InSARTrac: a novel approach for remote acquisition of 3D slope displacement vectors

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Abstract. The recent advent of terrestrial interferometric synthetic aperture radar (InSAR) has greatly enhanced the ability of monitoring slope deformation. However, the displacements obtained are one-dimensional, offering little insight into the underlying deformation mechanism. This study summarizes an approach for obtaining three-dimensional slope displacement vectors through the integration of InSAR and two-dimensional image feature tracking (FT) technologies. The method, referred to as InSARTrac, uses a single digital camera oriented in the InSAR line of sight (LOS) generating time-lapse imagery, from which FT extracts (sub-) pixel shifts of pixel clusters. The 1D LOS InSAR measurements are vectorially combined with the 2D normal to the LOS FT measurements to obtain the 3D displacement vector. Bench-scale target displacement tests using a high precision translation for displacement and reference gave a 3D accuracy of 0.05 mm at a distance of 13 m, which corresponds to 1.3 mm at 500 m, assuming linear behaviour. These initial results indicate that InSARTrac can provide a reliable means for obtaining accurate 3D slope displacement vectors remotely and without the use of reflectors. Current studies are focused on implementing InSARTrac in a number of different field environments to investigate outdoor measurement accuracy and the range of potential applications.

1. Introduction
Terrestrial interferometric synthetic aperture radar (InSAR) has greatly enhanced the ability to monitor slope deformations in real-time and gather time-series of displacements at incredible resolution. Some of the powerful aspects of InSAR monitoring relate to its ability to operate independent of lighting and most atmospheric conditions, fully remote (reflectorless) operation, sub-millimetre measurement resolution and full domain coverage. These attributes have proven valuable for tracking the temporal development of slope deformations and for making early warning predictions concerning potential collapse events. However, the displacements obtained with InSAR are one-dimensional in the line-of-sight (LOS) direction, and therefore offer little insight concerning the causative deformation mechanism and subset of geologic structures involved. In order to relate the measured deformations to subsurface structural geologic boundary conditions, the full 3D displacement vector pattern is needed. One method for obtaining additional dimensional information involves combining the results from multiple
It is straightforward to obtain 3D vectors from combined InSAR and 2D image feature tracking (FT). A single digital camera is oriented in the InSAR LOS direction and FT algorithms are used to calculate 2D displacement vectors with sub-pixel resolution orthogonal to the LOS. This is done by feature extraction and matching of time-lapse photographic imagery. Combining the InSAR LOS and 2D FT vectors results in 3D displacement vector estimates, and thus is advantageous under unclear weather conditions.

2. Methods
InSARTrac measurements were conducted in an ambient condition-controlled environment in the geodetic lab of the Institute of Engineering Geodesy and Measurement Systems at TU Graz. The laboratory has a size of 33.2 x 6.3 x 3.5 m² and is climatically controlled (temperature: 20.0°C ± 0.5°C, humidity: 50% ± 10%). It is situated on the ground floor of a building and its foundation is separated from the foundation of the building. Thus, the effect of movements of the building induced by temperature, wind or traffic are reduced. Aside several calibration facilities, the lab contains 10 stable pillars which are used to mount sensitive measuring devices. In the lab only artificial and therefore reproducible light is used. The camera, the target (15 cm side length radar corner reflector) and an InSAR reference corner reflector were mounted on three of the stable pillars. The target was lined with patterned to achieve high image feature density. The experimental setup and the coordinate system are shown in Figure 1.

Using a calibrated Nikon D800 with a 300 mm lens and a 2x teleconverter, the field of view is about 0.8 m x 0.5 m a distance of 13 m, with a pixel size of about 0.11 mm at the object. For a FT reference, the target was placed in front of a wall having high image feature density.

The InSAR system “Hydra-G” from IDS GeoRadar was utilized for measurements. This is an arcuate InSAR device referred to as “ArcSAR”. The synthetic radar aperture is achieved by a rotating arm upon which the radar head is mounted [1]. The Hydra-G was positioned in front of and along the camera LOS. The InSAR reference corner reflector was mounted left of the measurement LOS at a distance of 6.7 m.

