation linking source and target images; (2) similarity metrics measuring the similarity between target and source images; and (3) optimization methods determining optimal transformation parameters.

Non-rigid registration methods primarily fall into two categories: spatial transformation-based and physical model-based approaches. Among them, the Demons non-rigid registration method [?], proposed based on fluid diffusion theory in thermodynamics, offers advantages such as handling non-smooth deformations and good noise resistance. It has been widely applied in medical image registration [?] and aligns well with the physical characteristics of non-uniform local deformation of magnetofluids in the solar photosphere and chromosphere.

This paper employs the Demons method to measure the transverse velocity fields in NVST high-resolution photospheric and chromospheric observational data. The measurement results demonstrate that this method can accurately measure transverse velocity fields in high-resolution solar images, outperforming traditional FLCT and DAVE methods.

1.1 Principle and Procedure of Demons Registration

The classical Demons algorithm, proposed by Thirion, is known as the "Demons-base" algorithm [?]. Conceptually, it resembles Maxwell's experimental principle from the 19th century. The fundamental idea assumes that the grayscale of moving objects remains constant over time, allowing non-rigid registration to be treated as a gradual diffusion process where pixels in the floating image move toward the reference image. The diffusion speed of each pixel is determined by the grayscale gradient information of the reference image.

Assuming the reference image r represents a "snapshot" at a certain moment, and the image function maintains constant grayscale values, this assumption can be modeled as $\frac{\partial r}{\partial t} = 0$. Both the floating image f and reference image r are image functions in space and time. Initially, the image function equals f, and after a certain time, it becomes completely deformed into r. The registration process aims to derive a vector field that drives each pixel in f toward its corresponding pixel in r. To obtain the driving force, we differentiate equation (1) to get:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = 0$$

where $\mathbf{v}$ is the velocity field from the floating image to the reference image. This can be simplified to:

$$\mathbf{v} = -\frac{\partial f}{\partial t} \frac{\nabla f}{|\nabla f|^2}$$

where ∇f is the gradient vector of f. Further derivation yields:

$$\mathbf{v} = (r - f) \frac{\nabla r}{|\nabla r|^2}$$

If we consider the gradient information of the floating image as a positive internal force and that of the reference image as a negative internal force, using both forces to drive the deformation simultaneously yields a diffusion velocity of:

$$\mathbf{v} = (r - f) \frac{\nabla r}{|\nabla r|^2 + (r - f)^2} + (r - f) \frac{\nabla f}{|\nabla f|^2 + (r - f)^2}$$

The Demons algorithm utilizes local image information to drive deformation while ensuring global continuity, thereby preserving image topology.

1.2 Demons Method Based on Gradient Mutual Information

In the Demons model, each pixel in the floating image can move freely, potentially causing all pixels with a specific grayscale value in the floating image to map to the same pixel in the reference image, leading to incorrect registration results. To ensure pixels move in the correct direction, we improve the Demons algorithm by incorporating gradient mutual information. Building upon equation (7), we add the effect of gradient mutual information between the two images to the original diffusion velocity, maximizing the gradient mutual information upon registration completion. The improved Demons algorithm diffusion velocity model becomes:

$$\mathbf{v}_{new} = \mathbf{v}_{old} + \beta \nabla I_{grad}$$

where I_{grad} is the gradient mutual information between the two images, and β is a positive constant representing the weight of this term.

Registration methods based on grayscale mutual information have the major drawback of ignoring spatial information. In solar image registration, images of the same target may have different grayscale values, different resolutions, or even different sizes. However, for the same target, its boundaries are fixed and do not change significantly. When two images are registered, the gradient vectors at corresponding pixel positions will have the same or opposite directions. Based on this analysis, gradient mutual information is calculated using the Parzen window method.

2 Experimental Data

The 1-meter solar telescope, as China’ s largest solar telescope and one of the world’ s three major high-resolution imaging solar telescopes, has demonstrated excellent observational performance and high-quality imaging. To validate the applicability of the Demons method, three representative datasets from the 1-meter solar telescope were selected, comprising two photospheric image sets and one chromospheric image set. Each set contains two consecutive frames. By calculating the optical flow field or performing non-rigid registration between these frames, the corresponding velocity fields can be obtained.

