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MIMO Radar-Based System for Structural Health Monitoring and Geophysical Applications

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Abstract**—**The paper presents a methodology for real-time structural health monitoring and geophysical applications. The key elements of the system are a high performance MIMO RADAR sensor, an optical camera and a dedicated set of software algorithms encompassing interferometry, tomography and photogrammetry. The MIMO Radar sensor proposed in this work, provides an extremely high sensitivity to displacements making the system able to react to tiny deformations (up to tens of microns) with a time scale which spans from milliseconds to hours. The MIMO feature of the system makes the system capable of providing a set of two-dimensional images of the observed scene, each mapped on the azimuth-range directions with noticeably resolution in both the dimensions and with an outstanding repetition rate. The back-scattered energy, which is distributed in the 3D space, is projected on a 2D plane, where each pixel has as coordinates the Line-Of-Sight distance and the cross-range azimuthal angle. At the same time, the high performing processing unit allows to sense the observed scene with remarkable refresh periods (up to milliseconds), thus opening the way for combined static and dynamic structural health monitoring. Thanks to the smart TX/RX antenna array layout, the MIMO data can be processed through a tomographic approach to reconstruct the three-dimensional map of the observed scene. This 3D point cloud is then accurately mapped on a 2D digital optical image through photogrammetric techniques, allowing for easy and straightforward interpretations of the measurements. Once the three-dimensional image is reconstructed, a 'repeat-pass' interferometric approach is exploited to provide the user of the system with high frequency three-dimensional motion/vibration estimation of each point of the reconstructed image. At this stage, the methodology leverages consolidated atmospheric correction algorithms to provide reliable displacement and vibration measurements.

Keywords**—**Interferometry, MIMO RADAR, SAR, tomography.

I. Introduction

IT has been widely demonstrated that the interferometric analysis of the radar signal allows to change detection with submillimetre accuracy (as an example, for the space borne InSAR case, see [1]). Moreover, the joint exploitation of properly displaced multiple channels (MIMO radar case) allows to both gather progressive details from the radar signal and enable more performing processing schemes, like ground target velocity detection, advanced clutter cancellation capabilities and tomography [2], [3]. Such important features open the way for the use of radar as an effective tool for structural monitoring and disaster prevention. However, for the air/space-borne case, temporal availability of data does not match typical on-ground applications (landslide prevention, vibration estimation, analysis of deformations, etc.) strict requirements, due to long revisiting periods. Also, for indoor applications (like underground mining, solidity monitoring of historical buildings, etc.) the use of a more "portable" Ground-Based Radar (GBR) seems to be much more suitable since it can provide continuous monitoring of the area of interest. GBR typically works either moving on a linear actuator or as a stationary tool. In the first case, GBR exploits the SAR principle and data frequency is in the order of minutes, while in the latter case GBR operates in real aperture mode and data frequency is up to kilohertz, allowing both long term displacement and vibrations analysis. However, when applications require advanced performance, the MIMO principle could be applied to GBR, since it should be able to both ensure coverage over an adequate angular sector and provide high-rate data. Moreover, the effectiveness of advanced MIMO radar processing techniques has been already verified through GBR prototypes (see, as an example, [4], [5]).

In addition to the expertise in radar technology, ARESYS also has a long experience in signal data processing and SW development for real-time monitoring applications, which is object of the research topic here discussed. Starting from a single MIMO radar acquisition, it is possible to obtain a bi-dimensional image of the scene reflectivity, mapped on the azimuth-range directions. In other words, the backscattering energy is projected on a 2D plane, whose axes are the Line-Of-Sight distance and the cross-range azimuthal angle [6]. One of the first attempts to resolve the elevation direction is given by the interferometric approach derived from the SAR experience: if between two SAR images there is a non-zero spatial baseline, the phase difference of each pixel includes the topographic information, so that using this phase difference it is possible to retrieve the elevation angle (and so the height) of the points of the scenario. However, this approach has a big limit: if the range and cross-range coordinates are fixed, the heights of different hypothetical points are not uniquely determined and remain unknown [7].