Target displacements were achieved with a translation stage having sub micrometre resolution. In the following, accuracy is defined as deviation between the measurements and the translation stage position. The stage was aligned four degrees out of the radar’s LOS in order to produce an oblique resultant displacement. A single measurement series involved movement to the target in steps as follows: 0, -1, -3, -10, -3, 1, 0, 3, 10, 3, 1, 0 mm (directions indicated in Figure 1). At each measurement step, five photographic images with three different apertures (f16, f22 and f45) were taken in order to experimentally find the best balance between focal depth and lens diffraction.

The FT workflow principally involves an image registration and a displacement measurement. The image registration uses stable areas to repress minor camera movements and includes: (i) feature

**Figure 1.** Image (left) and sketch (right) of the measurement setup. The measurement coordinate system (x, y, z) and the translation stage directions (ts +, ts -) are indicated in the sketch. The solid surrounding line represents the walls of the lab where the lab continues to the left.

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detection and description, (ii) feature matching and (iii) image transformation. The first step involves feature extraction and their describing vectors. The feature matching algorithm involves nearest neighbour identification using either the L\(^2\)-Norm or the Hamming distance, combined with a ratio and a cross-correlation test to find the best matches [2–4]. The image transformation results in a homographic transformation matrix. Simultaneously wrong matches are filtered using the random sample consensus (RANSAC) [5]. The second image is warped into the position of the first using this matrix and 8x8 pixel Lanczos resampling [2, 6]. The displacement calculation is based on the image registration principle with two differences: (i) areas of interest (i.e. moving areas) are utilized instead of stable areas and (ii) a displacement extraction is used rather than image warping. To evaluate the FT performance, three indicator values were chosen: (i) the precision within each measurement step, represented by the standard deviation (s), (ii) the mean accuracy within each measurement interval, and (iii) the mean accuracy of the last measurement step (i.e. deviation from 0) as a reference for measurement drift.

The InSAR measurements involve extracting sub-millimetre displacements by means of phase shifts in the radar measurements [7]. These phase shifts are measured by angular differences in the reflected phase of the electromagnetic wave. The maximum unambiguous consecutive displacement that can be obtained corresponds to one quarter of the radar wavelength, which results in 1 mm for the Hydra-G [7]. The software Guardian from IDS GeoRadar was used for raw data analysis, filtering, correction and conversion to displacement values.

3. Results
The FT results are summarized in Table 1 and depicted in Figure 2, 3 and 4, respectively. Table 1 shows the results of the Accelerated KAZE (AKAZE) algorithm [8] in millimetres, and all further quantities are given as relative to these initial values. Eight different feature detection and description algorithms and multiple different FT workflow settings were tested. The following three algorithms outperformed the others in terms of accuracy and precision for the current setup: (i) AKAZE, (ii) Scale-Invariant Feature Transform (SIFT) and (iii) Speeded Up Robust Features (SURF) combined with the Visual Geometry Group Lab of Oxford University (VGG) (hereafter referred to as VGG) [4, 8–10]. The calculated horizontal (x) displacements from the AKAZE algorithm are displayed in Figure 2. The AKAZE, SIFT and VGG algorithms showed similar results, so for brevity only the results from the AKAZE algorithm are presented. The deviations in x- and y- (vertical) directions are depicted in Figure 3 (a)-(c). In the x-direction they show a small drift for SIFT and VGG in the second half of the time series. In the y-direction stronger variations are present, even within individual movement steps (e.g. step-3). The resultant mean accuracy of the three algorithms is less than 0.05 mm. In the final movement step, all three algorithms achieved accuracies better than 0.08 mm, with AKAZE achieving the best value (0.034 mm). Within a moving step the precision of the 5 measurements can be computed. All three algorithms yield a mean standard deviation \( s < 0.035 \) mm in the x- and y-direction (Figure 4). Figure 4 (a) and (b) show that \( s \) is somehow larger at some positions, with in general larger values in y-direction. The mean \( s \) only differs insignificantly. Only little correlation lies between the temporal precision evolvement in x and y direction. The mean \( s \) in x is 0.019 mm and 0.026 mm in y.
Table 1. Results of different FT workflow settings.