Dataset 1 consists of two photospheric Level 1+ reconstructed images observed in the TiO band by the 1-meter solar telescope. The observation times are 04:58:31 UT and 05:01:28 UT on November 3, 2013, with a temporal interval of 2 minutes 57 seconds. The field of view is 685×650 pixels, with a pixel resolution of 0.04 arcseconds. A typical photospheric transverse velocity of 1 km/s produces approximately 6 pixels of displacement, indicating super-pixel motion in the overall optical flow field.

Dataset 2 observes the same target, in the same band, and during the same period as Dataset 1, but the first frame was captured at 05:01:10 UT, only 18 seconds apart from the second frame—approximately one-tenth of Dataset 1’ s interval. Other parameters remain identical. Consequently, a 1 km/s transverse velocity yields merely 0.6 pixels of displacement, representing sub-pixel motion in the optical flow field.

Dataset 3 comprises two chromospheric Level 1+ reconstructed images in the H band. The observation times are 09:59:53 UT and 10:00:25 UT on August 6, 2017, with a 32-second interval. The field of view is 238×225 pixels, with a pixel resolution of 0.13 arcseconds. A 5 km/s chromospheric transverse velocity produces about 1.7 pixels of displacement, including both sub-pixel and super-pixel displacements in the overall optical flow field.

[Figure 1: see original paper] The second frame of dataset 1 and 2 (left) and the second frame of dataset 3 (right)

As shown in Figure 1, the photospheric images in Datasets 1 and 2 capture a local solar active region, featuring granules, umbrae, and penumbrae. Dataset 3 shows typical chromospheric fibrils with strong self-similarity in image structure.

3 Data Processing Results

The Demons method was applied to calculate the per-pixel displacement (optical flow field) of the second frame relative to the first for all three datasets, which was then converted to point-wise transverse velocity fields based on the corresponding time intervals. [Figure 2: see original paper] displays two frames from a small region in Dataset 1 and the displacement vectors calculated using the Demons method, clearly revealing subtle granule motions.

To evaluate the Demons results and compare them with commonly used FLCT and DAVE methods in solar data processing, we performed non-rigid registration between the second and first frames using bilinear interpolation after obtaining the optical flow fields with each method. The registration accuracy was then assessed using the Structural Similarity Index (SSIM) [**?**], where higher registration accuracy implies higher optical flow field (velocity field) measurement precision.

For two images x and y, the SSIM is calculated as:

$$\mathrm{SSIM}(x,y)=\frac{(2\mu_x\mu_y+C_1)(2\sigma_{xy}+C_2)}{(\mu_x^2+\mu_y^2+C_1)(\sigma_x^2+\sigma_y^2+C_2)}$$

where μ_x and μ_y are the mean values, σ_x^2 and σ_y^2 are the variances, and σ_{xy} is the covariance. C_1 and C_2 are constants to prevent division by zero, with values of 0.01 and 0.03 respectively for intensity-normalized images. The SSIM ranges from 0 to 1, with larger values indicating greater similarity. Identical images yield an SSIM of 1.

For pixel-wise comparison of the similarity between registered frames, an 11×11 pixel neighborhood window average was used as the local SSIM value. If more points have SSIM values close to 1 after registration, the method demonstrates more accurate overall displacement measurement and better registration quality. The average of all pixel-wise SSIM values represents the overall measurement level.

presents the average SSIM values for the three datasets before registration and after non-rigid registration using FLCT, DAVE, and Demons methods.

Table 1. The SSIM index after non-rigid registration with different methods

Dataset	Original	FLCT	DAVE	Demons
Dataset 1	-	-	-	-
Dataset 2	-	-	-	-

Dataset	Original	FLCT	DAVE	Demons
Dataset 3	-	-	-	-

The results show that the original similarity depends on both temporal interval and feature motion speed. For chromospheric data, rapid motion causes significant changes within half a minute. FLCT produces very limited SSIM improvement, indicating minimal motion detection. DAVE shows substantial improvement, but the Demons method performs even better. Dataset 1 has a longer interval, while Dataset 3 exhibits faster chromospheric motion. In these datasets, besides local motion, new features emerge and old structures disappear, resulting in relatively lower SSIM values. Dataset 2 has only an 18-second interval with slow photospheric motion and minimal image differences, yielding significantly higher SSIM values. Regardless of original image conditions, the Demons method demonstrates robust performance across different datasets.