Contrary to this, the tomography allows to achieve the real 3D location of the points seen by the sensor, and therefore it opens the way for many enticing applications. The tomography is a technique described exhaustively in literature, and is well consolidated in many scientific fields, especially in medical applications, like Computer-aided X-ray tomography (CT) and nuclear magnetic resonance tomography (NMR). Within SAR applications, the basic idea is to perform an additional synthetic aperture along the direction aligned to the elevation direction, that corresponds to the variations of off-

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nadir angle of each target of the scenario. In these terms, it is possible to see the SAR tomography as a multi-baseline interferometry, where the number of tracks is higher than two [8].

Such considerations prompted ARESYS to design and develop the MIMO radar-based system presented in this paper for real-time monitoring (3D motion/vibration estimation) of infrastructures and geophysical applications.

The paper is organized as follows. In Section II, an insight of the MIMO Radar system is given, while in Section III the tomographic tool is presented. Main benefits of the proposed solution are listed in Section IV. An overview of the obtainable results is provided in Section V, and finally, in Section VI conclusions are drawn.

II. The ScanBrick® MIMO Radar

ScanBrick® line comprises a set of innovative RADAR sensors operating at different frequencies (K, V and W band) able to support different ‘short-range’ applications especially in the industry, construction and infrastructure sectors [9]. The software-radio based technology allows the system to be quickly configured and customized depending on the specific application need.

ScanBrick® is a compact advanced MIMO radar sensor specifically designed for high resolution measurements at short-medium range (up to 1000 m). The system mounts a powerful on-board real-time data processing HW that can support any data processing task requested by the specific customer application.

The MIMO (multi-channel recording feature) allows ScanBrick® to be easily configured in term of acquisition beams and virtual target illumination in order to improve system angular resolution in elevation and range (up to a few degrees and 5 cm, respectively).

ScanBrick® model are available at three different bandwidths K, V and W to be selected depending on specific application.

The main features of the system span from excellent deformation/displacement measurement performances (up to 10 micrometre accuracy, range dependent) to 2D/3D capabilities (depending on number of channels). The high performing processing unit allows vibration and speed measurements up to 1 kHz. Thanks to the radar technology, there is no need to install artificial targets/pointers (the sensor performs non-contact measurement) which makes the proposed system a very interesting alterative solution to other contact-based technology (e.g., accelerometers).

Thanks to its features, the ScanBrick® radar is the ideal solution for the following applications:

- Sub-millimetre structural deformation monitoring (1D/2D/3D);
- Non-contact vibration monitoring;
- Industrial applications including level metering;
- Object accurate location and speed estimation;
- Metrology and gauging including thickness, dimensions, profiles measurements;
- Warehouse logistics, tracking, collision avoidance.

Fig. 1 reports the ScanBrick® system in its case.

Fig. 1 The ScanBrick® system

III. The Tomographic Approach for Real_Time Monitoring Applications

The tomographic processing is represented in Fig. 2, showing the schematic interaction of tomographic SAR processing with the optical photography module.

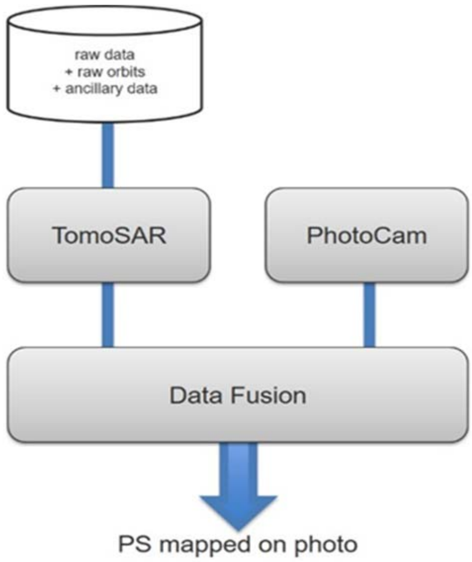


Fig. 2 Interaction of the tomographic processing with the photographic mapping

The tomographic SAR module takes as input radar raw data, raw trajectory (in the case the system is mounted over an actuator, like a pan&tilt unit) and some ancillary data (i.e. angular limits, minimum and maximum distances) and gives as output a 3D data point cloud in the radar reference system. This point cloud is then mapped by the data fusion module onto an optical photography acquired by a camera integrated within the system. This is done with existing computer vision ad-hoc routines through camera calibration parameters. The result is then an optical photography of the investigated scenario with 3D radar points mapped onto it.

