Multiparametric microsensor monitoring platform of the Enceladus Hellenic supersite: the PROION project

Konstantinos Nikolakopoulos, Aggeliki Kyriou, Efthimios Sokos, Stathis Bousias, Elias Strepelias, et al.

Konstantinos G. Nikolakopoulos, Aggeliki Kyriou, Efthimios Sokos, Stathis Bousias, Elias Strepelias, Peter Groumpos, Vassiliki Mpelogianni, Zafeiria Roumelioti, Anna Serpetsidaki, Dimitrios Paliatsas, Panagiotis Stephanopoulos, Athanassios Ganas, Vassiliki (Betty) Charalampoulou, Theodoros Athanasopoulos, "Multiparametric microsensor monitoring platform of the Enceladus Hellenic supersite: the PROION project," Proc. SPIE 12268, Earth Resources and Environmental Remote Sensing/GIS Applications XIII, 122680K (26 October 2022); doi: 10.1117/12.2638830

Event: SPIE Remote Sensing, 2022, Berlin, Germany

Multiparametric microsensor monitoring platform of the Enceladus Hellenic supersite: the PROION project

Konstantinos G. Nikolakopoulos*[a], Aggeliki Kyriou[a], Efthimios Sokos[a], Stathis Bousias[a], Elias Strepelias[a], Peter Groumpos[a], Vassiliki Mpelogianni[a], Zafeiria Roumelioti[a], Anna Serpetsidaki[a], Dimitrios Paliatsas[a], Panagiotis Stephanopoulos[a], Athanassios Ganas[b], Vassiliki (Betty) Charalampoulou [c], Theodoros Athanasopoulos[d]
[a]University of Patras, Patras, Greece; [b]National Observatory of Athens, Athens, Greece;
[c]Geosystems Hellas, Athens, Greece; [d] ES Systems, Athens, Greece

ABSTRACT

Climate change constitutes a serious global challenge with consequences that are directly affecting infrastructure. Thus, there is a great need to develop reliable cost-effective systems, which integrate remote sensing data, in situ measurements and advanced methods for infrastructure monitoring. In this framework, the European Union and the Hellenic government are financially supporting a R&D project, named "PROION". The purpose of the project is the development of a platform for the continuous monitoring of high-priority infrastructures (public infrastructure, dams, bridges, etc.) which are located in a particularly active area in terms of tectonics and seismicity. Monitoring is based on the combination of instrumental and remote sensing measurements along with fuzzy logic networks methods and machine learning algorithms in order to generate an innovative decision-making and decision-support tool. Specifically, measurements derived from three-axis accelerometers, Global Navigation Satellite System (GNSS) receivers and Persistent Scatterer Interferometry are imported into the platform. The measurements will be validated using high-accuracy reference representations arising from data acquired by Terrestrial Laser Scanning (TLS) surveys and Unmanned Aerial Vehicles (UAV) campaigns and subsequently, deformation maps will be generated. Intelligent data analysis methods will contribute to making decisions on the current as well as the future state of the infrastructure. At this initial stage of the project, the proposed monitoring system is described in detail.

Keywords: monitoring, infrastructure, UAV, TLS, GNSS, PSI, accelerometers, fuzzy logic

1. INTRODUCTION

Climate change is an undisputed global challenge with serious impacts on the environment, infrastructure and human life itself [1,2]. In fact, the last decade (2011-2020) has been considered as the warmest according to the World Meteorological Organization [3]. Constantly rising temperatures and frequent weather extremes (drought, floods, etc.) are directly affecting the health of infrastructure [4]. Since more than 40% of the world's population lives in highly vulnerable areas to climate change and infrastructure risks [5], scientists should develop reliable, cost-efficient and globally applied infrastructure monitoring methodologies towards ensuring resilience.

In this framework, remote sensing has emerged as an effective solution for infrastructure monitoring. The first documented attempt to use remote sensing technology for infrastructure damage assessment was traced back to 1906 [6] and since then the impressive technological advances have created opportunities to acquire a wealth of Earth observation data. Although approximately every type of remote sensing data (spaceborne/airborne, ground-based) has been utilized for infrastructure damage detection [7,8], it remains an active research topic.

Thus, numerous studies have been carried out, focusing on the development of innovative methodologies for an effective and comprehensive infrastructure monitoring. In particular, GNSS data and advanced differential interferometric techniques have been widely used to monitor and analyze the deformation (horizontal and/or vertical) occurring in dams [9]. The evolution of GNSS receivers resulted in the establishment of new approaches for the dynamic monitoring and structural health assessment, which are based on real-time kinematics (RTK), instantaneous displacement measurements and precise point positioning (PPP) [10]. In addition, TLS sensors have been utilized to create a 3D structural model,

Earth Resources and Environmental Remote Sensing/GIS Applications XIII, edited by Karsten Schulz,
Ulrich Michel, Konstantinos G. Nikolakopoulos, Proc. of SPIE Vol. 12268, 122680K
© 2022 SPIE · 0277-786X · doi: 10.1117/12.2638830

evaluate the construction quality, model the behavior of the structure and monitor the potential deformation of the investigated infrastructure, during the different phases of construction, operation and maintenance [11, 12]. In-depth descriptions of the design and execution of TLS surveys as well as the proper processing of the collected data for infrastructure monitoring purposes have been discussed in several studies [13]. In recent years, the monitoring and evaluation of infrastructure structural conditions is implemented through UAV sensors, mainly due to the ability to access remote and inaccessible areas and cost/time efficiency [14-16]. More than a hundred studies have been conducted, providing useful information on the appropriate collection and processing of UAV imagery, the factors which may affect UAV flight performance and the advantages and limitations of UAVs in infrastructure monitoring. Rapid advances in computer vision have been a milestone in infrastructure monitoring. Therefore, the more sophisticated approaches combine UAV imagery and machine learning algorithms to generate strategies and processing pipelines towards structural damage mapping and assessment [17]. Indeed, deep learning applications have proven their effectiveness in structural recognition, change detection, crack detection, damage identification, damage quantification, etc. [18, 19].