[Figure 3: see original paper] displays the histogram probability distribution of point-wise SSIM values for Dataset 1 after registration using the three methods. The Demons method shows a distribution shifted closer to 1, significantly outperforming DAVE and FLCT. FLCT results are very close to unregistered images, indicating poor measurement effectiveness. This aligns with Table 1 results, and Datasets 2 and 3 exhibit the same trend.

Regarding final velocity field measurements, all three datasets show the same trend: FLCT only produces measurements for relatively large displacements, DAVE systematically yields values smaller than Demons (typically half the precision), and the Demons method consistently provides the highest measurement accuracy.

4 Simulation Data Tests

Although the Demons method outperforms DAVE and FLCT, perfect matching is not achieved after non-rigid registration of the second frame (SSIM 1). The primary reason is that over time intervals, both photospheric and chromospheric features undergo not only displacement but also emergence of new features and disappearance of old structures, which cannot be captured by optical flow calculations alone.

To further compare the optical flow measurement accuracy of Demons and DAVE and test their reliability for sub-pixel and super-pixel displacements on different solar images (photosphere and chromosphere), two simulation experiments were designed. The first frame from Dataset 1 and Dataset 3 was shifted by a fixed amount in both X and Y directions to generate a second frame with rigid motion. Both methods then measured the optical flow field relative to the first frame. Since the displacement is global, the mean and standard deviation of the point-wise optical flow field effectively reflect measurement accuracy.

presents the statistical results for both methods when the global displacement is (5.7, -0.2) pixels.

Table 2. The statistical results of DAVE and Demons for simulation data

Method	Photosphere X	Photosphere Y	Chromosphere X	Chromosphere Y
DAVE mean	-	-	-	-
DAVE std	-	-	-	-
Demons mean	-	-	-	-
Demons std	-	-	-	-

Compared with preset values, Demons shows significantly better performance in both mean and standard deviation, achieving point-wise measurement accuracy of 0.1 pixel. DAVE not only has a standard deviation one order of magnitude higher than Demons but also exhibits substantial systematic bias in the mean, particularly for chromospheric images with strong autocorrelation. While DAVE is generally considered to have large errors for super-pixel measurements, the tests indicate that DAVE is also heavily influenced by the image' s characteristic structures, which is related to its correlation-based nature.

FLCT was excluded due to its inability to calculate sufficient pixels for statistical significance. Since the simulations involve rigid whole-image displacement, standard whole-image cross-correlation can directly measure the rigid displacement. The results are (5.7578, -0.1814) for photospheric images and (5.7446, -0.0654) for chromospheric images, showing significantly larger deviations than the mean results from Demons point-wise measurements. This suggests that Demons is not only suitable for non-rigid registration but can also measure rigid image displacement through averaging, applicable to rigid registration. This method offers particular advantages for targets with strong self-similarity, such as chromospheric fibrils and the solar limb.

5 Conclusions

This paper describes the Demons method in detail and applies it to measure transverse velocity fields in high-resolution solar images with different targets and displacement magnitudes. After non-rigid registration based on the measured velocity fields, the SSIM values improve significantly, demonstrating more accurate displacement measurement and confirming the method' s feasibility.

Comparisons with DAVE and FLCT reveal clear advantages of the Demons method. Sub-pixel and super-pixel simulation experiments using photospheric and chromospheric data indicate that the Demons point-wise measurement accuracy reaches 0.1 pixel magnitude. This translates to a transverse velocity precision of 200 m/s for 18-second interval photospheric images from the 1-meter solar telescope, and 500 m/s for 32-second interval chromospheric images. Additionally, for image registration with high self-correlation, this method shows clear advantages over traditional cross-correlation methods for both non-rigid and rigid registration.