| FT settings          | step s  | mean accuracy | accuracy last step |
|----------------------|---------|---------------|--------------------|
| AKAZE                | 0.032 mm| 0.041 mm      | 0.034 mm           |
| VGG                  | 0.4%    | 9.8%          | 116%               |
| SIFT                 | 7.4%    | -2.6%         | 100%               |
| BRISK                | 28%     | 58%           | 86%                |
| FREAK                | -49%    | 432%          | 1152%              |
| GFTT                 | 379%    | 940%          | 952%               |
| Harris               | 149%    | 723%          | 2161%              |
| ORB                  | 62%     | 797%          | 1970%              |
| Full affine transf. | 26%     | -29%          | -17%               |
| Partial affine transf. | 20%     | 63%           | 184%               |
| RANSAC repro. err. 0.5 | -5.6% | 15%          | 26%                |
| RANSAC repro. err. 1.0 | -4.7% | 20%          | 25%                |
| RANSAC repro. err. 2.0 | 1.4%  | 31%          | 103%               |
| RANSAC repro. err. 3.0 | 0.1%  | 78%          | 210%               |
| Aperture f16        | -16%    | 63%           | 175%               |
| Aperture f45        | 14%     | 22%           | 130%               |
| 2. image set        | 13%     | 28%           | 124%               |
| 200 % upsampling    | -1.6%   | 300%          | 369%               |

1) AKAZE refers to mm values, all other values are relative to AKAZE. Each line represents one setting modification compared to the best performing settings. BRISK, FREAK, GFTT, Harris and ORB are various feature algorithms [11–15].

The best performing settings with respect to accuracy had an aperture of f22, a homographic image transformation and a RANSAC reprojection threshold of 1.5 pixels [2, 5]. The best performing precision settings had an aperture of f16. For the AKAZE, SIFT and VGG algorithms, lower RANSAC reprojection thresholds resulted in poorer accuracy. The precision increased for AKAZE, but decreased for SIFT and VGG. For higher reprojection thresholds, the precision changed insignificantly, and for a reprojection threshold of 2.0 pixels the accuracy worsened for AKAZE, but improved for SIFT and VGG. Changes of transformation methods to full affine or partial affine (only 4 degree of freedom) further decreased the precision but increased the accuracy for AKAZE, whereas the accuracy decreased for SIFT and VGG [2]. An image upsampling by 200 % resulted in a major accuracy decrease. The settings were also tested with a second image set, which achieved an accuracy of 0.05 mm and a s of 0.037 mm. Major drifts are mostly present in the non-optimal algorithms such as Fast RetinA Keypoint (FRAK), Good Features To Track (GFTT), Harris and Oriented FAST and Rotated BRIEF (ORB) [12–15].

Figure 2. FT displacements of AKAZE algorithm in x direction.
Figure 3. Summary of FT accuracy time series for the AKAZE, SIFT and VGG algorithms in different directions: (a) in x direction, (b) in y direction and (c) resultant of x and y.

Figure 4. Summary of FT standard deviation ($\sigma$) time series for AKAZE, SIFT and VGG algorithm in x, y and resultant of x & y direction.
The InSAR measurements represent distance changes between radar and target (i.e. in z direction), where positive values indicate distance increases. The maximum measured InSAR displacement was 0.68 mm, corresponding to the 10 mm movement steps (Figure 5 (a)). The equipment specifications accuracy of 0.1 mm (standard deviation within one hour under exclusion of environmental effects) could be decreased by the factor of ten, but longer measurement times resulted in a drift of 10 µm per hour (involving 110 measurements). To further evaluate measurement drift, two experiments were undertaken that revealed a smaller drift of 0.03 mm over a six-day period and no drift over a three-day period (Figure 5 (b) and (c)). The drift in the six-day period started at noon at the 21. Dec, almost simultaneously with an outlier occurrence.

![Figure 5. InSAR displacement time-series. (a) Displacement time-series of movement steps; (b) displacement time-series of six-day measurements under stable conditions; (c) displacement time series of three-day measurements under stable conditions.](image)

From the translation stage experiments 3D vectors were obtained by combining the AKAZE FT and InSAR results. These are summarized in Table 2. The FT displacements represent the mean value of each displacement step and the Δ values are the mean deviations from the true position. The results show low deviation in the range of hundredths of a millimetre for each measurement step. These results indicate a FT mean absolute deviation of 0.033 mm and a total mean deviation of 0.039 mm, taken as system accuracy.