The current study describes in detail the architecture of the research project, named PROION (Figure 1). The main objective of the project is the development of a platform for the continuous monitoring of high priority infrastructure (public infrastructure, dams, bridges, etc.), located in a particularly active area in terms of tectonics and seismicity. Monitoring is based on the combination of instrumental and remote sensing measurements along with fuzzy logic networks methods and machine learning algorithms. Specifically, measurements obtained by three-axis accelerometers, GNSS receivers and Persistent Scatterer Interferometry will be imported into the platform, where they will be validated using high-precision reference representations derived from TLS surveys and UAV campaigns. Eventually deformation maps will be created, while intelligent data analysis methods will contribute to decision-making concerning the current and the future state of the infrastructure. "PROION" project is financially supported by the European Union and the Hellenic government. Similar initiatives have been financed by the European Commission (EC). The projects tCat, AutoScan and NeTIRail-INFRA are some indicative EC-funded projects for the evaluation and monitoring of transportation infrastructure [20-22].

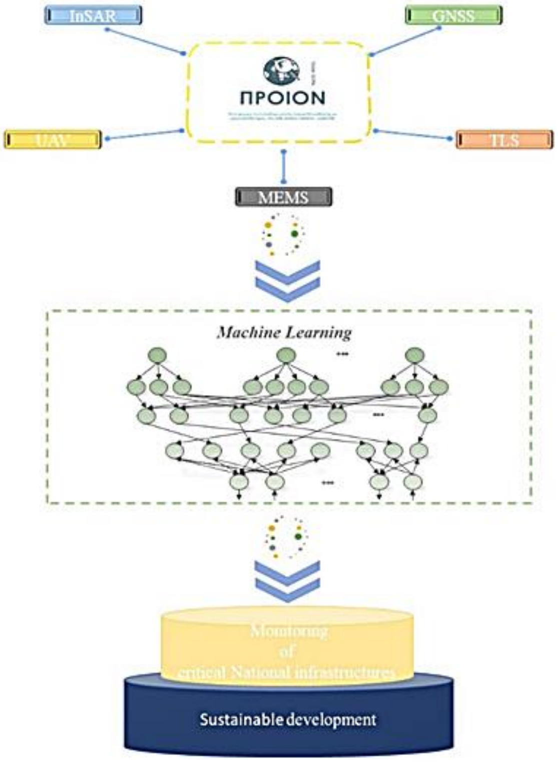


Figure 1. Schematic illustrations of the architecture of PROION project.

2. TEST SITES

Three areas with totally different characteristics were selected to be the test sites of Proion Project. The first one is the building of the Department of Geology, in the University of Patras Campus. Every day more than 200 hundred students and faculty members spend plenty of hours inside the building. Thus, it is a very crowded spot that should be monitored for safety reasons. The second test site is the Asteri Dam located about 12 km south-west of the city of Patras in the northwestern part of the Peloponnese Peninsula (Greece). The dam was built to secure the freshwater supply for three different municipalities (municipality of Patras, Erymanthos, and Dytiki Achaia). For this purpose, a 75-meter high and 900-meter long embankment dam and a diversion dam were built. Asteri Dam was chosen for monitoring in the frame of Proion Project because it is the largest and the most crucial one in the Achaia Prefecture in terms of agricultural economy and water supply. As the third study area we have selected an active landslide in Krini village, Western Greece. The specific landslide was investigated for the first time in 1985 by the Greek Geological Survey (IGME). As described in [23] the Krini landslide is a large earth flow with a mainly E-W slope-parallel displacement trend, which in its eastern (lower) part converts to a translational slide (based on the categorization proposed by [24], [25].

3. DESCRIPTION OF PROION PROJECT

3.1 Remote Sensing activities

The three selected areas will be monitored continuously by a combination of remote sensing technologies and in situ instrumentation (accelerometer and GNSS). Multidisciplinary remote sensing data and methodologies like Unmanned aerial Vehicles, Terrestrial Laser Scanning and Interferometric SAR are combined over the three test sites.

Unmanned Aerial Vehicles

A Vertical Takeoff and Landing (VToL) UAV purchased in the frame of Proion Project is used for the accurate 3D mapping of the three test sites. An example of the photogrammetric processing of the extra high resolution images (2cm spatial resolution) is presented in Fig 2a while, in Fig 2b an orthophoto of the Asteri Dam produced by the UAV images on 30/3/2022 is presented.