The TomoSAR block performs the orbit calibration, the 3D focusing and the successive PS extraction; the PhotoCam block performs the calibration of the optical image acquired by the camera installed on the system. Finally, the Data Fusion block allows to map the extracted PS on the optical image, in order to obtain an immediate localization.

A few details about the implementation of the PhotoCam block are given in the following subsection.

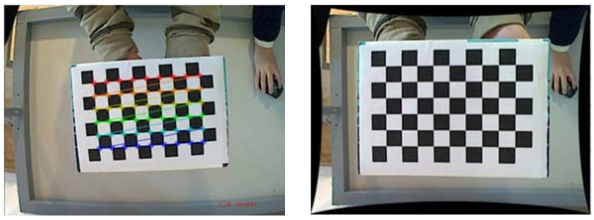
A. On Camera Calibration Module

Camera calibration process allows to estimate the parameters of a lens and/or image sensor of a camera. After this step, it is possible to correct the lens distortion, in order to use the compensated images for many different applications

There are two set of parameters to be estimated: intrinsic and extrinsic.

Intrinsic parameters are: (i) Radial distortion (six coefficients); (ii) Tangential distortion (two coefficients); (iii) Focal lengths (expressed in pixel units); (iv) Principal points (usualy at the image center).

Intrinsic parameters estimation is carried using OpenCV© routines applied on a known calibration pattern (e.g. through a chessboard, see Fig. 3).



(a) (b)

Fig. 3 (a) before intrinsic parameters compensation; (b) after intrinsic parameters compensation

Extrinsic parameters are described by a rotation matrix ***R*** and translation vector ***t*** (see Fig. 4).

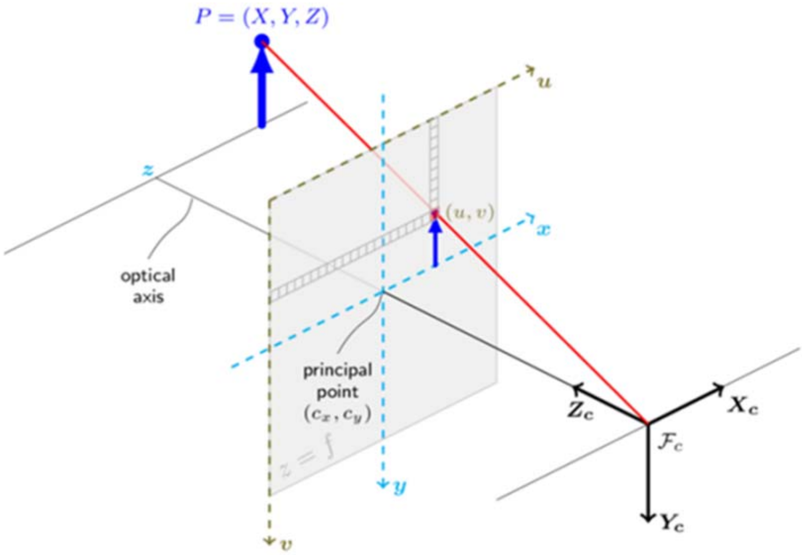


Fig. 4 Interaction of the tomographic processing with the photo-graphic mapping

They represent a rigid transformation from 3D world coordinate system to the 3D camera's coordinate system

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + t \quad (1)$$

To compensate for extrinsic parameters, the realignment tool is exploited. It consists of an on-field procedure established at ARESYS srl.