The comparative study also shows that FLCT is generally unsuitable for high-resolution image measurement, while DAVE applied directly to intensity images cannot achieve precise results.

The Demons method achieves high accuracy for both sub-pixel and super-pixel measurements. However, its algorithmic complexity results in high computational overhead and long processing times, making it less suitable for full-frame operations on large high-resolution images. Additionally, processed images exhibit noticeable boundary effects, requiring edge expansion of regions of interest in practical applications.

It must be noted that measuring transverse velocity fields using optical flow fundamentally assumes that material motion manifests as lateral intensity changes in images, and this represents only the projection onto the observation plane, not the actual material flow direction. Furthermore, the emergence of new structures and disappearance of old structures inherently limits this measurement approach, necessitating high temporal resolution observations to minimize such changes. However, shorter intervals mean smaller displacement magnitudes.

Theoretically, this method can be applied to process high-resolution observational images from other telescopes and may also be used for lower-resolution data or other image types, though further testing is required.

References

[1] Tsuneta S, Ichimoto K, Katsukawa Y, et al. The Solar Optical Telescope for the Hinode mission: an overview [J]. Solar Physics, 2008, 249(2): 167-196.

[2] Liu Z, Xu J, Gu B Z, et al. New vacuum solar telescope and observations with high resolution [J]. Research in Astronomy and Astrophysics, 2014, 14(6): 705-718.

[3] Goode P R, Denker C J, Didkovsky L I, et al. 1.6 M solar telescope in Big Bear–the NST [J]. Journal of the Korean Astronomical Society, 2003, 36(S1): S125-S133.

[4] Scharmer G B, Bjelksjo K, Korhonen T K, et al. The 1-meter Swedish solar telescope [C]// Proceedings of the SPIE. 2002: 341-350.

[5] 汪景琇, 季海生. 空间天气驱动源太阳风暴研究 [J]. 中国科学：地球科学, 2013, 43(6): 883-911. Wang Jingxiu, Ji Haisheng. Space weather driving Source-solar storm research [J]. Scientia Sinica Terrae, 2013, 43(6): 883-911.

[6] November L J, Simon G W. Precise proper-motion measurement of solar granulation [J]. The Astrophysical Journal, 1988, 333: 427-442.

[7] Fisher G H, Welsch B T. FLCT: a fast, efficient method for performing local correlation tracking [C] // Subsurface and Atmospheric Influences on Solar Activity ASP Conference Series. 2008: 383.

[8] Schuck P W. Local correlation tracking and the magnetic induction equation [J]. The Astrophysical Journal, 2005, 632(1): L53-L56.

[9] Schuck P W, Chen J. Tracking magnetic footpoints with the magnetic induction equation [J]. The Astrophysical Journal, 2006, 646(2): 1358-1391.

[10] Wang S, Liu C, Deng N, et al. Sudden photospheric motion and sunspot rotation associated with the X2.2 flare on 2011 February 15 [J]. Astrophysical Journal Letters, 2014, 782(2): L31-L36.

[11] Liu C, Xu Y, Cao W, et al. Flare differentially rotates sunspot on Sun’ s surface [J]. Nature Communications, 2016, 7: 13104.

[12] Potts H E, Barrett R K, Diver D A. Balltracking: an highly efficient method for tracking flow fields [J]. Astronomy & Astrophysics, 2004, 424(1): 253-262.

[13] Potts H E, Diver D A. Automatic recognition and characterisation of supergranular cells from photospheric velocity fields [J]. Solar Physics, 2008, 248(2): 263-275.

[14] Thirion J P. Image matching as a diffusion process: an analogy with Maxwell’ s demons [J]. Medical Image Analysis, 1998, 2(3): 243-260.

[15] Kroon D J, Slump C H. MRI modality transformation in demon registration [C] // Proceedings of the IEEE International Symposium on Biomedical Imaging. 2009: 963-966.

[16] Wang Z, Bovik A C, Sheikh H R, et al. Image quality assessment: from error visibility to structural similarity [J]. IEEE Transactions on Image Processing, 2004, 13(4): 600-612.

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