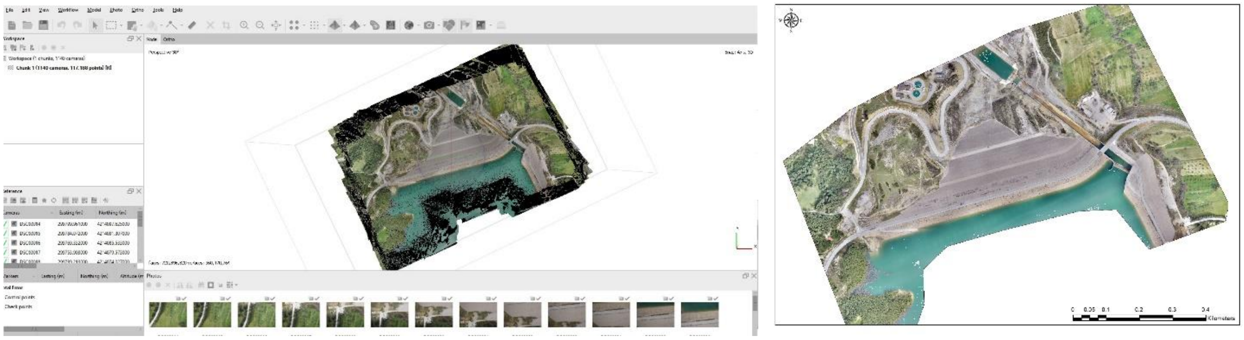


Figure 2. (a) Photogrammetric processing of the UAV images in Agisoft Metashape software. (b) Orthophoto of the Asteri Dam on 30/3/2022.

Terrestrial Laser Scanning

For the precise 3D representation of the test sites a Leica P50 laser scanner purchased in the frame of Proion Project was used. The specific sensor performs extremely fast scanning (1 million points per second) of large areas along with the extraction of high-quality 3D representations. The precison of the specific laser scanner is estimated at about 1.2 mm for distances varying from 120 m to 270 m. In Figure 3 the 3D representations from the department of Geology building (Fig. 3a) and from the Asteri Dam (Fig. 3b) are presented. The TLS and the UAV point clouds are georeferenced and they are combined in order to create the 3D base map of the three test sites. Repeated campaigns are planned in order to monitor the stability of the study areas.

Figure 3. (a) 3D representation of the Geology Department building. (b) 3D representation of the Asteri Dam. Both point clouds are captured with Leica P50 scanner.

Interferometric SAR

Monitoring the structural deformations and possible movements of critical infrastructures like Dams, bridges or crowded buildings is essential for safety reasons. In the current project we will exploit SAR image time series with the technique Persistent Scatterer Interferometry (PSInSAR) to detect and map any possible deformation. The technique was developed to address the phenomena of Decorrelation and Atmospheric Phase Delay. Both phenomena have an immense influence on the accuracy of a deformation map derived from a single interferogram. PSInSAR exploits a time series of interferograms to identify pixels that distinguish themselves by having a low noise level. Only these pixels are then used to create a deformation map [26]. As the PSInSAR is known to provide very accurate displacement measurements all the three sites will be monitored by this technique using the Copernicus freely available Sentinel-1 data. The individual PS displacements are provided with an accuracy up to millimeter-level [27], [28]. For the specific purpose a trihedral scatterer was designed in the GIS and Remote Sensing Laboratory, University of Patras and three scatterers were installed in the three test sites. In Figure 4 the installed scaterrers in the Patras University Campus and in Krini village are presented with images acquired from a UAV.

Figure 4. Persistent Scatterer (corner reflector) installation next to the Geology Department building. (b) Persistent Scatterer installation in Krini village.

3.2 Accelerometer (construction, calibration and data processing)

Construction

A three-axis accelerometer was integrated in the frame of Proion Project by European Sensor Systems. The ES Systems Company specializes in the design and development of MEMS technology sensors as well as sensor systems including their interface and recording algorithms. The new 3D MEMS accelerometer is presented in Figure 5.

Figure 5. The new MEMS accelerometer

The sensor was calibrated at the Seismic Simulator Laboratory of the Departments of Civil Engineering at the University of Patras.

Calibration

The response of the accelerometer was checked through a series of tests carried out at the Seismic Simulator Laboratory of the Departments of Civil Engineering at the University of Patras. For the validation, two reference accelerometers based on different operation principles were employed, i.e. an IEPE accelerometer (identical to that used for controlling the table) and a capacitive MEMS accelerometer, measuring accelerations up to 5g and 10g, respectively. The latter accelerometers were used as reference accelerometers which were connected to two different and independent data acquisition systems. The sampling rate of data recording was 800Hz for the IEPE sensor and 500Hz for the MEMS sensor. The Esdas3X accelerometer was set to its default parameters, the maximum acceleration was set to 2g and the sampling rate defined at 500Hz.

All three sensors were mounted on the same aluminum plate, constructed specifically for the calibration procedure and firmly fixed on the shake table (Figure 6). Special care was taken so that the three sensors were aligned with each other and with the axis of the shake table.

An ensemble of 33 natural earthquake records (both near- and far-field ones) were used to (non-simultaneously) excite the sensors along three directions of response of the Esdas3X sensor- the records were selected so as to comprise various characteristic properties in terms of peak ground acceleration and frequency content. The data recorded from Esdas3X accelerometer were compared against those of the two reference sensors in terms of the accuracy of reproducing the acceleration time history and the frequency content of the signal imposed. As depicted in Fig.8 (Superstition Hills, 1987, El Centro Imp Co Center) - and evidenced also by all the tests performed - Esdas3X measurements satisfactorily matched those of the two reference sensors, especially those from the MEMS accelerometer, regarding the acceleration time history (Fig. 7a) and frequency content (Fig. 7b).