As an example, from Fig. 5, it can be noted a slight misalignment between the corner of camera image and the energy peaks of radar map.

After the realignment step (see Fig. 6), the corners of camera image are well alignment to the energy peaks of radar map.

IV. Main Benefits of Solution

The main benefits of proposed solution are:

- It is a totally not intrusive technology (contactless);
- It performs both static and dynamic (vibration) monitoring;
- 1D, 2D measurements can be provided (also 3D with an additional sensor installed);
- Up to thousands of points can be tracked (not just some few points);
- It provides easy data interpretation thanks to the photogrammetry-based approach;
- Measurement results are provided on-site with instant processing;
- The system is compact, easily transportable and installable;
- It can work night and day, also in harsh environmental conditions.

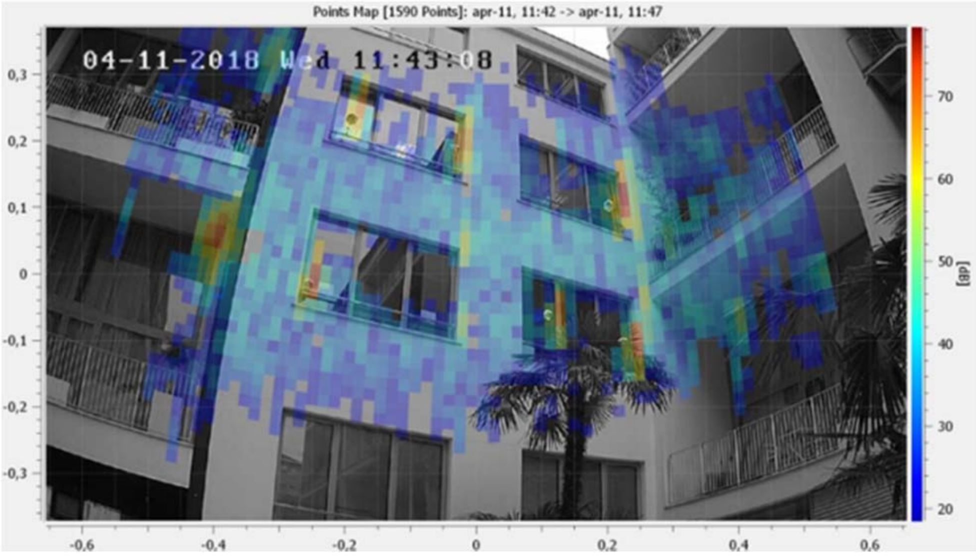


Fig. 5 Before realignment

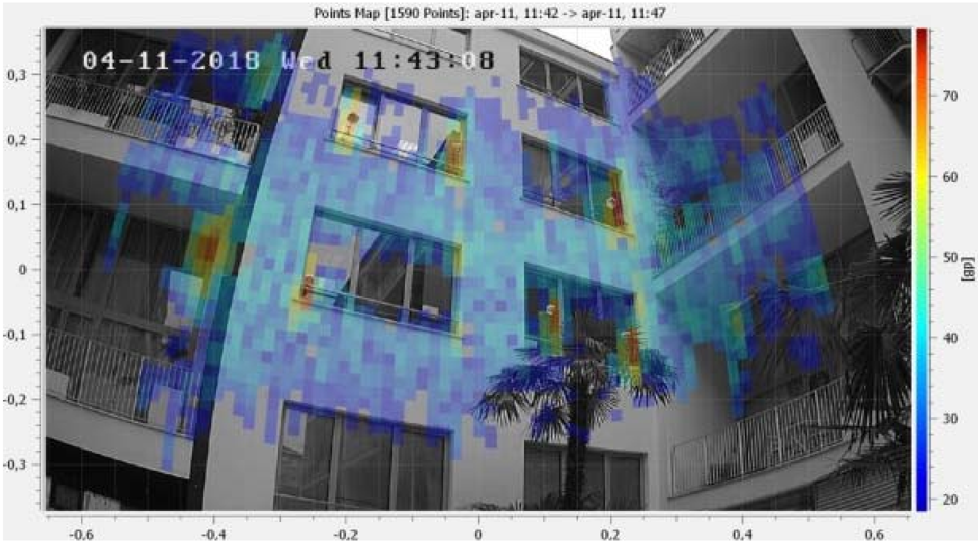


Fig. 6 After realignment

The main innovation lies in the possibility to get all these benefits from just one single solution. Looking at the state-of-the-art, no other solutions can provide all these advantages at once.

