Robust and fine 2D displacement computation in vicinity of discontinuities - focus on seismic faults

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Starting date: May 2023
Duration: 1 year (2nd year renewable)

Keywords: photogrammetry, computer vision, 3D geometry, deformations, deep-learning, earth sciences

1. Context

Understanding how earthquake rupture proceeds and how it relates to ground surface deformation bear critical information for seismic hazard assessment. Fault Displacement Hazard Assessment is in fact becoming of primary importance as ground disruption could directly affect the integrity of infrastructures. In recent years, combining the tremendous increase in resolution of space imagery including sub-metric optical satellites such as Pleiades with image correlation methodology, it has become possible to identify detail of ground deformation, localised and distributed, in the fault zone. Fig. 1 shows an example of such an image of deformation where we could distinguish zones of localised deformation (sharp discontinuities) and zones where deformation seems to be more diffuse. To quantify precisely each mode of the deformation, however, we need to ensure that in the direct vicinity of the rupture, our measurement is not affected by a bias in measurement due to processing artefacts, such as averaging deformation over correlation windows that would span the rupture.

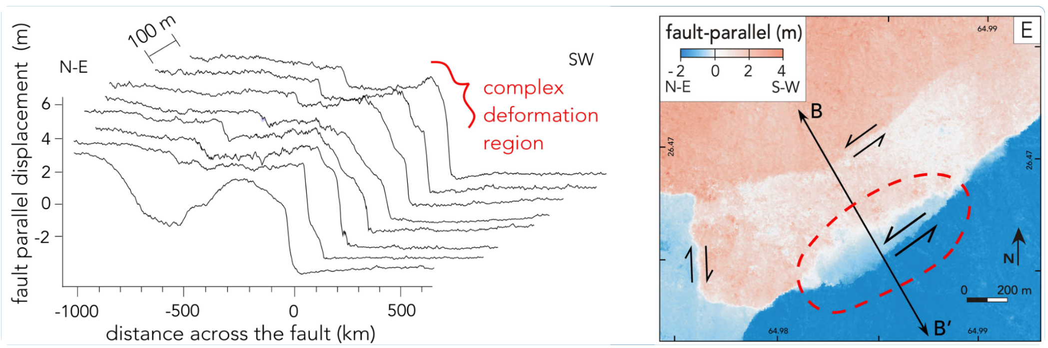

Figure 1. Correlation of Pleiades images for the 2013 Mw7.8 earthquake in Pakistan [1]. Some deformations are localised while in some areas (dashed red) it is currently unclear if the fuzziness of measurement truly corresponds to diffuse deformation or to an artefact of measurement.

Calculating displacement with cross-correlation defined over squared windows implies that all pixels belonging to a window undergo the same displacement. This is true in regions of constant or smoothly evolving displacements, but is violated if the measurement window crosses a discontinuity, for instance a seismic fault (see Fig. 2(a)). As a consequence, measurements at discontinuities are noisy and possibly biased, as can be observed in Fig. 1 within the encircled region.

The aim of this project is to improve the robustness and accuracy of displacement computation by defining the measurement over a triangulated mesh that is geometrically coherent with the underlying fault. By doing so, we believe to be able to improve the characterization of the fault itself, and of the behaviour of the tectonic plate in its vicinity. In particular, the proposed method will be beneficial in scenarios where (1) multiple faults are closely situated to one another, (2) the fault is poorly discriminative, and (3) the surface follows a non-Lambertian reflection leading to decorrelation for different Sun and sensor positions.

2. Methodology

The method is meant to be applied "on top" of 2D displacements obtained with traditional methods, and it introduces two novelties with respect to the *state-of-the-art*: **first, it proposes an adaptive measurement region, and second, it reformulates the way the displacement between two regions is computed**. To achieve the first, we propose to build a triangulated mesh (e.g., constrained delaunay triangulation [2]) by leveraging displacement maps computed with the classical cross-correlation techniques [3]. To enforce the mesh consistency with the fault, the mesh can be conditioned on the points lying along the fault. In the first instance, these points will be manually inserted, however, at a later stage, a semi-automated framework can be developed. Fig. 2(b) illustrates a toy-example of the region adaptive framework. The triangulated mesh is marked in green, and the fault is in blue. Note that the mesh perfectly respects the fault's boundary, as opposed to the classical approach in Fig. 2(a).