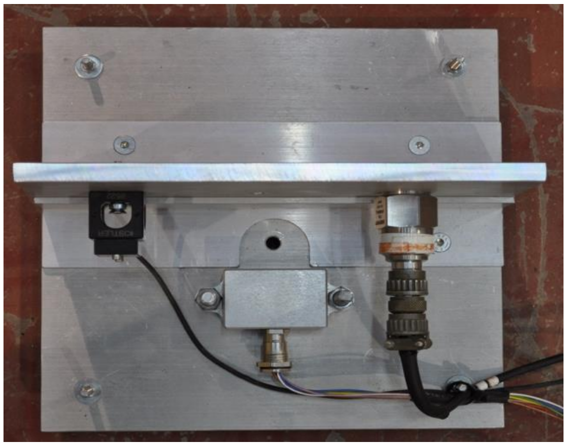
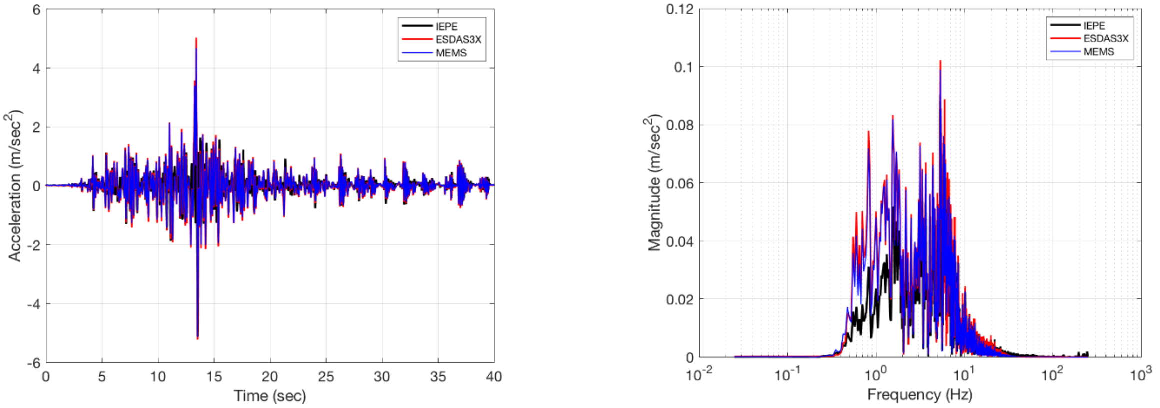


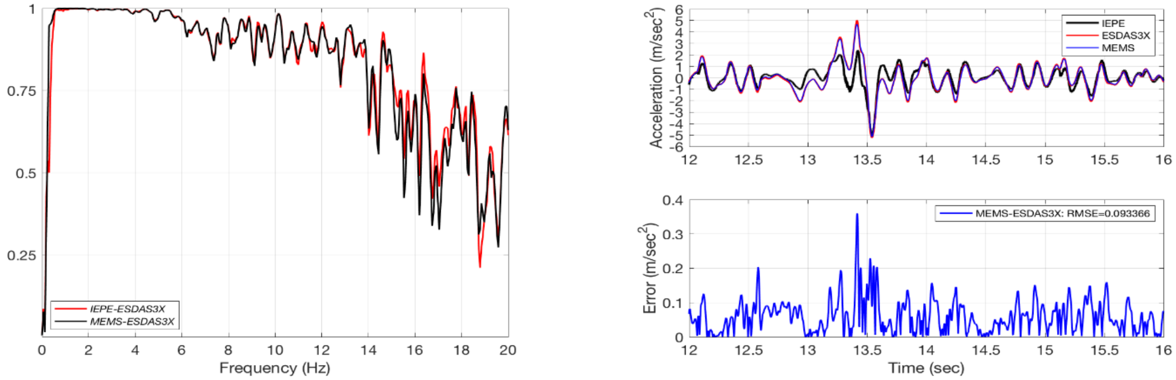
Figure 6. Sensors mounted on auxiliary plate on the shake table.



(a) (b)

Figure 7. Test under the Superstition Hills (1987) record: (a) Acceleration time history, and (b) frequency content

Additionally, the coherence between data from the Esdas3X accelerometer and the two reference sensors, alongside with the root mean square (RMS) error, were determined and, as depicted in Fig. 8a, the coherence between the reference signals and that from Esdas3X in the range of frequencies of interest are satisfactory - the same holds for the error between the data recorded from the Esdas3X and the MEMS accelerometer (Fig. 8b, lower).



(a) (b)

Figure 8. Superstition Hills (1987) record: (a) Coherence and, (b) RMS error

The per-record RMSE (normalized to the peak acceleration value of each record) is less than 4%, as shown in Fig. 9.

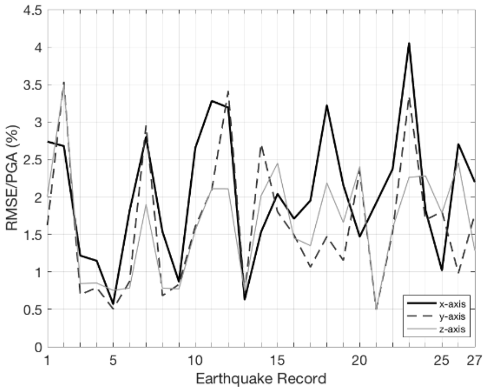


Figure 9. Per-record normalized RMSE

After the calibration of the accelerometer prototype, three sensors are installed in the three test sites and the recordings are collected and processed.

Data processing

Strong motion data are being recorded by the MEMS sensor of the monitoring system in the form of ground acceleration time series in three components (vertical plus two horizontals). During its initial, pilot operation, the system has been set to record ground motion at triggering mode, i.e., acceleration data are being stored only when a pre-defined level of ground acceleration is exceeded, currently set at 0.05g. Upon exceedance of the threshold level, an "event" file is being created. Initially, event files are stored in the local Raspberry-Pi 4 SD card as JSON files and are latter transmitted to the central acquisition unit for processing. Data processing is done in an automatic mode. Once a file arrives, it is being processed using a Matlab script to derive strong motion parameters, such as the Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Arias Intensity (AI) and Spectral Acceleration at discrete period values, which shape the Response Spectrum (RS). This information is subsequently sent to a machine learning algorithm, which incorporates information from other sensors as well, with the ultimate goal of assessing the structural integrity of the structure in an automatic, continuous and updatable manner.