V. Examples of Obtainable Monitoring Results

The developed tomography tool has been successfully tested on many scenarios; in this section the main experimental results are reported. Fig. 7 is referred to the Arco Della Pace (Milan) experiment and shows the extracted PS, correctly mapped on the optical photo after the step of Data Fusion (see Section III). It is worth noticing that, in this experiment, the system has been mounted at about 40 meters from the target, in excellent agreement to the found y-coordinate.

The results in Fig. 7 demonstrate the easy on-field installation of the proposed system and open the way for many short-range monitoring applications.

Fig. 8 shows a static monitoring result, achieved in monitoring campaign carried out in collaboration with Uretek (world leader company in solutions for consolidating foundation soils). While Uretek operators were injecting resins in the soils in order to fix the structural problems of the church of Marano (Verona, Italy), the MIMO Radar-based system had measured the displacement of the building. Fig. 8 (a) shows 3D points cloud of the church of Marano; each point is coloured based on the Line-Of-Sight displacement (“red” points are going far, “blue” ones are approaching). Fig. 8 (b) shows the points time series, i.e. the displacement behaviour versus time, for each point picked in the cloud of Fig. 8 (a).

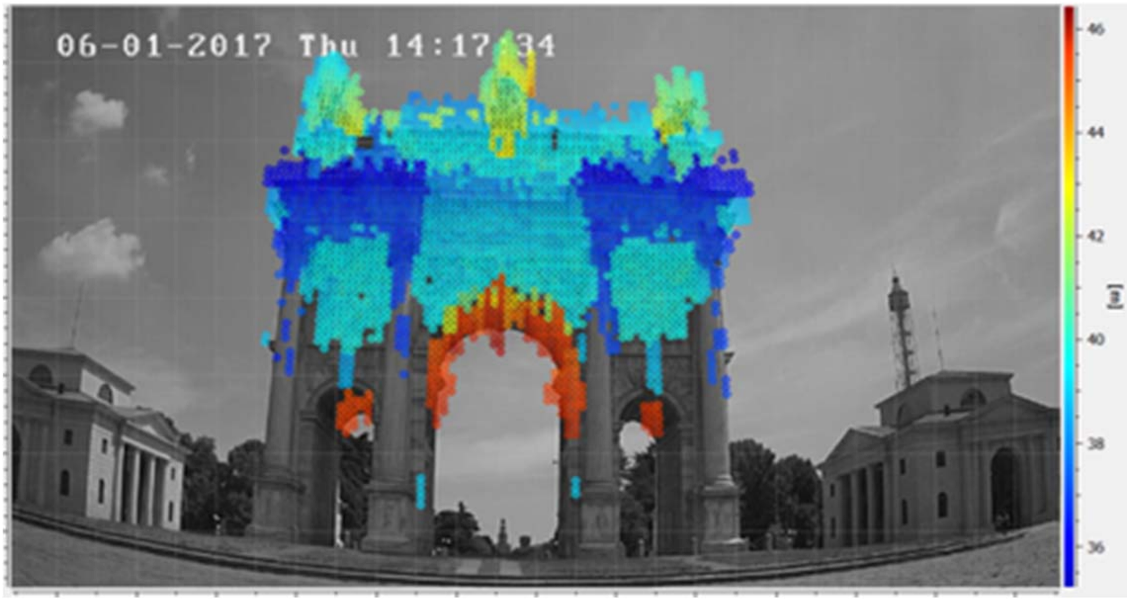
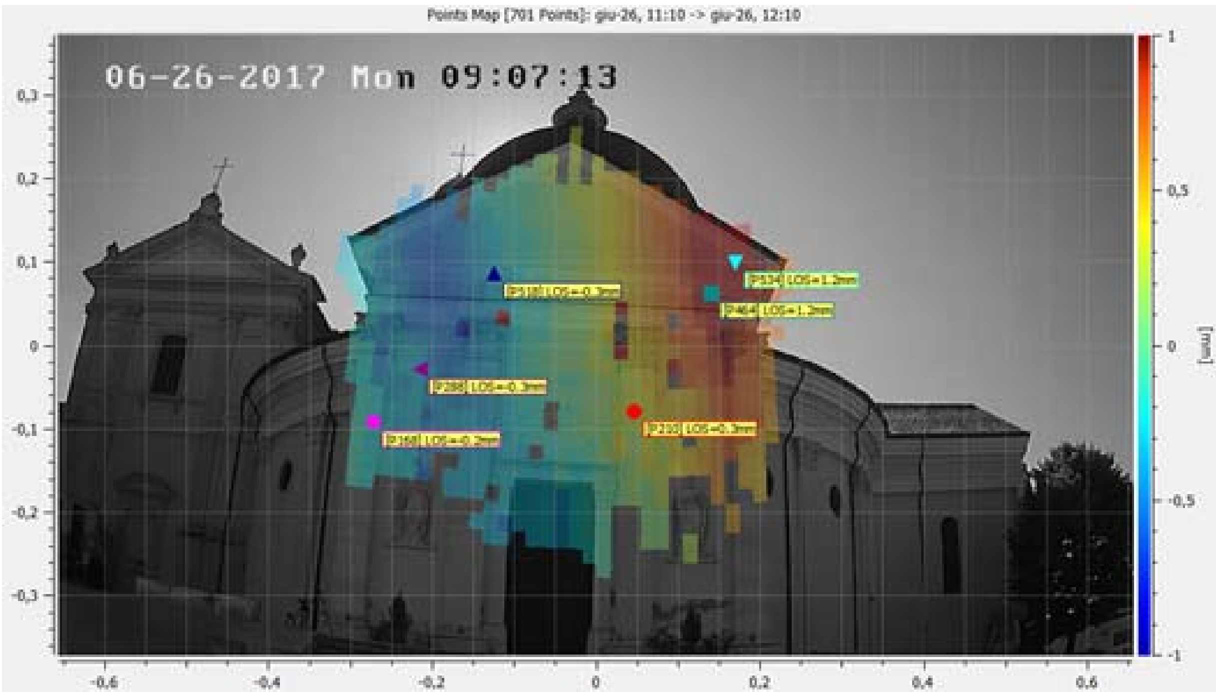
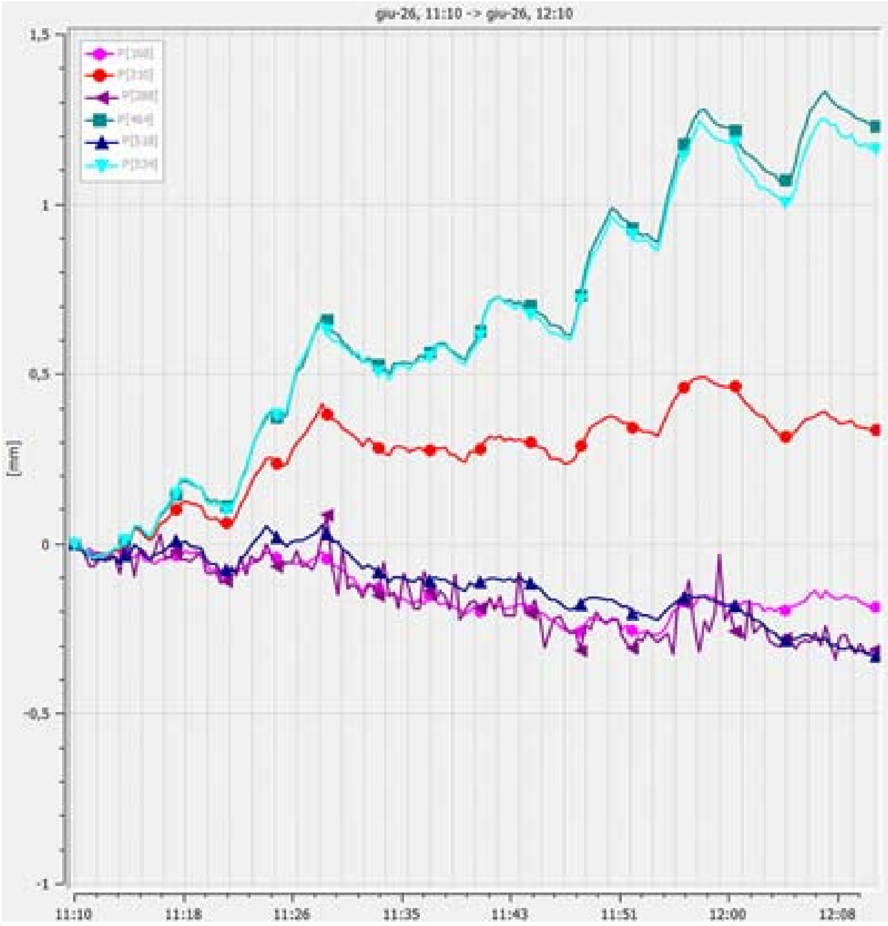