**Table 2.** 3D vectors calculated by InSARTrac and their deviation (Δ) from the true position.

| Step [mm] | x [mm] | Δx [mm] | y [mm] | Δy [mm] | z [mm] | Δz [mm] | Δ 3D vector [mm] |
|-----------|--------|---------|--------|---------|--------|---------|------------------|
| 0         | -0.005 | 0.005   | 0.004  | -0.004  | -0.003 | 0.003   | 0.007            |
| 1         | -0.981 | -0.017  | -0.001 | 0.001   | 0.064  | 0.006   | 0.018            |
| 3         | -2.950 | -0.042  | 0.014  | -0.014  | 0.200  | 0.009   | 0.046            |
| 10        | -9.929 | -0.047  | 0.013  | -0.013  | 0.684  | 0.014   | 0.050            |
| 3         | -2.959 | -0.033  | -0.040 | 0.040   | 0.200  | 0.010   | 0.053            |
| 1         | -0.992 | -0.006  | -0.042 | 0.042   | 0.053  | 0.016   | 0.046            |
| 0         | 0.002  | -0.002  | -0.041 | 0.041   | -0.002 | 0.002   | 0.042            |
| -1        | 0.989  | 0.008   | -0.035 | 0.035   | -0.068 | -0.002  | 0.036            |
| -3        | 2.991  | 0.002   | -0.036 | 0.036   | -0.202 | -0.007  | 0.037            |
| -10       | 9.983  | -0.007  | -0.047 | 0.047   | -0.671 | -0.027  | 0.054            |
| -3        | 3.017  | -0.024  | -0.035 | 0.035   | -0.201 | -0.008  | 0.043            |
| -1        | 1.014  | -0.017  | -0.04  | 0.04    | -0.066 | -0.004  | 0.044            |
| 0         | 0.009  | -0.009  | -0.028 | 0.028   | -0.009 | 0.009   | 0.031            |

Mean abs. Δ 0.017 0.029 0.009 0.039
4. Discussion

The high accuracy and precision of InSARTrac determined in the lab indicates a robust potential for this hybrid monitoring approach. InSARTrac achieves an accuracy of better than 0.05 mm with an associated s of less than 0.03 mm at 13 m distance. Time series correlations between the AZAKE, SIFT and VGG algorithms indicate that very slight movements in the experimental setup may have occurred (such as slight movement of the reference wall). Considering the very high intrinsic InSARTrac measurement accuracy, even small air ventilation movements could cause infinitesimal system displacements. The lower performance of the affine transformations is interpreted as a better adaption of the homographic image transformation to remaining distortion effects as consequence of the strong lens and the teleconverter. Potential ways of increasing the measurement accuracy include: (i) a median filtering method, where for each step only the image with the median displacement to the previous step is considered, and (ii) a back-testing method, where the cumulative calculated position is compared to a displacement calculation over several displacement steps (e.g. between the first and the last image). The first proposed method strongly increases the data reliability, as outliers are filtered properly. The second method can effectively remove drift issues, but its use strongly depends on the feature tracking, as the same features need to be detected. Both methods need to be tested in natural conditions.

The InSAR showed an accuracy of < 0.01 mm but also exhibits some drift which might be connected to the strong reflecting walls of the indoor measurements. The long-term (three and six-day) measurements showed almost no drift. The two outlier measurements in the six-day measurements are interpreted as consequence of people in the lab, which might have caused a relaxation start in the system resulting in the drift. In natural conditions, the atmospheric effects are expected to lower the accuracy of the InSAR, but at the same time a better drift performance is expected due to the absence of strong reflecting walls, correction algorithms and longer measurement periods.

Using these bench-scale results, an outdoor system accuracy at different distances can be estimated. Taking the FT accuracies of the AKAZE algorithm at 13 m distance, an intrinsic FT accuracy of 1.3 mm at 500 m is expected. As the intrinsic accuracy of InSAR does not change with distance, but the atmospheric effects do, an accuracy of approximately 0.1 mm can be expected under rather stable conditions. Taking these values, the overall intrinsic system accuracy is still at 1.3 mm. Weather, illumination; temperature and other effects may worsen this accuracy further, but for most monitoring situations in geosciences even half the accuracy is considered sufficient.

5. Conclusion

InSARTrac is a hybrid monitoring system with great potential for obtaining 3D displacement information through 1D + 2D vector combination. The first bench-scale results of InSARTrac show accuracies in the submillimetre range. Not considering atmospheric effects, at a range of 500 m an intrinsic accuracy of 1.3 mm is expected. Ongoing studies are now focusing on field implementation of InSARTrac and further quantification of measurement drift.

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