3.3 Low cost GNSS (development and data processing)

Methods based on Global Navigation Satellite Systems (GNSS) have been widely applied for monitoring displacements and deformations of ground surfaces [29] and building structures [9], [30]. Dual-frequency receivers, which receive signals of all available GNSS, offer great possibilities for accurate measurements, regardless of cost [31]. In this project we designed a low-cost instrumentation set that includes a multi-GNSS dual-frequency chip (Ublox F9P module) mounted on a Raspberry-Pi 4 board (Fig. 10) together with an industry-standard MEMS accelerometer. The GNSS data are collected via 4G wireless channels, are quality-checked and finally processed by use of open-source software. The daily rinex version 3.x multi-GNSS files are available from the NOA web server with a latency of a few hours. For example, the GNSS station data at the University of Patras (Rio campus) are available from: http://194.177.194.200/GPS/GEDP/

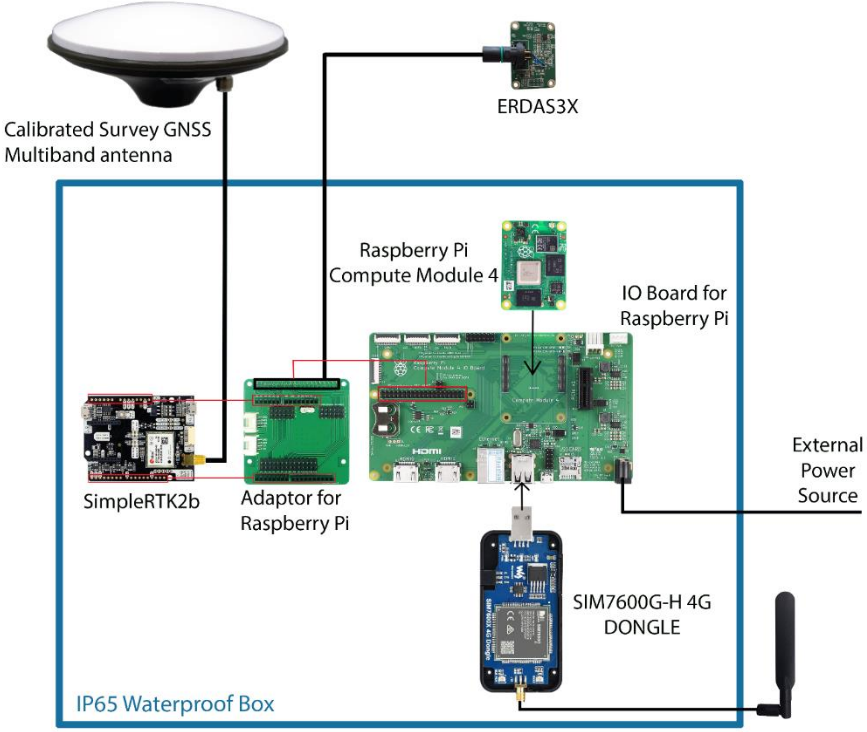


Figure 10. The basic elements of the PROION system architecture showing the integration of the low-cost GNSS receiver and the MEMS accelerometer.

We processed data of two low-cost GNSS instruments currently in use. The data were processed by the PRIDE-AR software [32]. The accuracy of the solution is within a few millimetres, except for the vertical component. We obtained geocentric coordinates in the IGS14 reference frame which we converted to topocentric position time series (Fig. 11).

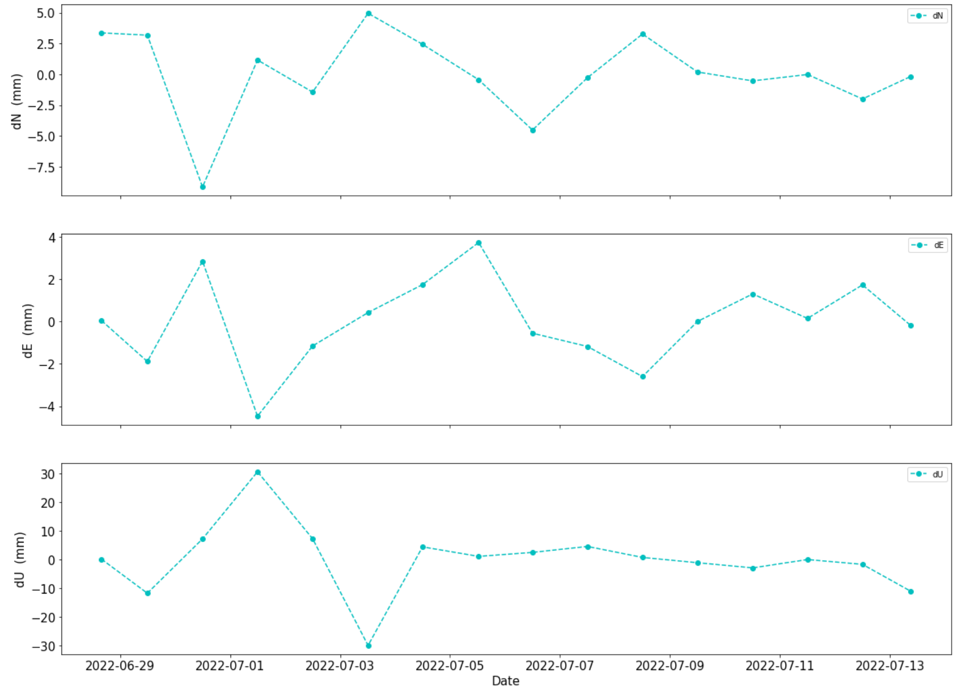


Figure 11. Graphs showing position time series for PROION station GEDP (University of Patras, Rio). Top panel shows the N-S component, middle panel the E-W component and bottom panel the Up-Down component, respectively.