Fig. 7 Arco Della Pace, Milan. The color scale is proportional to the y-coordinate, so the “blue” is referred to the nearest points, while the “red” is referred to the far points

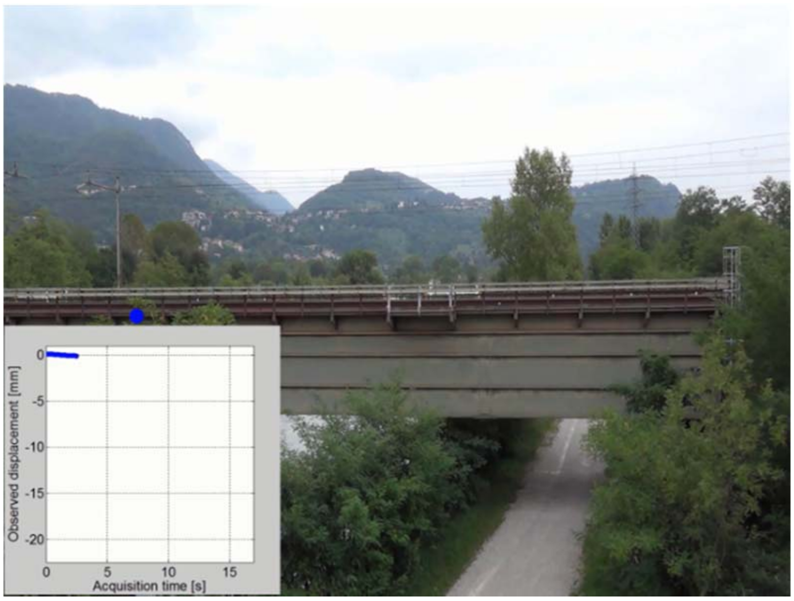


(a)

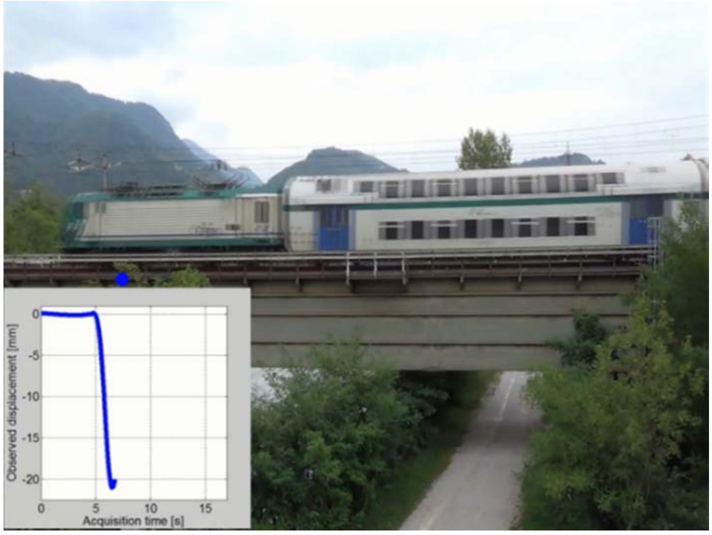


(b)