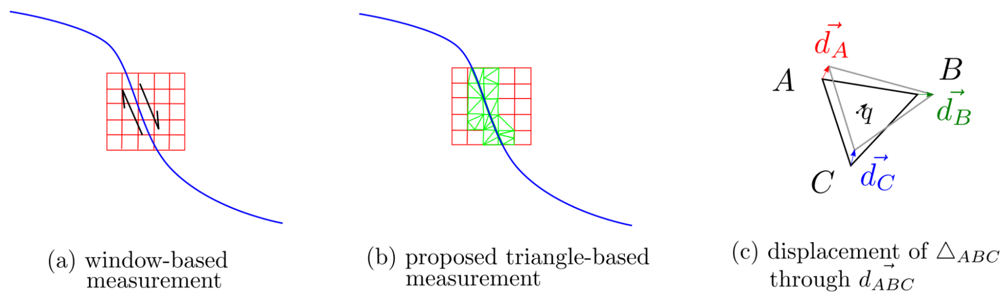

Figure 2. Toy example of the proposed method. In blue is the fault, in red is a classically window measurement (a) and in green is the proposed triangulated mesh (b). A,B,C are triangle vertices in the pre-event image, and they are displaced by the differential vectors d_A, d_B and d_C (see Eq. 2), q is any pixel location within the triangle.

To address the second point, the project envisages two scenarios: classical and learning-based. The classical approach is inspired by the optical flow method [4]. Each point of the mesh will be associated with at least 4 unknowns: two displacements in dx and dy, and two additional parameters to model the brightness inconsistency between images taken at different times. Following the optical flow equation, the vertices of homologous triangles are related by

$$\begin{gathered}\mu_{(p_{m_i})} + s_{(p_{m_i})} \cdot I_{(p_{m_i})} = I'_{(p'_{m_i})}, \\ p \in \{x, y\}, m_i \in \mathcal{M},\end{gathered} \tag{1}$$

$$I'_p = I_p + \frac{\partial I}{\partial p} dp = I_{(x,y)} + \frac{\partial I}{\partial x} dx + \frac{\partial I}{\partial y} dy. \quad (2)$$

where μ and s are the shift and multiplicative factor compensating for radiometric differences between acquisitions, m_i is a triangle within the set of triangles $\mathcal{M}$ (i.e., the mesh), and p_{mi} is the position of vertex belonging to the triangle m_i. I and I' are images taken pre- and post-event, for which pixel intensities follow the known differential relationship (see Eq. (2) and Fig. 2(c)).

For unsynchronized or cross-platform acquisitions, in the presence of non-Lambertian surfaces such as forest canopies or icy surfaces, modelling the illumination differences between images with 2 parameters (see Eq. (1)) may be too simplistic. Therefore, in the alternative scenario it is planned to leverage deep learning techniques to learn a similarity between homologous triangles. To this end, a possible approach will involve comparing triangles through features computed with pre-trained feature extraction networks (e.g., ResNet [5]). The network model will be tuned to fit the earth observation context. To account for the irregular and triangle-shaped patches, Pixel-Set Encoder [6] or pooling layers [7] will be considered. The training datasets will be provided through synthetically generated displacement maps. By way of example, given a pair of Pléiades orthophotos and a synthetically generated displacement maps (i.e., ground truth), one can "deform" via resampling one of the orthoimages to induce the underlying displacement. By applying this strategy to orthophotos of a geometrically stable scene, practically an unlimited number of ground truth datasets can be generated.

Datasets and evaluation: Modern high-resolution optical satellites such as Spots, Pléiades, Pléiades-Neo will be the focus of this project. To benefit from the extensive archives of satellite images stored in the lab, the methodology will be evaluated on the *Balochistan* (Pakistan) and *Ridgecrest* (USA) ruptures. A supplementary study will be carried out to see if the methods are advantageous in zones far from the tectonic fault. The developments will be carried out within MicMac, the open-source software for photogrammetry [8]. With MicMac being the core of online processing platforms such as DSM-OPT of ForM@TeR [9] and GEP of ESA [10], the fruit of this project will readily give access to the developed functionalities to scientists and practitioners across France and Europe.

3. Candidate's profile

- PhD in computer science, applied mathematics, photogrammetry or remote sensing
- Good command of Python and/or C++
- Previous experience in deep learning
- Previous experience in aerial/satellite image processing (optional)

4. Contacts

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