3.4 Soft computing techniques for infrastructure monitoring

Condition assessment of civil engineering structures for their safety and remaining lifetime has been the epicenter of many researchers the past years. The development of advanced data monitoring equipment and the increase of the volume of data generated has led to the need of using data analysis techniques to process them and extract the necessary conclusions for the monitored infrastructures. The methods mainly used in such cases fall under the research sector of soft computing. Machine learning, neural networks, deep learning, fuzzy logic are some of the many methodologies utilized for processing the large volume of data generated from remote sensing data equipment such as SAR, UAVs, LIDAR, GNSS.

In the field of Machine learning, Support Vector Machines, Principal Component Analysis, Random Forests are used to perform off road surface monitoring. Landslide susceptibility, railway monitoring, detecting cracks in concrete surfaces are only some of the cases where machine learning algorithms such as boosted regression trees, bayesian optimization, logistic regression are being applied. However, in cases where more computational complexity is required, Artificial Neural Networks and especially Deep Neural Networks offer an optimized implementation. Civil infrastructure monitoring such as bridges, tunnels, roadways are some cases that have benefited from the application on such methods [33].

The aforementioned methods are strictly focused in the analysis of the large volume of data which in demands high computing capabilities in terms of equipment and requires a lot of time. Fuzzy logic and expert based techniques in general offer a more versatile way detecting critical cases when monitoring infrastructures. By combining the expert knowledge with existing data these methodologies can operate under uncertain and vague information without requiring precise figures of the system parameters [34].

The project “PROION” will attempt to use classic machine learning techniques along with fuzzy logic based techniques to combine data from different data sensing sources to assess the state of several important infrastructures.

3.5 Web platform

At the implementation phase, a dedicated PROION web platform will be developed. As a main PROION component, the platform will also act as a portal for the end-users to interact with the project's data and results. The platform's main aspect it to manage the data deriving from the acquired measurements and provide accurate information to the end-users/stakeholders. This information will be provided via the Web-GIS platform in order to closely monitor the micro kinetics analysis of the critical infrastructure, located at the Greek supersite by the name of "Enceladus".

The developed methodologies will combine the real-time and near real-time measurements. A simple graphic example explaining the functioning of the web platform follows:

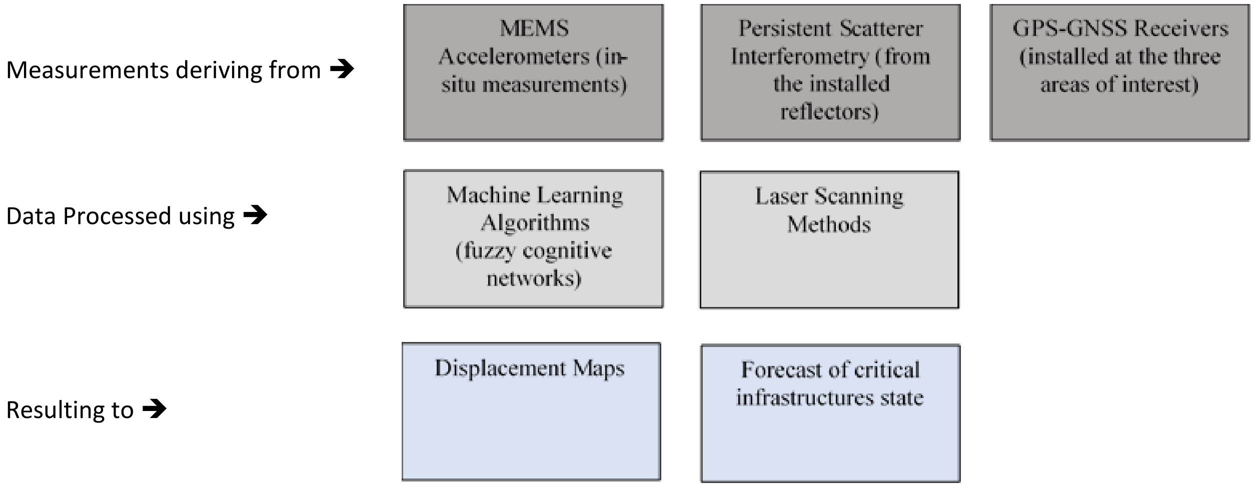


Figure 12. Description of PROION web platform key-elements

This approach combines change detection monitoring of the critical infrastructure and live forecasting of its future condition. PROION web platform will be used as a modern decision-making tool that will systematically provide information prior to a disaster. Furthermore, the service can be exploited for commercial use either to be sold partially or entirely as a service, including technical support and training. Moreover, the project's technical equipment parts are also available to the stakeholders.