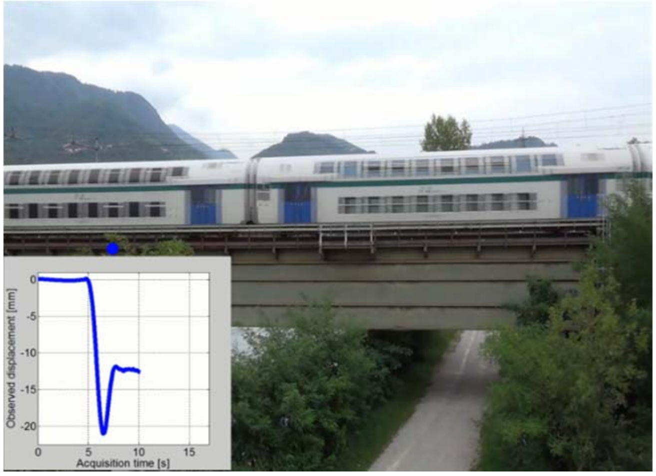
Fig. 8 Marano Church, Verona, Italy. Monitoring campaign in collaboration with Uretek. (a) 3D points cloud; each point is coloured based on the Line-Of-Sight displacement; (b) Line-Of-Sight displacement versus time, for some points of the cloud



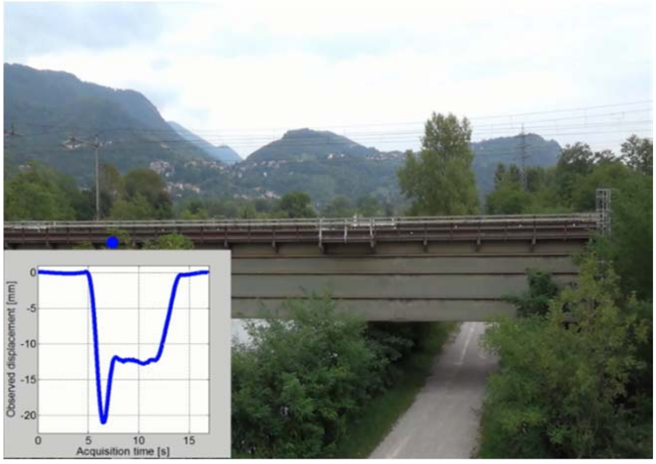
(a)



(b)



(c)



(d)

Fig. 9 Displacement/vibration analysis of a bridge, during the passing of a train. From (a) to (d), the LoS movement of the blue point picked up on the bridge is shown in four consecutive instances

Finally, in Fig. 9 performing a static and dynamic analysis, the displacement/vibration of a bridge due to a crossing train is captured.

VI. Conclusion

This paper presented an innovative methodology for real-time structural health monitoring and geophysical applications. This solution is based on a MIMO radar designed and developed at ARESYS srl (the ScanBrick® system) and a set of interferometry, tomography and photogrammetry algorithms.

The preliminary experimental results shown demonstrate the advanced capabilities of the proposed system for short-range monitoring applications.

Acknowledgment

This research is the result of the experience accumulated over years of collaboration with the company IDS Georadar, with whom we developed HYDRA (a high-resolution microwave interferometric Single-Input-Single-Output RADAR). Hence, we really thank our colleagues from IDS Georadar.

We also thank the colleagues from Uretek Company for the insight and expertise they shared with us. They really gave us the chance to improve our solution.

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