Web platform components	Potential customers
- The whole service including technical support and training of the platform - The produced services (displacement maps, …)	- Construction- technical companies for infrastructure projects - Public technical services - Organizations or research institutes responsible for monitoring of critical infrastructure - Private organizations managing critical infrastructure (e.g. dams) - Educational institutions for student education
Technical equipment	
- MEMS Accelerometers including technical support and training - Reflectors including technical support and training	

4. FUTURE WORK

Fuzzy Cognitive Networks (VLS) is a new and innovative method belonging to the field of computational intelligence first introduced by Bart Kosko in 1986 [35]. They offer the ability to deal with problems in a way similar to that of the human brain, through a process that may involve vague and ambiguous situations. In this way they offer an economical, flexible and easy way to model systems behavior. The research team of UoP under the guidance of Prof. Petros Groubos continued these theories and has developed new methodologies with very good and useful results that are gaining worldwide recognition. Due to the specifics of each infrastructure (physical and / or human) it is necessary to use machine learning techniques in order to achieve the combination of users' knowledge with the data that will be taken from the meters to ensure the best knowledge of the system and achieving the most accurate and accurate results.

In particular, the proposed platform / web application will implement:

a) Using special algorithms that will be developed in near real time data merging application by MEMS 3-axis accelerometers & GPS/GNSS full system and will generate movement changes and distortion

b) Using special algorithms that will be developed in the almost near real time, notations will be generated from radar data using persistent scatterers and these results will be "calibrated" (checked, calibrated, adjusted) by the results of **a**.

Total displacements will be monitored based on the results of laser scanner and UAV fused 3D point clouds and a comprehensive map of changes, displacements and distortions will be generated. The set of methodology and the three new technological products will be a "commercially innovative product" for use in the Greek, European and global market.

Acknowledgments: We thank Ioannis Karamitros, Dimitris Anastasiou, Varvara Tsironi, Yiannis Maroufidis, Christos Kontopoulos and George Mavropoulos for many comments, suggestions and assistance in the field. «This research has been co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code: T2EΔK-02396 Multiparametric monitoring platform with micro-sensors of eNceladus hellenIc supersite)» https://proion-hellas.eu/

REFERENCES

[1] Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., Lenoir, J., Linnetved, H.I., Martin, V.Y., McCormack, P.C., McDonald, J., Mitchell, N.J., Mustonen, T., Pandolfi, J.M., Pettorelli, N., Popova, E., Robinson, S.A., Scheffers, B.R., Shaw, J.D., Sorte, C.J., Strugnell, J.M., Sunday, J.M., Tuanmu, M.N., Vergés, A., Villanueva, C., Wernberg, T., Wapstra, E., Williams, S.E. "Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being.", American Association for the Advancement of Science, 355, 6332 (2017), doi: 10.1126/science.aai9214

[2] Hunt, A., Watkiss, P., "Climate change impacts and adaptation in cities: a review of the literature.", Climatic Change,104, 13–49 (2011), https://doi.org/10.1007/s10584-010-9975-6

[3] World Meteorological Organization. Available online: https://public.wmo.int/en (accessed on 2 May 2022).

[4] Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N. K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneroz, B., Kattsov, V., Lee, H., Mach, K. J., Marotzke, J., Mastrandrea, M. D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J. J., Pichs-Madruga, R., Plattner, G. K., Pörtner, H. O., Power, S. B., Preston, B., Ravindranath, N. H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T. F., Tschakert, P., van Vuuren, D., van Ypserle, J. P., "Climate Change 2014: Synthesis Report. ", Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change / R. Pachauri and L. Meyer (editors) , Geneva, Switzerland, IPCC, 151 p (2014).

[5] Climate Change 2022: Impacts, Adaptation and Vulnerability. Available online: https://www.ipcc.ch/report/ar6/wg2/ (accessed on 2 May 2022).

[6] Baker, S., "San francisco in ruins: The 1906 aerial photographs of george r. Lawrence. ", Landscape, 30, 9–14 (1989).

[7] Kerle, N., "Disasters: Risk assessment, management, and post-disaster studies using remote sensing. ", In Remote Sensing of Water Resources, Disasters, and Urban Studies (Remote Sensing Handbook), Thenkabail, P.S., Ed., CRC Press: Boca Raton, FL, USA, pp. 455–481 (2015).

[8] Dong, L.G., Shan, J., "A comprehensive review of earthquake-induced building damage detection with remote sensing techniques. ", ISPRS-J. Photogramm. Remote Sens., 84, 85–99 (2013).

[9] Scaioni, M., Marsella, M., Crosetto, M., Tornatore, V., Wang, J., "Geodetic and remote-sensing sensors for dam deformation monitoring.", Sensors (Switzerland), 18(11), 1–25 (2018), https://doi.org/10.3390/s18113682

[10] Shen, N., Chen, L., Liu, J., Wang, L., Tao, T., Wu, D., Chen, R., "A review of Global Navigation Satellite System (GNSS)-based dynamic monitoring technologies for structural health monitoring.", Remote Sensing, 11(9) (2019). https://doi.org/10.3390/rs11091001

[11] Rashidi, M., Mohammadi, M., Kivi, S. S., Abdolvand, M. M., Truong-Hong, L., Samali, B., "A decade of modern bridge monitoring using terrestrial laser scanning: Review and future directions.", Remote Sensing, 12(22), 1–34 (2020). https://doi.org/10.3390/rs12223796

[12] Soilán, M., Sánchez-Rodríguez, A., Del Río-Barral, P., Perez-Collazo, C., Arias, P., Riveiro, B., "Review of laser scanning technologies and their applications for road and railway infrastructure monitoring.", Infrastructures, 4(4) (2019). https://doi.org/10.3390/infrastructures4040058

[13] Mukupa, W., Roberts, G. W., Hancock, C. M., Al-Manasir, K., "A review of the use of terrestrial laser scanning application for change detection and deformation monitoring of structures.", Survey Review, 49(353), 99–116 (2017). https://doi.org/10.1080/00396265.2015.1133039.

[14] Sony, S., Laventure, S., Sadhu, A., "A literature review of next-generation smart sensing technology in structural health monitoring.", Structural Control and Health Monitoring, 26(3), 1–22 (2019). https://doi.org/10.1002/stc.2321

[15] Feroz, S., Dabous, S. A., "UAV-based remote sensing applications for bridge condition assessment.", Remote Sensing, 13(9) (2021). https://doi.org/10.3390/rs13091809

[16] Outay, F., Mengash, H. A., Adnan, M. "Applications of unmanned aerial vehicle (UAV) in road safety, traffic and highway infrastructure management: Recent advances and challenges.", Transportation Research Part A: Policy and Practice, 141(October), 116–129 (2020). https://doi.org/10.1016/j.tra.2020.09.018

[17] Kerle, N., Nex, F., Gerke, M., Duarte, D., Vetrivel, A. "UAV-based structural damage mapping: A review.", ISPRS International Journal of Geo-Information, 9(1), 1–23 (2019). https://doi.org/10.3390/ijgi9010014

[18] Azimi, M., Eslamlou, A. D., Pekcan, G., "Data-driven structural health monitoring and damage detection through deep learning: State-ofthe- art review.", In Sensors (Switzerland), Vol. 20, Issue 10 (2020), https://doi.org/10.3390/s20102778

[19] Ye, X. W., Jin, T., Yun, C. B., "A review on deep learning-based structural health monitoring of civil infrastructures.", Smart Structures and Systems, 24(5), 567–585 (2019). https://doi.org/10.12989/sss.2019.24.5.567

[20] tCat-Disrupting the Rail Maintenance Sector Thanks to the Most Cost-Efficient Solution to Auscultate Railways Overhead Lines Reducing Costs up to 80%. Available online: https://www.fabiodisconzi.com/open-h2020/projects/211356/index.html (accessed on 24 May 2022).

[21] AutoScan. Available online: https://cordis.europa.eu/project/rcn/203338/factsheet/en (accessed on 24 May 2022).

[22] NeTIRail-INFRA. Available online: https://cordis.europa.eu/project/rcn/193387/factsheet/en (accessed on 24 May 2022).

[23] Tsironi, V.; Ganas, A.; Karamitros, I.; Efstathiou, E.; Koukouvelas, I.; Sokos, E. Kinematics of Active Landslides in Achaia (Peloponnese, Greece) through InSAR Time Series Analysis and Relation to Rainfall Patterns. Remote Sens. (2022), 14, 844. https://doi.org/10.3390/rs14040844.

[24] Varnes, D.J. Slope movement types and processes. Spec. Rep. (1978), 176, 11–33.

[25] Hungr, O.; Leroueil, S.; Picarelli, L. The Varnes classification of landslide types, an update. Landslides (2014), 11, 167–194.

[26] Evers M., A. Kyriou, A. Thiele, H. Hammer, K. Nikolakopoulos, and K. Schulz "How to set up a dam monitoring system with PSInSAR and GPS", Proc. SPIE 11534, Earth Resources and Environmental Remote Sensing/GIS Applications XI, 115340L (20 September 2020); https://doi.org/10.1117/12.2573880

[27] Adam, N., Parizzi, A., Eineder, M., Crosetto, M., “Practical persistent scatterer processing validation in the course of the Terrafirma project,” Journal of Applied Geophysics, 69(1), 59-65 (2009).

[28] Marinkovic, P., Ketelaar, G., Van Leijen, F., Hanssen, R., "InSAR quality control: Analysis of five years of corner reflector time series," Proc. Fringe 2007 Workshop, 1-8 (2007).

[29] Ganas, A., Elias, P., Briole, P., Valkaniotis, S., Escartin, J., Tsironi, V., Karasante, I, Kosma, Chr. 2021. Co-seismic and post-seismic deformation, field observations and fault model of the 30 October 2020 Mw = 7.0 Samos earthquake, Aegean Sea. Acta Geophys., 69, 999-1024 https://doi.org/10.1007/s11600-021-00599-1

[30] Moschas F, Stiros S. 2015. Dynamic deflections of a stiff footbridge using 100-Hz GNSS and accelerometer data. J Surv Eng.; 141(4). 04015003, 04015001-04015008

[31] Janos, D. and Kuras, P., 2021. Evaluation of low-cost GNSS receiver under demanding conditions in RTK network mode. Sensors, 21(16), p.5552, https://doi.org/10.3390/s21165552

[32] Geng J, Chen X, Pan Y, Mao S, Li C, Zhou J, Zhang K 2019. PRIDE PPP AR: an open source software for GPS PPP ambiguity resolution. GPS Solutions, 23(91):1-10. doi:10.1007/s10291-019-0888-

[33] Mpelogianni, V., & Groumpos, P. P. (2018). Re-approaching fuzzy cognitive maps to increase the knowledge of a system. AI & SOCIETY, 33(2), 175-188.

[34] Azimi, M., Eslamlou, A. D., & Pekcan, G. (2020). Data-driven structural health monitoring and damage detection through deep learning: State-ofthe- art review. In Sensors (Switzerland) (Vol. 20, Issue 10). https://doi.org/10.3390/s20102778

[35] Kosko, B.: Fuzzy Cognitive Maps. Intern. Journal of Man-Machine Studies 24, 65–75 (1986)